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Review

HBIM: Background, Current Trends, and Future Prospects

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Abstract: Historic building information modeling (HBIM) represents an emerging field that extends traditional building information modeling (BIM) to the preservation, management, and analysis of heritage structures. This paper provides a comprehensive overview of HBIM, tracing its evolution from its origins and early applications to its current state and future prospects. The processes of data collection and modeling are thoroughly examined, addressing levels of detail, digitization methods, and commonly used software and data formats. Attention is also given to existing BIM standards and protocols and their potential application to HBIM. The paper emphasizes the importance of appropriate data selection and management, both for geometrical and non-geometrical (historical and architectural) information. Furthermore, it explores the integration of HBIM with structural analysis tools, a subject of growing interest, particularly in light of its potential for integration with structural health monitoring systems and advanced computational models. The results of this review highlight the increasing role of HBIM in heritage preventive preservation and management, a topic that accounted for 40% of the articles on this subject in 2023. These findings demonstrate that HBIM offers significant potential for managing and preserving heritage buildings, but to fully realize its capabilities, advancements in data interoperability, standardized protocols, and real-time structural analysis are essential to make it a widely effective tool in conservation efforts.

Keywords: HBIM; BIM; built heritage; cultural heritage; historic building; preventive preservation; heritage management

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1. Introduction

Building information modeling (BIM) refers to a collaborative method for generating and managing structured digital information of the physical and functional characteristics of a building or construction project. Although often associated with modern practices, BIM has its roots in object-based parametric modeling applications originally developed for mechanical systems design in the 1980s [1]. However, the origins of the BIM concept trace back to the early days of computing. As early as 1963, architect D. C. Englebart described a vision for the future of architecture that closely resembles the current concept of BIM: *"the architect next begins to enter a series of specifications and data—a six-inch slab floor, twelve-inch concrete walls eight feet high within the excavation, and so on. When he has finished, the revised scene appears on the screen. A structure is taking shape. He examines it, adjusts it… These lists grow into an evermore-detailed, interlinked structure, which represents the maturing thought behind the actual design"* [2].

Over the past two decades, BIM has transformed the conventional methods of design and construction by fostering enhanced integration and collaboration among all parties involved throughout the lifecycle of a project [3]. This technology facilitates a more coordinated approach, allowing architects, engineers, contractors, and other stakeholders to work from a shared, real-time model. By streamlining communication and minimizing errors, BIM not only improves efficiency but also contributes to more sustainable and cost-effective project outcomes. Its ability to provide a comprehensive view of the project at every stage, from planning and design to construction and maintenance, has made it a game-changer in the architecture, engineering, construction, and operations sectors [4].

The growing development of BIM techniques and their successful application in new construction has sparked interest in applying them to historic buildings as well. In this context, the term historic building information modeling (HBIM), also referred to as heritage building information modeling, began to emerge in the early 2010s as a specialized adaptation of the BIM method for cultural heritage (CH) structures [5]. HBIM seeks to extend the BIM principles to address the unique challenges presented by heritage assets [6], including irregular geometries, incomplete historical records, and the need to preserve cultural significance alongside structural stability, which is often at risk.

As with standard BIM, the core concept of HBIM involves the modeling of a detailed digital replica of a built asset, in this case, a heritage structure, integrating physical and historical information. This model serves as a dynamic database that can be used not only for restoration and conservation purposes but also for ongoing maintenance and monitoring [7]. Unlike conventional BIM, where most data are available or generated during the project, HBIM requires specialized approaches to data collection, modeling, and analysis due to the complexity and uniqueness of historical buildings. Considering the growth of HBIM and its applications in recent years, it is reasonable to hypothesize that it is emerging as a critical tool for the documentation, preservation, and management of heritage structures. However, an analysis of the practical application and usability of these models in real-world heritage contexts is necessary to fully understand their current use and potential impact and limitations.

Therefore, the HBIM methodology can be structured into three phases: data acquisition, data processing and modeling, and management. During the data acquisition phase, various techniques are employed to gather geometric information (e.g., laser scanning, photogrammetry, and total station measurements) [8] along with non-geometric data (e.g., historical context, architectural details, material properties, functional and structural pathologies, and condition assessments). The documentation process plays a crucial role in collecting all relevant non-geometric information necessary for the development of the model. Next, the collected data must be processed, verified for accuracy, and evaluated for their applicability to the HBIM model's purpose [9]. The geometric data are then used to create a 3D model of the building using appropriate BIM software, while non-geometric data are either embedded directly into this geometric model or stored in an external database linked to it [7]. This 3D information model is subsequently used for the management of the building, serving multiple purposes with the overarching aim of guiding the conservation plan and planning any necessary interventions [8,10]. Additionally, any new data obtained during the management phase, whether through model analysis or further tests on the building, should be processed and incorporated into the HBIM model to ensure they remain up-to-date. This workflow is illustrated in Figure 1.

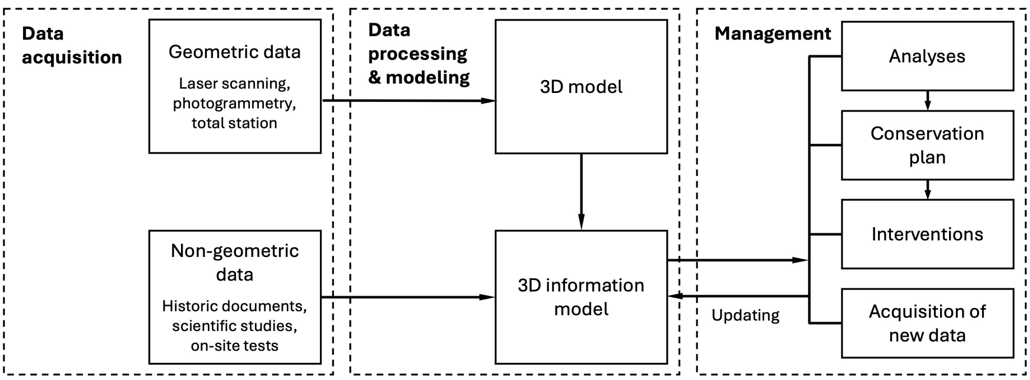


Figure 1. HBIM general workflow.

Over the past decade, research on HBIM has focused on three fundamental aspects: data acquisition processes and modeling techniques, the use of HBIM for heritage building management, and the conduction of structural condition analyses within HBIM environments. These areas aim to address the main challenges and applications of HBIM methodology. While early research primarily concentrated on data capture techniques and model creation, attention in recent years has shifted toward the use of HBIM models for building management and condition analysis. The introduction of real-time monitoring systems and the development of digital twins of heritage structures within an HBIM environment has great potential for transforming building management by optimizing lifecycle efficiency, resource use, and sustainability [4].

This paper offers a comprehensive review of historic building information modeling, tracing its origins and development and exploring current standards, protocols, and data collection methods. It delves into modeling methodologies, common data requirements, and the growing range of HBIM applications. Additionally, the paper discusses the potential for integrating structural analysis tools within HBIM environments, highlighting their expanding role in heritage preventive preservation and management. This review aims to analyze the major advancements in the field of HBIM over recent years and how these developments have improved the management of architectural heritage. Furthermore, it seeks to examine the main current research areas in HBIM to identify and discuss key strengths, weaknesses, challenges, and potential future advancements.

2. HBIM's Origins and Development

The concept of HBIM, as an acronym for "Historic Building Information Modeling", was first proposed by Murphy et al. [11] in 2009 as a novel system of modeling historic structures involving the collection of survey data about an asset using a terrestrial laser scanner combined with digital cameras, meshing the point cloud data, and finally, texturing it to create a three-dimensional model.

At the beginning of the 2010s, the first examples of the application of the HBIM methodology began to appear in scientific publications. In 2012, M. Murphy presented his PhD thesis [12], which showcased the first application of HBIM by using the concepts proposed in [11] to document CH buildings in Ireland. This was followed by the development of a library of interactive parametric objects with 3D geometry, including details on methods of construction and material composition [13]. The introduction of interactive parametric 3D objects was essential for HBIM, enabling customizable and accurate representations of heritage structures' unique and complex elements and simplifying documentation and management. Simultaneously, Boeykens et al. [14] presented, without using the term HBIM, the generation of a BIM model of Vinohrady synagogue in Prague, a CH building that was already destroyed, using only historical documentation. During these early years, other authors also explored aspects related to BIM for heritage structures, including techniques for the reconstruction of the geometry of architectural details [15], the generation of a library of parametric objects of classical architectural buildings [16], or the development of software applications for processing the parametric data [17].

Soon, other researchers began to show interest in the application of the BIM methodologies to historical constructions, and the term HBIM started to become popular. Since 2015, several studies have explored the possibilities and the particular requirements of HBIM, focusing on its application in specific case studies [18,19], data collection and modeling techniques [20], the usefulness of HBIM as a tool to manage built heritage [6,21–23], or the possibilities of using the HBIM model to conduct structural analysis on a specific software (i.e., the export–import process between software) [24,25].

The growing concern for the preservation of the vast architectural heritage in many countries, together with the advancements in data collection technologies, 3D modeling techniques, and information management systems, has led to increased interest in HBIM projects worldwide. The scientific community has responded to this trend, as evidenced by the nearly exponential rise in publications related to HBIM in recent years, as shown in Figure 2. The publications included in this graph and analyzed in the current study are those indexed in the Web of Science, including in their topic (*"BIM" OR "HBIM" OR "building information modeling" OR "building information modeling" OR "building information model") AND ("heritage" OR "historical architecture" OR "historical building"*). These results were limited to the period 2010–2023 and filtered by excluding the research areas not related to historical heritage building models, leaving a total of 1094 publications.

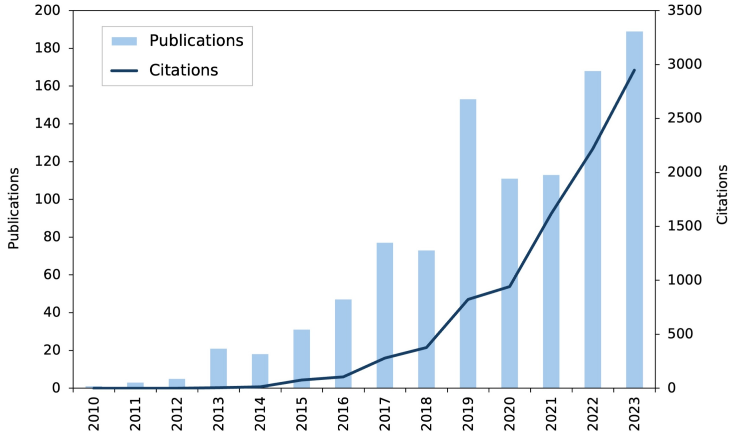


Figure 2. Publications and citations in the Web of Science regarding HBIM between 2010 and 2023.

Since its introduction, the term HBIM has been broadly adopted to refer to the general application of BIM techniques to historical and heritage buildings, including not only the creation of a 3D model but a whole collaborative process for the production and management of structured electronic information about historic constructions. Additionally, in recent years, several authors have used the term HBIM as an acronym for "Heritage Building Information Modeling", considering *heritage* a broader term that includes historical data, conservation policies, and significance values [6].

In any case, the need to differentiate between traditional BIM and HBIM stems from their differing purposes and the specific characteristics of the buildings they are designed for. While BIM focuses on new building design and construction, HBIM is centered on existing constructions that usually require interventions such as conservation, restoration, repurposing, and rehabilitation [8]. In addition, historical buildings often present complex geometries and structural systems, and the information available is limited or incomplete, having to deal with several uncertainties. This complexity requires a multidisciplinary collaboration among various experts to ensure the accurate acquisition and processing of data, as well as to value the historical significance of the building, which is critical for decision-making regarding its maintenance and potential interventions [26,27]. In fact, the HBIM-related scientific publications analyzed in this review span a wide range of research areas, including Computer Science, Engineering or Construction Building Technologies, Art and Humanities, Geography, and Environmental Sciences, among others. The main research areas to which these publications belong are shown in Figure 3 (only categories with values over 5% are represented; the total exceeds 100% since several publications are indexed under multiple categories).

Regarding the geographical distribution of the studies, HBIM has generated interest in many countries worldwide (see Figure 4), especially those who are eager to explore its potential for preserving their architectural heritage. Notably, a significant number of scientific publications have been developed in Italy, accounting for up to 44% of the total, followed by Spain (14%), China (11%), and the UK (8%). These numbers can be attributed to the vast architectural heritage found in these countries, along with a strong awareness and tradition of its preservation and maintenance. In fact, countries like Italy and Spain have been global leaders in the development and implementation of BIM policies and are at the forefront of advancements and scientific research in the HBIM field [28].

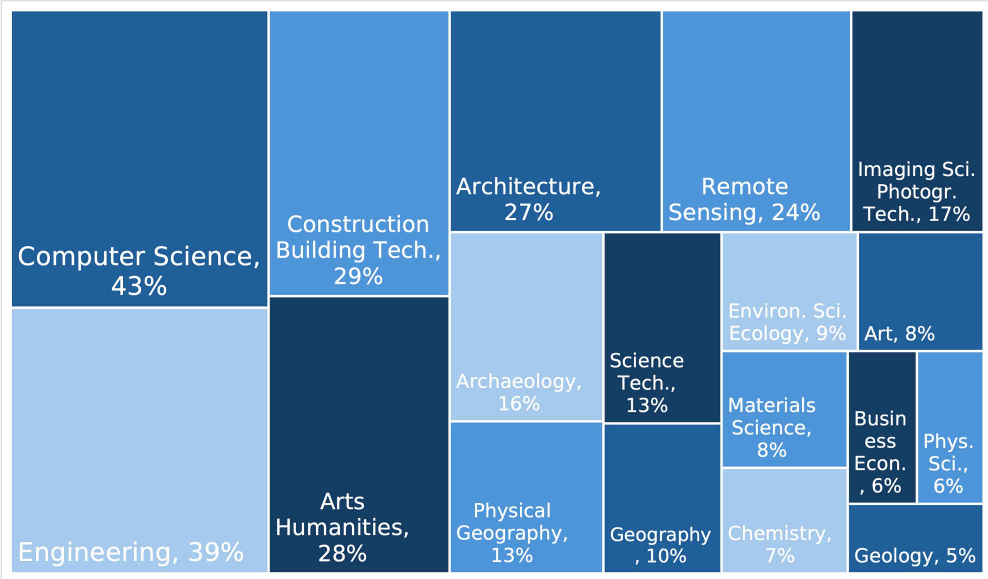


Figure 3. Percentage of HBIM publications by research area in the Web of Science database (2010–2023).

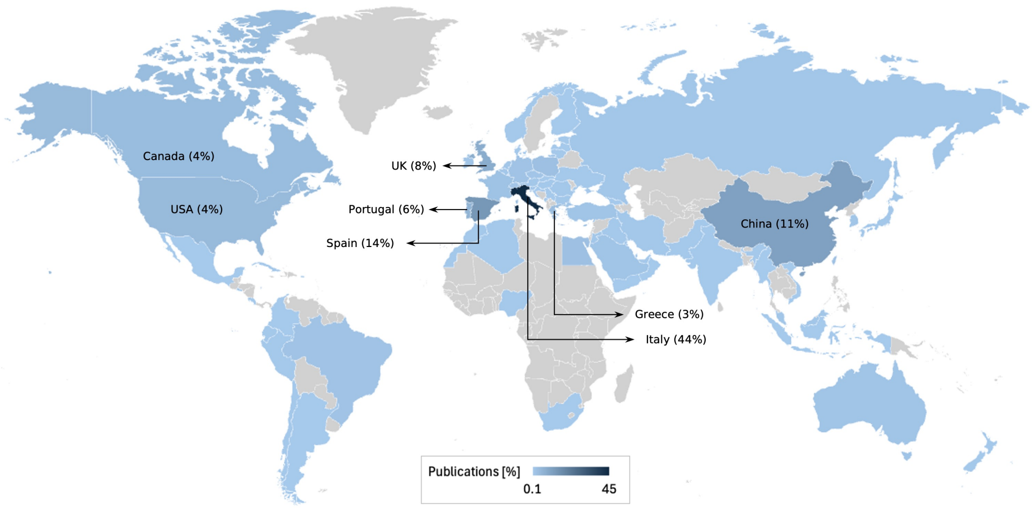


Figure 4. Distribution of HBIM-related publications by country (2010–2023).

3. Standards and Protocols

Since the beginning of the 21st century, there has been growing interest among international heritage preservation institutions in promoting modern technologies to digitize tangible cultural heritage as a means of preserving it in the event of the loss of a physical asset. To ensure that these digital versions of heritage assets are reliable, accurate, and representative, some international standards, protocols, and recommendations have been developed in recent years. The International Council on Monuments and Sites (ICOMOS) has been a pioneer in promoting scientific methodologies for the preservation of architectural heritage (Figure 5), and the digitization of historic structures is no exception. In fact, the first international call for the digitization of CH buildings was introduced in the 2000 ICOMOS Charter of Krakow [29], three years before UNESCO approved the Charter on the Preservation of Digital Heritage [30].

Figure 5. ICOMOS charters and declarations about heritage preservation and digitization.

These initiatives were further strengthened by the Vancouver Declaration [31] in 2012 and the 2015 recommendation on preserving documentary heritage. In 2017, the International Principles of Virtual Archaeology (Seville Principles) [32] were ratified by the 19th ICOMOS General Assembly, following the guidance set forth in The London Charter for computer-based visualization of cultural heritage [33]. These standards and protocols outline procedures for digitizing tangible heritage and making these models accessible to experts and the public. However, despite the development of protocols about heritage digitization, the lack of international standards governing the application of BIM methodology to heritage buildings is still one of the most significant challenges that HBIM technology has to face.

There is an international standard for BIM, ISO 19650 [34], developed by the Architectural Engineering and Construction Industry, which defines a procedure for the digital management of built assets. The standard includes recommendations for defining a management framework for BIM model information, covering aspects like information exchange, registration, version control, and organization, applicable across the entire lifecycle of a building. It aims to ensure that all information is sufficiently detailed to support decision-making at every project stage. According to the standard, information should be accessible to any user and reliable enough to facilitate seamless exchange between all stakeholders involved in different project phases. However, even though ISO 19650 provides a valuable framework for digital collaboration in BIM, there are certain ambiguities and gaps in the standard, such as the lack of a definition of the specific content requirements for various levels of detail or its focus on new construction, that can pose challenges in heritage applications [7].

Another relevant BIM standard is the Italian UNI 11337 [35], which provides a framework for managing building information modeling processes across various phases and disciplines. This standard outlines guidelines for the structured flow of project information, ensuring alignment between client expectations and project execution. UNI 11337 introduces a unique level of development classification from A to G, combining geometric detail and information quality, and defining essential roles like BIM coordinator, BIM manager, and common data environment manager to streamline team collaboration. Additionally, the standard incorporates BIM's extended dimensions (4D to 7D, covering time, cost, operation, and sustainability), positioning it as a comprehensive tool that supports Italy's evolving public procurement requirements and aligns with international standards while adapting to local industry needs. Despite the large number of historic buildings and the notable development of HBIM models in the country, this Italian regulation does not specifically address the application of BIM methodologies to heritage structures.

The lack of standardization in HBIM methodologies creates issues with the interoperability of both the models and their associated information, hindering one of the main goals of utilizing BIM technology for the digitization of CH. To address this challenge, some countries have developed national protocols or guidelines for creating HBIM models. In the UK, Historic England published a guide in 2017 on the use of available data from historical buildings for the development of HBIM, titled "BIM for Heritage" [1]. In Spain, the Spanish Cultural Heritage Institute has published a guide on best practices, drawing from previous intervention guides and outlining the differences depending on the type of heritage to be modeled [6]. Similarly, Historic Environment Scotland has translated BIM standards to cultural heritage by adapting the usual levels of development from BIM for heritage case studies [36]. Some regions, like Singapore, have developed BIM protocols and templates that can be adapted for HBIM, even though they are not specifically designed for CH. Meanwhile, countries such as Germany and Poland are working on HBIM guidelines through public institutions like the Building Research State Offices for Monument Preservation and the National Institute of Cultural Heritage, respectively [37]. Additionally, in Poland, public templates or cards known as "White Cards" allow non-graphical information to be obtained from the HBIM model. This template, similar to the one developed in Singapore, was designed by the National Heritage Board of Poland and has already been tested on cultural heritage assets [38].

Other examples of protocols and guidelines have been created, implemented, and evaluated in heritage buildings across different countries, cultural contexts, and historical periods by HBIM model authors [6,39,40] based on previously mentioned guidelines. However, these protocols have limited applicability due to the diversity of CH, although some common characteristics can be identified among them. The specific, often national characteristics of these protocols and guidelines limit their adaptability to other countries or contexts. To address this challenge, some authors have attempted to develop more generalized strategies and protocols for HBIM modeling that are applicable to various CH cases, although they are often tested on specific heritage examples [41]. However, some protocols have been successfully created and tested in multiple countries [42], defining categories of non-graphical data for similar heritage buildings and establishing common workflows and data collection strategies.

To overcome the heterogeneity of protocols and guidelines and their specificity, the European Union has developed an interoperable platform to facilitate the sharing of HBIM models, collecting and distributing graphical and non-graphical data through an open standard semantic web [43]. This platform, based on an open-access format, allows the use of data across different operating systems and software. As a result, it serves as an international tool to standardize templates, formats, and data acquisition processes, consolidating various national guidelines [43]. A common feature among all these initiatives is the establishment and definition of formats and semantic fields that incorporate non-graphical information based on international charters, converging on specific levels of non-graphical data, similar to the approach used in BIM technology. This framework is sometimes complemented by other authors [44] with additional information categories such as maintenance, manufacturer details, monitoring, and other non-graphical data relevant to modeling and acquisition procedures. At the same time, the European Union is also encouraging data transparency and availability through the definition of a standardized Digital Building Logbook, which aims to be a common repository for all building-related data [45].

A recent example of the use of open-access formats as an attempt to standardize the HBIM modeling process involves Roman concrete, known as *opus caementicium* [46]. This material can now be found in the vocabulary database for Industry Foundation Classes (IFC) formats, and the Getty Art and Architecture Thesaurus and can be used in any HBIM model of a Roman building. The information in the database was validated according to the accuracy and fidelity requirements set by the BIM standards. The material has a unique reference found in the vocabulary database of IFC formats, enabling any user to integrate this material and its associated data without risk of information loss or misinterpretation. This is an example of how IFC formats may adopt well-established vocabularies, allowing them to be used in any HBIM model that includes this material. However, since CH is diverse, materials or techniques are rarely identical from one construction to another, making it necessary to adapt standardized materials to the regional, cultural, or other specific characteristics of the CH being modeled [47]. Therefore, it is necessary not only to standardize families, materials, and construction techniques, in a similar way as it has been done in traditional BIM, but also to develop a strategy for adapting historical elements to international standards to homogenize procedures and models.

4. Data Collection and Modeling

The HBIM methodology, primarily based on BIM technology, can be considered an adaptation of the BIM approach to address the challenges presented by the unique characteristics of historical and heritage buildings, which often have more complex geometries than modern constructions. The peculiarities of these structures, along with the need for their preservation and structural safety assessment, make data collection one of the most critical aspects of the HBIM methodology. It is essential that the final model is both reliable and accurate yet simplified enough to avoid unnecessary increases in computational cost [48]. Also, the collected data should fit the specific requirements and applications of the BIM model. After all geometrical information is collected, it is crucial to supplement this information with non-graphical data. In terms of interoperability, this non-graphical information enables HBIM models to be exchanged between different software platforms. However, the format used must ensure both interoperability and compatibility between various systems and software [49]. Nevertheless, without an accurate and reliable geometrical model, these HBIM models will have limited practical value for exchange. As a result, methods for data collection and modeling are continuously being refined to improve accuracy and reduce computational cost [50] while simultaneously advancing interoperability through universal data formats.

4.1. Model Definition

As described in the previous section, current HBIM protocols and guidelines are primarily focused on standardizing the collection and transfer of both graphical and non-graphical information, ensuring consistency in the formats used to store and exchange this data. For HBIM, the classification of information and the formats employed for its exchange are derived from those already established in BIM technology. Data gathered through 3D scanning or photogrammetry techniques, among others, forms the basis of the graphical information, which includes the geometry, dimensions, location, and orientation of the modeled CH asset [44]. This graphical data determines what is referred to as the levels of detail. However, to provide a complete understanding of the CH and its context, this graphical information must be complemented by non-graphical data, such as details related to maintenance, monitoring, manufacturers, and other relevant aspects. These non-graphical details define the level of information (LOI). The combination of the level of detail and the level of information establishes the level of development (LOD) [44]. The concept of LOD, first introduced by the American Institute of Architects in 2008, refers to the degree of completeness and accuracy to which a BIM element is developed. Typically, these levels of development are classified into six stages:

- LOD 100. Pre-design or conceptual design: The information is purely graphical and limited to the primary external and physical characteristics. No metadata are included (no LOI).
- LOD 200. Schematic design: This is the first level of development that incorporates LOI (non-graphical information). At this stage, the size, form, and location of the element are defined.
- LOD 300. Design development: This level includes an accurate representation of the real dimensions of the element, along with material specifications and non-graphical aspects, such as their chemical or mechanical properties.
- LOD 350. Construction-ready model: An intermediate level that adds additional information about the relationships between the modeled elements within the building.

- LOD 400. Construction stage: A high level of graphical detail is provided, along with manufacturer and construction-related information pertaining to the material and structural elements. A precise description of the connections and interactions between elements is included.
- LOD 500. As-built: The highest level of detail and information, including all necessary data, to fully represent the modeled element. It is suitable for building management and maintenance.

The definition of the level of development of the model is crucial for enhancing the interoperability of HBIM across researchers, users, software, and systems. However, the diversity of cultural heritage poses challenges for homogenizing the criteria used to define various LODs. In this regard, a few authors have adapted these criteria specifically for HBIM modeling [10], and there is a general consensus that HBIM models often require a higher LOD due to their complex geometric structures and historical intricacies [51,52].

4.2. Data Collection Techniques

The unique characteristics of cultural heritage buildings make it difficult to standardize the collection of geometrical data required for the creation of an HBIM model. Hence, prior historical analysis and research should be conducted to establish a strategy for data collection, identify the structural and architectural elements, and determine the appropriate graphical scales to be collected [53]. When designing data collection processes for an HBIM model, other factors must also be considered, such as the scale and accessibility of the element or building to be modeled, access to equipment, cost, the time required, and expertise [54]. Additionally, for complex CH models, it is necessary to combine large-scale spatial information with specific detailed information. Two of the most commonly used techniques for data collection, laser scanning and photogrammetry, are described below. Several authors also combine both techniques to achieve high-accuracy 3D models [55–57]. These techniques, particularly 3D laser scanning, were initially rooted in traditional topographical technologies, such as theodolites and total stations, which are now used as auxiliary tools to complement data collection from both photogrammetry and 3D laser scanning sources [58,59].

4.2.1. Laser Scanning

Three-dimensional scanners use lasers to generate millions of points that create a point cloud representing the geometrical composition of the scanned element [54]. This point cloud can subsequently be processed and optimized to reduce the number of points without losing relevant information. Various 3D laser scanners are currently available, and several factors influence their selection [53]. Depending on the angle of capture, there are aerial and terrestrial lasers. The scale of the element to capture (since CH can range from small decorative elements to monumental complexes or urban settlements) determines whether a long-range, medium-range, or short-range laser scanner should be used [60]. Other 3D laser scanners may vary based on whether they can be used with or without contact, whether they consist of passive or active systems, or whether they employ static or dynamic methods. The availability of these scanners is one of the main challenges for both public and private institutions, as the prices of the scanners, particularly those designed for longer ranges, are often prohibitive. This makes it difficult to ensure the homogenization of data acquisition among HBIM models [61]. Moreover, software that facilitates working with the acquired data to simplify the model without loss of accuracy can also be considerably expensive and is rarely open access [62].

4.2.2. Photogrammetry

Photogrammetry is a more affordable alternative to laser scanners for accurately acquiring geometrical data from historical buildings. This technique uses photographs combined with reference site measurements, allowing different lenses to be employed to capture various scales of detail with the same camera. In contrast, different laser scanners are needed for varying ranges, significantly increasing the cost of data collection from monumental complexes, especially when the surrounding area must also be documented [54]. Similar to laser scanning, the results obtained through photogrammetry are transformed into a point cloud, and in most cases, post-processing is necessary to optimize the graphical data [63].

One advantage of photogrammetry is that it generally requires less expertise for data acquisition compared to laser scanners. However, there are limitations when collecting data in outdoor sites due to changing ambient lighting conditions [54]. Additionally, photogrammetry can be time-consuming, especially when high accuracy is required, compared to the time spent using laser scanners for the same level of precision [55].

4.3. Software and Data Formats

4.3.1. Software

The BIM software that is currently available can be categorized into two main groups: 3D modeling and 3D visualization. Three-dimensional modeling software features parametric design tools primarily focused on modeling new constructions but can also be employed to create digital representations of existing buildings [47]. Most modeling software, in any case, facilitates the creation of standard elements typical of contemporary construction, requiring more manual modeling work for buildings with unique geometries, such as heritage buildings. On the other hand, 3D visualization software is designed, as its name suggests, solely for viewing the geometry of the BIM model and, in most cases, for consulting the associated metadata. Minor operations, such as taking measurements or creating sections, are typically available, but they do not allow for editing the model.

The current BIM market offers a wide range of 3D modeling and visualization software, providing diverse options tailored to various needs in heritage and construction modeling. Commonly used 3D modeling software includes Autodesk Revit, ArchiCAD, Nemetschek Allplan, Bentley OpenBuildings Designer, Edificius, SketchUp, Tekla Structures, Vectorworks, and 3DExperience. Popular choices for 3D visualization include Autodesk Viewer, SketchUp Viewer, Tekla BIMsight, and Navisworks Freedom. While not exhaustive, this list offers a snapshot of the most frequently adopted tools, reflecting the broader range of BIM software available for modeling and visualizing both contemporary and historic structures.

Autodesk Revit is by far the most used BIM software. In fact, according to the European Architectural Barometer [64], 45% of architects in Europe use Autodesk Revit as BIM software, followed by Graphisoft's ArchiCAD, which is used by about 33% of professionals. However, there are differences between countries; for instance, in Spain, up to 74% of BIM users use Revit and only 4% use ArchiCAD [65], while in Germany, the main BIM software is Nemetschek's Allplan, chosen by 31% of architects for BIM purposes.

Although BIM software can be affordable for large companies and public institutions, it is typically very expensive, making accessibility a challenge for small businesses and private users. Among the most commonly used modeling software in the BIM sector, only Edificius is completely open access. Visualization software is generally designed and developed by BIM software suppliers. Tekla and Autodesk, for example, have created BIM software in response to the need to adapt 2D and 3D drawing tools to the current trend of using BIM technology as the primary working method in the construction and structural design of new buildings. Accessibility to BIM tools presents a challenge as the methodology expands, especially since some countries have mandated the use of BIM technology for project presentations of newly constructed buildings to ensure their safety and accuracy.

4.3.2. Data Formats and Interoperability

The interoperability of HBIM among models and software relies on the effective export and import of both graphical and non-graphical data, as well as the ability to work with this data regardless of the software used. After defining the level of development as previously described, the next step is to disseminate and export the data in a unified format. This format must contain and preserve all graphical and non-graphical information without alteration, ensuring that it remains readable at all times.

Formats that can import and export all information at once can be categorized as either proprietary or non-proprietary file formats. Proprietary formats are not readable by other software, even though they typically contain similar information created by the same BIM modeling software developers. The most used and well-known example of a non-proprietary format is the IFC format, which allows for readability across various software platforms [34]. It includes the same information as proprietary formats but offers open-access data, facilitating a more democratic use of HBIM technology and enhancing interoperability between software systems [53]. In contrast, the transferability of proprietary formats to other software often depends on separate agreements.

The IFC standard continues to evolve, with the introduction of the IfcAlignment entity in version 4.1 and further enhancements in IFC 4.3, which incorporates specialized domains to address both land and maritime infrastructure specifications. These updates are designed to facilitate high-level semantic representation for infrastructure projects, aiding software developers in achieving greater precision in project contexts [66]. However, there remains a significant gap in the development of IFC standards tailored to heritage structures. Diara et al. [67] proposed a workflow to enhance HBIM interoperability using experimental IFC classifications, addressing the challenge that IFC formats for HBIM cannot directly align with ISO standards by introducing semantic fields and classifications. Similarly, Barrotini et al. [39] applied IFC standards in a case study of the Ducal Palace of Guimarães (Portugal), successfully demonstrating interoperability, although the application was limited to open-access BIM software.

Another non-proprietary format is the Construction-Operation Building Information Exchange (COBie), which focuses on asset data rather than graphical data. While the IFC format is more equitable in its approach, COBie serves a different purpose. As mentioned earlier, these non-proprietary formats are increasingly favored for use with HBIM models [68]. This trend is evident in the fact that most BIM software developers have recently incorporated the capability to work with these open-access formats alongside their proprietary formats.

5. Applications and Data Management

Since the early emergence of HBIM, most scientific studies and publications have focused on four main areas: data collection methods and tools, 3D modeling, the establishment of procedures and workflows for infrastructure management, and, to a lesser extent, interaction with external software for additional analyses (mainly structural). Although these topics seem to cover a broad range, there is a noticeable lack of information on the actual application of the developed HBIM models in practice.

Despite the growing popularity of HBIM, significant shortcomings have been identified that jeopardize their practical usefulness, and, in many cases, there is little evidence that the HBIM models developed during the last years are currently being used in practice [7]. Several HBIM models were created without a clear and well-defined purpose, rendering them ineffective in addressing the practical needs that arise during the management of the building. Frequently, the required data are unavailable, either because it was not collected or was improperly stored, and, in some cases, the software used or the way the geometry is defined is incompatible with the current needs. In some other cases, HBIM models were created during a specific project with a limited scope (e.g., a specific restoration project), so they are abandoned after serving that function [9,51].

These issues could be addressed, or at least mitigated, by properly defining the objectives of the HBIM model from its initial conception, allowing for the selection of necessary data to fulfill its intended purpose, while at the same time developing models flexible enough to accommodate new data for potential future applications.

5.1. Common Data Requirements

The various uses of HBIM models and the absence of harmonized standards result in each case measuring and storing different data about the asset under evaluation. However, there is fundamental information that is common to most BIM models for architectural heritage.

5.1.1. Geometric Data

The first essential information any BIM model must contain is the geometric data, which will be the basis for defining all other attributes [69]. Having an accurate geometry is particularly important for the preservation of historic buildings [70], especially considering the often complex nature of these structures. Therefore, the key factor to be defined when planning the creation of the model is the level of detail to be achieved. A higher LOD allows for a more precise representation of specific geometric features but comes at the cost of increased model size and a greater workload for its creation. Additionally, it will be limited by the available data collection tools. The state of the art of data collection and modeling tools have been explained in further detail in Section 4.

5.1.2. Non-Geometric Data

The need to include heritage-specific information unique to each individual asset is what truly sets HBIM apart from conventional BIM. Although the incorporation of non-graphical information is also essential in BIM models for contemporary structures, the unique characteristics of historical structures make this aspect particularly relevant and complex. Historic buildings derive their value from a range of historical, architectural, and artistic features that make them unique, and these must be included in a comprehensive HBIM model. These characteristics are often qualitative and generally difficult to standardize, as many of them are specific to each particular building. While the Nara Document on Authenticity of the UNESCO [71] emphasizes that avoiding the imposition of mechanical formulas and standardized processes is crucial to preserving cultural and heritage diversity, this lack of standardization presents a significant challenge for the creation of HBIM models and associated tools.

Since incorporating non-parametric data is not typically a native feature of BIM, the common approach to including qualitative information is to develop an external database that can be linked to the HBIM model, with only a few cases directly embedding intangible data, such as descriptions and images, associated with specific objects. Regardless, information transfer between models remains a challenge due to the lack of a standardized vocabulary. Several authors [51,72–75] have proposed the adoption of standardized ontologies commonly used in cultural heritage data exchange, such as the one defined in ISO 21127 [76] (based on the CIDOC-CMR or Conceptual Reference Model of the International Committee for Documentation). Some examples demonstrate how well-defined semantics can be integrated with common metadata formats [77,78]. While CIDOC-CMR excels at clarifying instances of semantic complexity, its focus on empirical data limits its effectiveness in describing family relations, rights, and intellectual processes [79]. An example of ontology for cultural heritage elements is shown in Figure 6.

Another major challenge associated with historical data is the difficulty of acquisition. Unlike the relative ease of gathering geometric data, historical information often comes with considerable uncertainties and requires extensive documentation work to ensure its reliability. Consulting experts in the field [80] or analyzing texts (e.g., building standards) from the same period as the building or from structures with similar characteristics (e.g., age, location, structural type, materials, and use) [47,81] can help fill gaps in the available historical documentation regarding the asset itself.

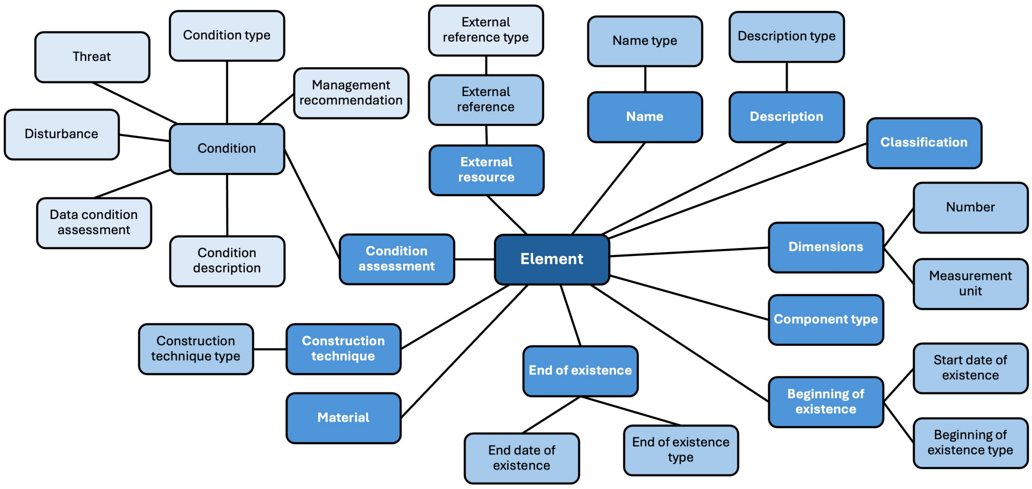


Figure 6. Example of ontology for a tangible cultural heritage element. Adapted from [73].

However, in many cases, historical data are not required. As HBIM models transitioned from being merely a geometry with a historical database for the asset to becoming a tool for its management and preservation, it became essential to incorporate information about the condition of various building components, in particular, the structure, due to its crucial role for the stability of the building. These data can be quantitative, such as the value of specific material properties, by the definition of some kind of damage index for the whole structure or for some areas, or qualitative, as a mere description of the condition of the building's components.

Accurate data on the building's condition and structural properties must be gathered through on-site inspections and tests. While qualitative assessments can be provided by experts during site visits, other essential quantitative information, such as material properties or internal defects, must be directly measured. In the case of CH structures, invasive, destructive testing is often impractical, making nondestructive testing (NDT) techniques an ideal alternative [82]. NDT methods, such as ultrasonic pulse velocity, infrared thermography, ground penetrating radar, and spectral analysis of surface waves, have proven effective in estimating the material properties of traditional building materials like stone and rammed earth [83–86].

The structural condition of a building, among other factors, is inherently dynamic, introducing a fourth dimension into HBIM: time. While 4D standard BIM models are commonly used to capture changes over time in construction or demolition processes, early HBIM models were static and developed to represent the current or "final" state of the building [1]. Since then, several studies have explored the development of 4D HBIM models, mostly to capture large-scale variations over time in CH assets, such as construction phases [87–90], past interventions [91,92], and global deterioration and damage [93–95]. However, when designed for management purposes, HBIM models should also accommodate future modifications resulting from interventions, whether or not they involve geometric changes [6,96]. Additionally, if the model is used to store and manage the building's structural condition, it must incorporate both quantitative and qualitative data about material properties, detected defects, and damage states, with the ability to update this information over time [91,95,97].

5.2. Scope of Existing HBIM Models

In accordance with the origin of the BIM concept itself, the general purpose of HBIM models is to systematically store all relevant and available data about a specific historical building on the basis of a three-dimensional geometry. However, beyond this, it is important to understand the specific goals of the various HBIM models developed over recent years. In general, as already observed in other literature reviews on the subject [7,28], HBIM studies have focused on three main areas: the data acquisition process and modeling techniques, the use of HBIM for the management of heritage buildings, and the conduction of analyses (primarily structural) within HBIM environments.

Based on the publications analyzed in this review, and as illustrated in Figure 7, a significant number of studies over the past decade have focused on data collection procedures and techniques, although the percentage compared to other topics has slightly decreased in the last few years. From the outset, the dominant focus of the HBIM literature has been the management of cultural heritage assets and the development of strategies for their preventive preservation, conservation, and restoration. Within this topic, since the mid-2010s, the authors have paid special attention to the introduction of workflows and protocols aimed at standardizing the management of cultural heritage buildings within BIM environments. In the past five years, there has also been a notable rise in research exploring the integration of HBIM models with virtual, augmented, and extended reality technologies, especially due to their potential as educational and outreach tools. In addition, there has been a significant increase in the number of publications related to the conduction of analyses to assess the structural condition of heritage buildings within BIM environments. These studies have explored topics such as data exchange processes, interoperability between BIM and structural analysis software, and the possibility of continuously updating the structural condition through SHM systems.

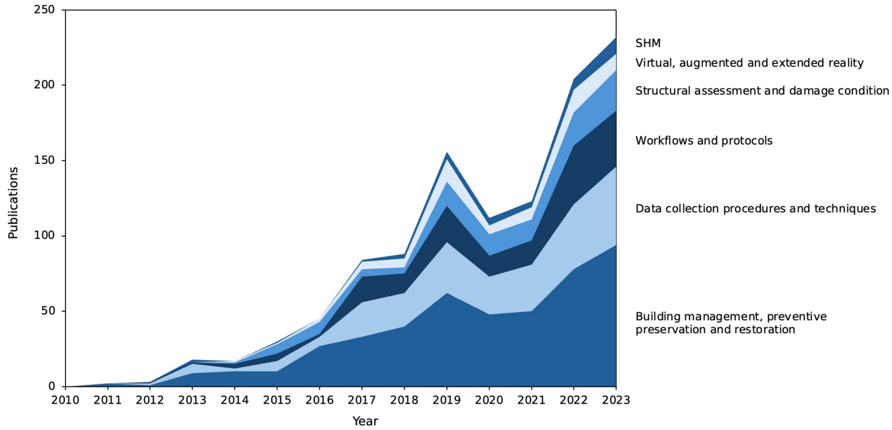
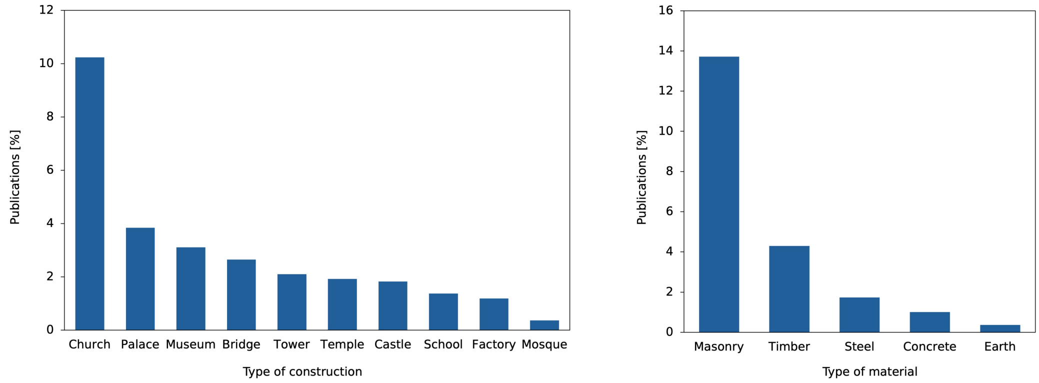


Figure 7. Main topics of HBIM publications in the Web of Science database between 2010 and 2023.

A significant number of the published articles, though not all, focus on the development of an HBIM model for a specific heritage building or apply their research to a particular case study. As shown in Figure 8a, among the publications indexed in Web of Science between 2010–2023 considered in this study, about 10% refer to HBIM models of churches (including basilicas and cathedrals), making this by far the most represented building type. Other relevant types of buildings evaluated in the literature are palaces, museums, and bridges, each accounting for between 3% and 4%. There is also coverage of other monumental buildings, such as towers, temples, and castles, as well as schools, historic factories, and mosques. Other more particular and difficult-to-classify building types were excluded from this analysis.

In terms of construction materials (Figure 8b, approximately 15% of HBIM publications focus on masonry buildings (including both stone and brick masonry), while timber structures account for around 4%. More modern materials, such as steel and concrete, are each featured in less than 2% of the articles, and only a small number address earthen structures (e.g., adobe and rammed earth). Although these figures might be only indicative, as not all studies explicitly reference the construction materials of the heritage buildings they address, they still provide a general sense of the representation of the different construction materials (and, by extension, the associated building techniques) in HBIM models.



(**a**) (**b**)

Figure 8. Percentage of HBIM publications by type of building (**a**) and construction material (**b**) of the heritage asset evaluated.

5.3. HBIM for Structural Analysis

Although the idea of linking HBIM models with structural analysis models has been considered almost from its beginnings [24,25,98], the interest in this possibility has grown as HBIM has gained popularity and solidified its role as a comprehensive building management tool. The most common way to integrate structural analysis into an HBIM environment involves developing a 3D model in BIM software using the data collected from the cultural heritage building. From this complex HBIM model, a simplified geometry is extracted and imported into analysis software, typically finite element analysis (FEA) software, where the necessary calculations are performed [62,99]. The results from these analyses should then be incorporated back into the HBIM model, updating it accordingly.

This type of workflow was followed by Santini et al. [100], who proposed a methodology that began with the development of an HBIM model in Revit, incorporating data from a historical survey, laser scanner measurements, and local NDT. The model was then exported to the FEA software Midas in a *.sat* or IFC (Industry Foundation Class) format, where it was meshed, and modal and pushover analyses were conducted. All steps, i.e., exporting, meshing, and analysis, had to be done manually. A similar methodology was proposed in the project "CHARMING PISTOIA" [101] for the preservation and maintenance of heritage structures, although the application was limited to a single architectural element. Alternatively, Russo et al. [102] presented a different approach, starting with the creation of a parametric model in Rhino–Grasshopper, which could be exported to the SAP2000 FEA software or to an HBIM digital archive using specific plug-ins and the IFC format. This workflow allowed them to model and analyze 3D shells, but there was no integration or data exchange between the structural analysis software and the final HBIM model. The interaction between Rhino–Grasshopper and FEA software, Midas, in this case, was also successfully explored by Pepe et al. [103] using a scan-to-BIM procedure to build both an HBIM and a structural model from a 3D point cloud.

In the last few years, there has been a growing interest regarding the possibility of constantly updating HBIM models with real-time data about the structural condition of the building as a powerful tool for preventive conservation and heritage management. The goal is to use the information measured on-site through a continuous structural health monitoring (SHM) system to analyze the structural behavior of the CH asset and then store and update this information in the HBIM model, doing all this in a continuous automated process [97,104,105]. While finite element models can be used to assess specific structural aspects or evaluate particular load conditions, their complexity and high computational demands often render them impractical for real-time SHM schemes. As a result, damage identification frequently requires the development of computationally efficient surrogate models, such as physics-based or machine-learning approaches, which utilize continuous monitoring data to infer and classify the building's health condition, effectively functioning as a structural digital twin [106].

Digital twins can enhance HBIM models by capturing dynamic data from the physical heritage asset, enabling updates to the virtual model and providing predictive insights [107], but there are still unresolved challenges related to the interoperability between HBIM and digital twins used for continuous structural performance analyses [97,108]:

- Developing 3D models for heritage structures with intricate geometric features.
- Ensuring the right level of detail and accuracy in the digital model to capture typical heritage elements, deterioration patterns, and cracks while balancing costs, time, and results.
- Interoperability between tools and datasets.
- Difficulties in 3D representation and visualizing real-time data updates.
- Integrating the cultural and historical significance of heritage sites into their HBIM models.
- Determining the amount of real-time data to be included in the development of object models.

There are only a few examples of integration between HBIM and continuous SHM. Wang et al. [62] developed a parametric multi-dimensional HBIM model of a timber cultural heritage building using Revit, incorporating four stages: construction, repair, monitoring, and FEA. In the FEA stage, a simplified structural geometry was exported to the finite element software ABAQUS. An SHM system with fiber grating strain sensors was installed, with safety thresholds set to trigger early warnings if anomalies were detected. While the finite element model could be updated with measured data, there is no indication of an automatic link between SHM readings and the structural model. Another example of SHM-HBIM integration was presented by Meoni et al. [109], who proposed a methodology to monitor both the structural behavior and human-centric environmental comfort of CH buildings within an HBIM environment. This study developed a Python-based software application that integrated a Revit model with data from operational modal analysis and continuous SHM. Another advanced example of HBIM and continuous monitoring integration was demonstrated by Bouzas et al. [99], who developed a cyclic procedure starting with the creation of a BIM model of a steel frame bridge. From this model, a structural model was derived, which was then calibrated by adjusting cross-section dimensions and elastic properties in a modal analysis using SHM data, employing the modal assurance criterion (MAC). Once calibrated, the architectural model was updated with the new properties. This process was performed directly on the finite element model (built in ANSYS) without the need for a surrogate model due to the limited number of iterations and the relatively simple structural configuration (beam model).

However, despite recent advances, further research is still required to achieve full integration between continuous monitoring systems, HBIM models, and structural analysis software. This complete integration would enable the automatic processing of SHM data, its incorporation into the structural (surrogate) model for analysis, performing real-time defect detection that activates an early alert system, and the periodic updating of the HBIM model with this information. A simplified flowchart illustrating this process is provided in Figure 9.

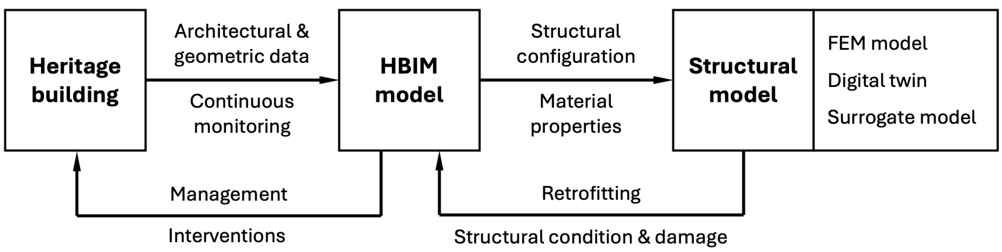


Figure 9. Idealized flowchart for the integration of the structural condition assessment of a building within a HBIM environment.

6. Future Directions

Since its emergence in 2009, interest in HBIM methodologies for heritage management has steadily grown, leading to the development of numerous models and a significant increase in published research. This trend has remained consistent over the past decade and is expected to continue in the near future. While early research primarily focused on tools for creating 3D models and data collection techniques, recent years have seen a growing interest in utilizing HBIM as a comprehensive tool for managing historic buildings. This includes not only data acquisition and model development within HBIM software but also the ability of these models to exchange information with other software and perform various types of analyses on the assets under consideration.

Accordingly, terms like structural analysis, digital twin, building preservation, artificial intelligence, the Internet of Things, and building sustainability have become more prevalent in HBIM publications in recent years [28]. Similarly, terms related to data collection and modeling techniques, such as laser scanning or point cloud, have also gained prominence in the last few years. Considering this and the studies analyzed in the present review, it is reasonable to assume that these will be some of the most relevant directions that HBIM research will follow in the coming years:

- Inclusion of BIM for historic structures in national and international regulations, similar to what has occurred over the past few decades for new constructions, along with the development of standards and protocols to help standardize HBIM procedures.
- Increased use of HBIM models for the comprehensive management of architectural heritage, with a special focus on preventive preservation and incorporating the environmental sustainability component in management practices.
- Improvement of data collection methods (laser scanning, drone photogrammetry, and LiDAR) and data conversion into entities recognizable by BIM software. Although significant progress has already been made in these areas in the last few years, technology continues to advance, offering ongoing improvements and new possibilities.
- Development of open-access formats (similar to those initiated with IFC) and software solutions to enhance the interoperability of HBIM models, along with improvements in the ability to export HBIM models across various platforms.
- Real-time or near-real-time updating of the structural condition of historic buildings within an HBIM environment, improving the interaction between HBIM models and computationally efficient analysis models (in the form of a digital twin of the structure). The process would enable us to integrate continuous monitoring data, assess the structural condition of the building and the potential occurrence of damage, generate alerts in case of detected issues, and update the HBIM model accordingly.
- Development of urban-scale HBIM models, expanding beyond individual heritage assets to cover larger areas such as historic city centers and archaeological sites, encompassing multiple historic buildings.

These future directions align with overcoming significant limitations currently affecting HBIM's practical utility. The integration of HBIM into national and international regulations, as well as the development of standards and protocols, directly addresses the lack of uniformity in HBIM procedures, which has hindered broader adoption and consistent application across projects. Establishing a regulatory framework would not only encourage the use of HBIM models in practice but also reinforce their legitimacy and relevance in heritage preservation.

Furthermore, advancements in data collection methods and model interoperability will help to enhance the practical application of HBIM by streamlining the capture, processing, and sharing of complex heritage data. Integrating real-time monitoring and expanding HBIM to urban-scale applications marks a shift toward more responsive management, allowing for up-to-date structural assessments and preventive maintenance for individual buildings and broader city planning. These developments suggest that HBIM is moving closer to becoming a practical and sustainable tool for heritage preservation and management.

7. Overall Results and Discussion

The analysis of the results of the present review highlights that, over the last 15 years, HBIM has transformed heritage building management by merging digital modeling, historical data integration, and structural analysis into a cohesive framework. The primary findings reveal both the progress HBIM has made and the current challenges it faces, specifically in data accuracy and accessibility, standardization, and software integration.

Data collection for HBIM models is complex, with heritage buildings often characterized by irregular geometries and incomplete documentation. Techniques like laser scanning and photogrammetry have been pivotal in capturing these intricate details. However, the high cost and limited accessibility of advanced equipment pose challenges for widespread HBIM adoption. The necessity of balancing detail with computational efficiency is also clear: highly detailed models are beneficial but can lead to significant computational overheads, hindering their practical use.

Interoperability remains a central barrier to the consistent application of HBIM. While frameworks such as IFC and COBie offer promising solutions for standardizing data across platforms, these are often geared toward general BIM applications and lack heritage-specific adaptations. Efforts within Europe and other regions are advancing toward developing open-access formats and semantic web standards that could enable more seamless data exchange for heritage models. Improved interoperability would support broader adoption and facilitate collaboration between institutions in preserving culturally significant buildings.

A particularly promising aspect is the integration of HBIM with structural analysis and real-time monitoring systems. Structural health monitoring and finite element analysis tools are increasingly embedded within HBIM environments, allowing heritage managers to monitor the physical state of buildings continuously and address potential issues preemptively. This transition from static documentation to dynamic makes HBIM a valuable tool not just for preserving these buildings but also for managing them proactively. It also opens the door for HBIM models to become detailed, interactive digital representations, or digital twins, that mirror the real-time condition of heritage buildings.

Practical applications of HBIM have demonstrated its versatility through numerous case studies focused on churches, museums, palaces, and other monumental buildings. Despite these successes, challenges remain in moving HBIM models from project-specific or experimental use to long-term, practical applications within routine heritage management. The lack of standardized practices and the high variability of heritage buildings contribute to difficulties in achieving this transition.

HBIM has shown substantial promise as a digital management and preservation tool, although full realization of its potential requires further advancements. Improving data interoperability, establishing standardized protocols, and enhancing real-time structural analysis capabilities are essential steps for HBIM to become a universally practical and powerful resource in heritage conservation.

8. Conclusions

The development of BIM technologies, their success in improving the construction and management of new buildings and infrastructures, and the growing concern for the preservation of architectural heritage, characterized by unique features that differentiate it from new constructions, led to the introduction of the concept of historic building information modeling (HBIM) in the early 2010s.

Since then, HBIM has significantly influenced heritage management practices, with numerous BIM models built for relevant heritage assets and an increasing number of scientific studies and publications about the topic (seeing a 950% growth in the last 10 years). Initially focused on the technical aspects of 3D modeling and data collection, HBIM research has evolved into the development of comprehensive methodologies that encompass not only the digital representation of historical assets but also the management and preservation of these structures, a topic that currently represents about 40% of HBIM-related articles published every year. Over the past decade, HBIM has increasingly been seen as a tool not only for documentation but for the holistic management of historic buildings.

Future research and development in HBIM are expected to focus on several key areas. One is the formal integration of HBIM into regulatory frameworks, similar to how BIM has been adopted for new construction projects. The standardization of procedures and the establishment of guidelines tailored to historical structures will help unify HBIM practices, ensuring consistency and reliability across projects. Another significant area of progress lies in the enhancement of data collection techniques, such as the use of LiDAR, drone-based photogrammetry, and laser scanning. While these technologies have already made substantial contributions, continued advancements will enable more efficient and accurate model generation, particularly for complex and large-scale heritage sites.

Additionally, the development of open-access formats will be crucial for improving interoperability between different software platforms, thus facilitating wider use and more collaborative efforts in the field. The incorporation of real-time monitoring systems into HBIM models, coupled with the integration of data-driven analysis techniques, will further strengthen the ability to assess and maintain the structural integrity of heritage buildings. This trend, alongside the shift toward urban-scale HBIM models that include entire historic districts or archaeological sites, represents a significant evolution in heritage management. These advancements will position HBIM not just as a documentation tool but as a dynamic system capable of real-time asset management, ensuring the long-term preservation of built heritage.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modeling
CH	Cultural heritage
COBie	Construction–Operation Building Information Exchange
FEA	Finite element analysis
HBIM	Historic Building Information Modeling
IFC	Industry Foundation Classes
LiDAR	Light detection and ranging
LOD	Level of development
LOI	Level of information
MAC	Modal assurance criterion
NDT	Nondestructive testing
SHM	Structural health monitoring

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