Frontiers of Architectural Research xxx (xxxx) xxx

Higher Education Press

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.keaipublishing.com/foar

SOUTHEAST UNIVERSITY

REVIEW ARTICLE

Reframing the "H" in HBIM: from systematic review to UML-based conceptual modeling

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Received 8 November 2025; received in revised form 3 February 2026; accepted 18 February 2026

KEYWORDS
Heritage building information modeling (HBIM);
Cultural heritage;
Technological integration;
Unified modeling language (UML);
3D Gaussian splatting (3DGS);
Architectural heritage information infrastructure (AHII)

Abstract As Heritage Building Information Modeling (HBIM) emerges as a key digital approach for documenting and managing architectural heritage, its conceptual basis and technological scope remain fragmented due to ambiguity in defining the "H" as "Historic," "Historical," or "Heritage." Additionally, current HBIM implementations are predominantly limited to conventional surveying tools, such as terrestrial laser scanning and photogrammetry, with minimal adoption of immersive, semantically rich, and interactive technologies. This paper clarifies the definitional scope of HBIM, systematically investigates integrated heritage information across structural, material, historical, artistic, and conservation dimensions, and proposes a unified UML-based schema integrating HBIM with Smart Point Cloud (SPC) technology. Further, we introduce a comprehensive four-stage Architectural Heritage Information Infrastructure (AHII), emphasizing semantic enrichment, interoperability, and advanced Gaussian Splatting visualization, thus positioning HBIM as a dynamic node within an inclusive digital heritage ecosystem.

Contents

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Peer review under the responsibility of Southeast University.

https://doi.org/10.1016/j.foar.2026.02.007

Please cite this article as: Y. Yu, Z. Wang, P. van Oosterom et al., Reframing the "H" in HBIM: from systematic review to UML-based conceptual modeling, Frontiers of Architectural Research, https://doi.org/10.1016/j.foar.2026.02.007

1. Introduction

"HBIM" is commonly known as a paradigm that integrates historical data, conservation policies, and cultural value assessments (Jordan-Palomar et al., 2018; López et al., 2018; Lovell et al., 2023). While "HBIM" borrows from the broader building information modeling (BIM) paradigm, its application in the heritage domain is largely concentrated in documentation, analysis, and conservation planning, rather than in conventional design or construction workflows. Given the increasing adoption of digital technologies in heritage conservation, HBIM has the potential to become a standard practice supporting informed decision-making and long-term asset management (Pocobelli, 2021). However, the current state of "HBIM", from its definition to its application, remains somewhat ambiguous. There is no consensus on the meaning of the "H" whether it stands for "Historic," "Historical," or "Heritage" (Aksin and Karaş, 2021; Iovane and Cera, 2016; Rolim et al., 2024; Şentürk and Şimşek, 2025; Shehata et al., 2024).

To address these research gaps, this paper conducts a systematic and quantitative literature review on HBIM to clarify its conceptual scope, particularly regarding the ambiguity around the definition of "H," and to explore its technological landscape and integration possibilities. The ultimate goal is to contribute to a clearer theoretical framework and enhance practical implementation in heritage documentation and preservation (ICOMOS, 2000; Smith, 2006). Furthermore, it seeks to develop and discuss a Unified Modeling Language (UML)-based conceptual model to systematically structure heritage-related information, and to discuss existing and potential technologies that can be integrated with HBIM to enhance its application in heritage conservation and management, and beyond in redesign and adaptive reuse.

1.1. "H" BIM and BIM

Eastman et al. (2011) stated that BIM is not merely a three-dimensional digital model but a platform that supports information integration and collaborative decision-making throughout the entire lifecycle of a building project. In the context of heritage, this perspective invites a broader interpretation of what constitutes a 3D representation. Rather than relying solely on polygonal geometry, alternative formats such as dense 3D point clouds (Wang et al., 2018) and, more recently, 3D Gaussian Splatting (3DGS) have demonstrated the capacity to support collaborative decision-making (Christodoulides et al., 2025; Yu et al., 2025). The BIM methodology has been evolving into what is described as "a new historic building modeling system" (Murphy et al., 2009). The primary distinction between BIM and HBIM is that BIM is fundamentally future-oriented for new construction (Bastem and Cekmis, 2022), whereas HBIM is retrospective, documenting existing heritage structures with inherent historical complexities (Dore and Murphy, 2017; Sampaio et al., 2021). In addition to the commonalities shared by "H" in comparison with BIM, the three distinct interpretations of "H" reveal the following differences in connotation and research focus, as observed through both lexical semantics and intuitive examination of the research content (Fig. 1).

(a) **Historic:** Historic-BIM, a concept that extends traditional BIM methodologies to historic structures, incorporating historical records, material data, and conservation principles into a structured digital framework (Dore and Murphy, 2017; Murphy et al., 2009, 2013). Unlike standard BIM, which relies on predefined parametric libraries for modern materials and structures, it requires the development of customized parametric objects that accurately reflect the complexity of historic architecture (Getuli et al., 2025; Monaco et al., 2019).

(b) **Historical:** Historical-BIM is inherently retrospective, emphasizing the integration of historical research, archival records, and past restoration interventions into digital models (Bagnolo et al., 2019; Castagnetti et al., 2017; Santos et al., 2023). This approach is crucial for understanding how buildings and sites have evolved over time, allowing researchers, conservationists, and policymakers to track changes, analyze past interventions, and make informed restoration decisions (Oreni et al., 2017). By extending BIM's capabilities to support multi-temporal analysis and historical inquiry, Historical-BIM ensures that built heritage is documented in its current state while also being interpreted within the context of its transformations over time (Nespeca, 2019).

(c) **Heritage:** The concept of Heritage-BIM extends beyond the physical characteristics of buildings, encompassing cultural significance derived from conservation policies and intangible elements such as traditions, narratives, and cultural identities (Ahmad, 2006; Ruggles and Silverman, 2009; Vecco, 2010). Unlike "Historic-BIM," which primarily documents architecturally significant structures based on age or designation, or "Historical-BIM," emphasizing archival data and past interventions, Heritage-BIM integrates social, cultural, and policy dimensions holistically (Xiao et al., 2018; Zhang and Zou, 2022). While BIM serves as a data-rich digital model for building design, construction, and facility management, Heritage-BIM expands its scope to include heritage values, conservation policies, and cultural narratives (Khan et al., 2022). UNESCO defines heritage as encompassing both tangible elements, such as monuments, buildings, and landscapes, and intangible aspects, such as knowledge systems, craftsmanship, and community traditions. Consequently, Heritage-BIM transforms conventional BIM, originally a technical tool for design, construction, and facility management, into a comprehensive heritage management framework that digitally preserves and integrates both tangible and intangible heritage into decision-making processes.

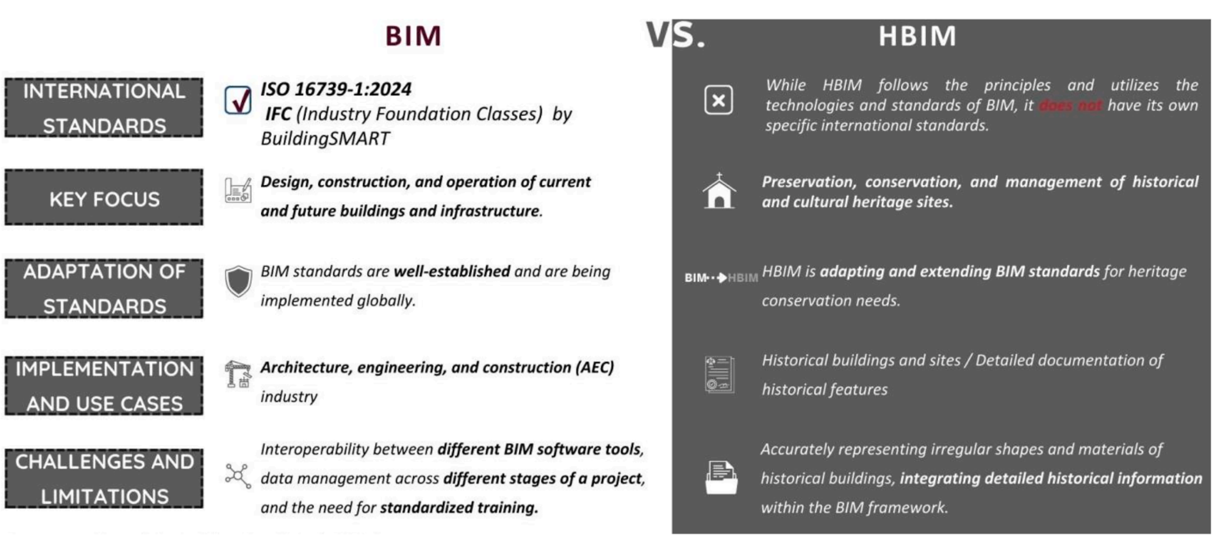

Fig. 1 Comparison of the current status of BIM and HBIM.

1.2. The applications of HBIM

While some studies define the HBIM workflow in terms of technical processes, such as data acquisition, processing, and management (see Fig. 2) (Ávila et al., 2024), this paper proposes a complementary classification based on HBIM's functional roles. Furthermore, regardless of whether the "H" in HBIM refers to historic, historical, or heritage, its application scope and technological integration exhibit significant complexity. Specifically, HBIM applications can be grouped into three interrelated categories: (a) documentation and modeling, (b) management and maintenance, and (c) visualization and communication. These categories reflect not only the technological stages of HBIM development, but also its evolving uses in heritage interpretation, monitoring, and public engagement.

(a) **HBIM as a tool for documentation and modeling:** The data processing stage involves the development of parametric HBIM models or digitized models based on semantic segmentation, utilizing advanced techniques such as laser scanning, photogrammetry, and structured light scanning to ensure geometric accuracy and semantic richness (Liu et al., 2023; Moyano et al., 2021; Radanovic et al., 2020).

(b) **HBIM serves as a platform for management and maintenance:** HBIM also serves as a critical foundation for risk management and assessment of historic buildings, disaster prevention, sustainable development, and long-term maintenance (González et al.; Liu et al., 2023; Yu et al., 2025a). By integrating Geographic Information Systems (GIS), Digital Twin (DT) technologies, sensor networks, and structural health monitoring (SHM) systems, HBIM enables real-time diagnostics, predictive analysis, and lifecycle management of heritage structures (Rossi and Bournas, 2023). These technologies enhance HBIM's capacity to monitor structural integrity, detect early signs of deterioration, and support data-driven decision-making for preventive conservation and adaptive reuse (Mazzetto, 2024; Saricaoglu and Saygi, 2022).

(c) **HBIM's as a basis for visualization and interactive communication:** HBIM serves as a foundation for interactive heritage communication, including immersive exhibitions of heritage architecture, public heritage education, and professional applications in building management and research (Banfi, 2021; García et al., 2018; Salvador-García et al., 2020). The interaction and integration stage focus on the convergence of HBIM with immersive visualization tools such as Virtual Reality (VR) and Augmented Reality (AR) to enhance spatial analysis, real-time monitoring, and interactive engagement with heritage assets (Banfi, 2020; Banfi et al., 2019). The dissemination and accessibility stage leverages web-based 3D visualization platforms, and shared digital infrastructures established by organizations such as DOCOMOMO International and European Collaborative Cloud for Cultural Heritage (ECCCH), facilitating collaborative enrichment and accessibility of heritage data. Furthermore, various private and institutional repositories, such as Europeana, EPFL's HERITAGE Lab, also contribute to increasing the accessibility and long-term preservation of annotated 3D heritage content (Kaptan et al., 2023; Pottgiesser and Quist, 2023). By integrating cloud computing, WebGL, and open-access infrastructures, HBIM fosters broader knowledge dissemination and facilitates participatory heritage documentation (Diara and Rinaudo, 2021). Beyond visualization and engagement, the parametric and semantic nature of HBIM also supports redesign and adaptive reuse by enabling simulations of conservation interventions and structural strategies. Together, these developments underscore HBIM's evolving role in the architectural heritage information infrastructure (AHII) ecosystem.

In summary, beyond the ambiguity in its definition, HBIM also exhibits considerable complexity in its applications, necessitating a systematic review. Existing review papers predominantly focus on specific aspects of HBIM applications, such as risk management, or discussing HBIM as one of several digital technologies employed in heritage documentation, often alongside DT and other spatial analysis tools rather than as a distinct subject of analysis. This fragmented approach underscores the need for a comprehensive and integrative examination of HBIM, addressing both its conceptual foundations and its diverse technological and methodological implementations.

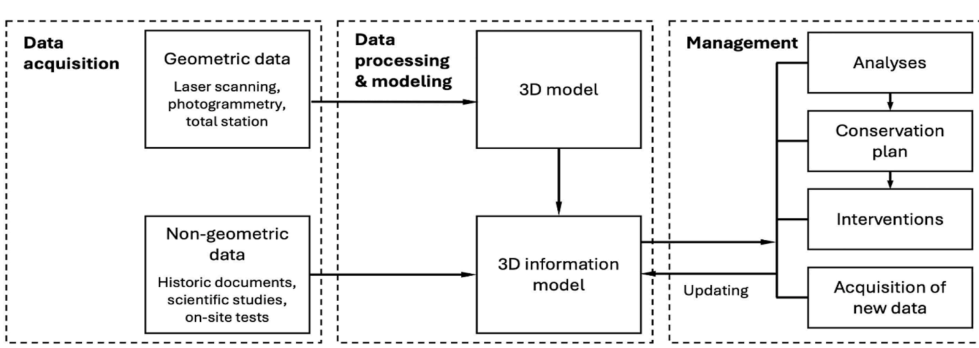

Fig. 2 Hbim workflow (Ávila et al., 2024).

1.3. UML for HBIM

While HBIM research has expanded rapidly in terms of applications and data acquisition techniques, the underlying data structures and semantic frameworks remain largely fragmented. As heritage documentation moves toward semantically rich, multi-source environments, the need for standardized conceptual modeling becomes increasingly urgent. UML has emerged as a widely accepted tool to formalize the representation of heritage data and to bridge gaps between geometry, semantics, and interoperability.

Dore and Murphy introduced a UML-augmented Industry Foundation Classes (IFC) schema for historic façades, enabling structured representation of architectural elements such as ornamental components and parametric features (Matrone et al., 2019). Similarly, Poux et al. (2020) implemented conceptual modeling using UML-like schemas to support their Heritage Information System—Point Cloud (HIS-PC), which links 3D point cloud data with spatiotemporal semantics and multi-user information workflows. While these precedents demonstrate the utility of UML for organizing complex heritage data, they rarely span multiple 3D data formats or incorporate advanced visualization layers.

1.4. Knowledge gap and research objectives

Through the above discussion, it becomes evident that despite the growing importance of HBIM in the digital documentation and preservation of architectural heritage, several critical gaps remain in existing research.

(a) **The Scope and Categorization of "H" in HBIM and its Integrated Information:** Existing definitions of "H" (Historic, Historical, Heritage) in HBIM remain inconsistent (Baik et al., 2015; Lovell et al., 2023; Penjor et al., 2024). Additionally, heritage-related data types integrated into HBIM, such as historical, material, cultural, and conservation-related information, lack systematic classification, restricting a clear understanding of HBIM's scope and documentation role.

(b) **Technological Integration and Application Scope of HBIM:** While specific tools and methods are frequently studied, comprehensive reviews of HBIM's integrated technologies and data sources remain limited, hindering holistic assessment of its interoperability and technical potential. Moreover, future directions regarding data expansion, interoperability, and advanced capabilities are rarely discussed. Consequently, HBIM's long-term applicability for heritage management and predictive modeling is inadequately defined, highlighting the need for exploring emerging technological integrations.

(c) **Semantic Structure and Interoperability of HBIM Data:** Although UML (Unified Modeling Language) schemas have shown potential in formalizing heritage data semantics, existing studies predominantly focus on specific data types or isolated semantic aspects, without fully integrating structural, material, historical, cultural, and conservation information. Consequently, current UML-based schemas do not adequately support interoperability, data reuse, or multi-source integration within HBIM workflows. This highlights an urgent need for a standardized, comprehensive UML-based semantic model that systematically organizes and integrates diverse heritage-related data.

To bridge these research gaps, this paper aims to **conduct a systematic and quantitative literature review on HBIM, providing a clearer understanding of its conceptual workflow, technological scope, and potential integrations**. Specifically, it focuses on the following objectives: (a) Clarification of the "H" in HBIM: This paper examines the varying definitions of Historic, Historical, and Heritage in HBIM, analyzing their conceptual and practical implications; (b) Categorization of Heritage-Related Information: This paper classifies the types of historical and heritage-related data integrated into HBIM, establishing a structured taxonomy for its role in heritage documentation and management; (c) Technological Integration and Future Extensions: This paper reviews the technologies, software, and data sources used in HBIM, exploring its potential expansion through additional heritage data and emerging digital technologies, such as those applicable to heritage conservation, predictive modeling, and risk assessment; (d) Development of a UML-Based Semantic Model for HBIM—Smart Point Cloud (SPC) Integration: To address the fragmented semantics in HBIM practice, this paper develops a UML-based conceptual model that enhances the representational depth of heritage information through SPC integration. Unlike existing HBIM schemas that focus primarily on geometric or typological structures, this model foregrounds semantic richness by formalizing the relationships among structural, material, historical, and cultural attributes.

2. Materials and methods

This paper adopts a dual-method approach combining systematic literature analysis with UML-based conceptual modeling to investigate the semantic and technological foundations of HBIM.

2.1. Literature review and thematic analysis

The literature analysis method employed in this paper can be divided into three parts. Firstly, we utilized PRISMA to visually obtain an overview of the paper's basic information (e.g., the number of papers published each year and site coverage) (Page et al., 2021). PRISMA was also used to establish multiple criteria to classify and identify the specific content of the target literature in a detailed manner (Fig. 3) (Rethlefsen et al., 2021). Secondly, We used VOSviewer to construct and visualize scient metric networks at the macro level, and thirdly, a coding-based content analysis was conducted to categorize the selected literature thematically, identifying recurring themes and conceptual patterns in detail (Van Eck and Waltman, 2010).

2.1.1. Data collection

To identify relevant literature on Heritage Building Information Modeling (HBIM), including studies using the alternative terms Historic Building Information Modeling and

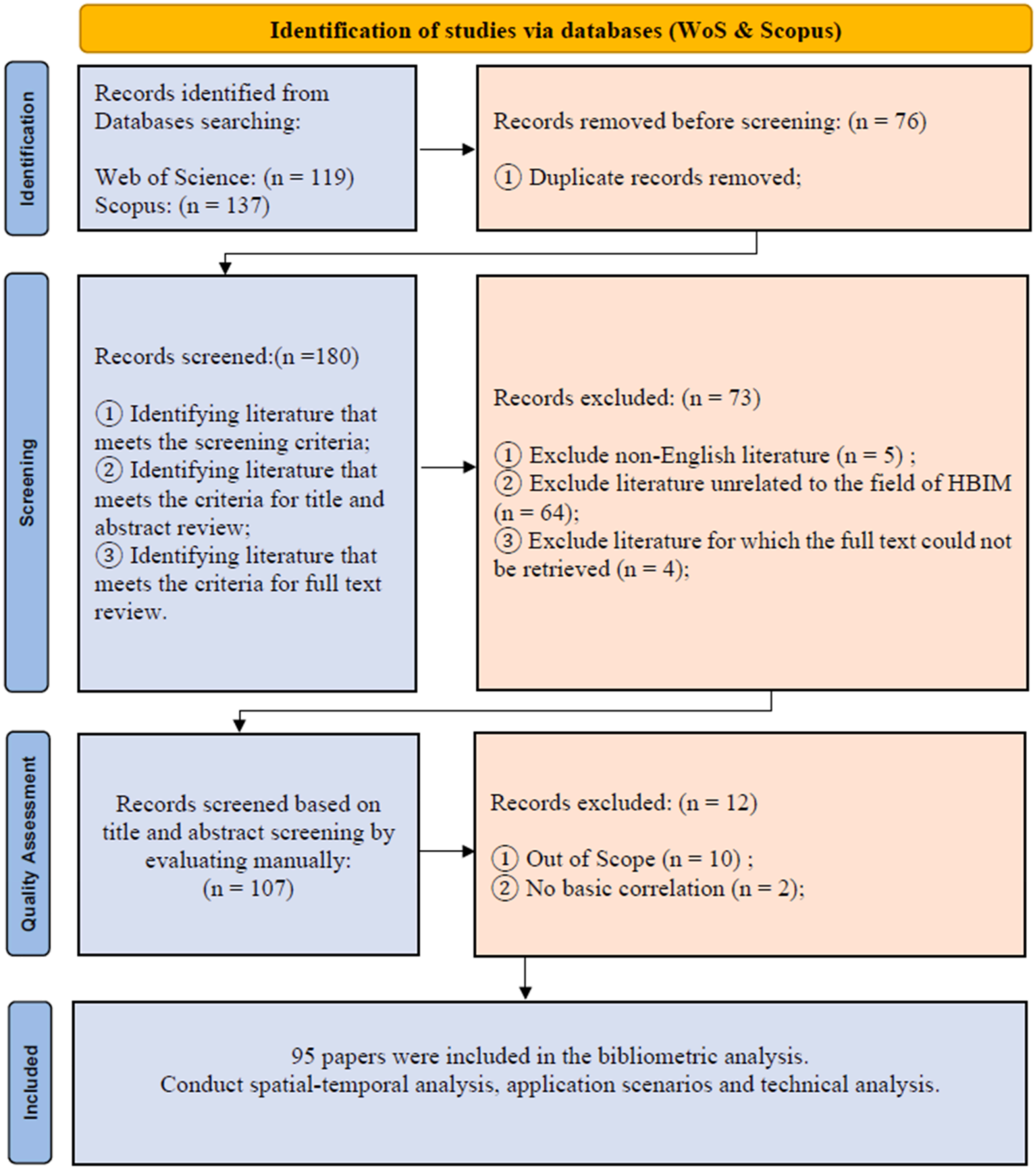

Fig. 3 PRISMA Flow for this research.

Historical Building Information Modeling, this paper examined publications that provide synthesized insights, including articles, review articles, proceedings papers, and books. Two major academic databases were selected: Web of Science (WoS) and Scopus, both offering multidisciplinary coverage across architecture, engineering, and heritage conservation.

From the WoS Core Collection, to ensure the academic rigor and relevance of the literature analyzed, only peer-reviewed journal articles indexed in the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), and Emerging Sources Citation Index (ESCI) were included.

In addition, a selective set of conference proceedings indexed in the Conference Proceedings Citation Index, Science (CPCI—S) and CPCI, Social Science & Humanities (CPCI-SSH) were included, provided that they are known to involve rigorous peer-review of full papers—such as the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences and select IEEE or ACM conference series. The search was based on the following topic keywords:

(a) TS = ("historic NEAR/1 building information" OR "historic* building information model∗" OR HBIM OR "heritage building information model∗" OR "historic∗ BIM" OR H-BIM);
(b) TS = (review OR overview OR survey OR synthesis).

An equivalent query was conducted in Scopus to capture comparable literature.

2.1.2. Literature screening and paper coding

In accordance with the PRISMA 2020 guidelines and as shown in Fig. 3, a comprehensive search was conducted across two major academic databases, Web of Science ($n = 119$) and Scopus ($n = 137$), yielding a total of 256 records. Following the removal of 76 duplicate records, 180 records were retained for initial screening. The automation tool was used to preliminarily filter out publications lacking core keywords or exhibiting low semantic relevance to HBIM-related topics based on co-word clustering and keyword frequency analysis. During the subsequent manual screening stage, 73 records were excluded: 5 were non-English publications, 64 were unrelated to the field of HBIM, and 4 were excluded due to the unavailability of full-text access.

Following this, 107 records underwent a detailed quality assessment based on title and abstract review. An additional 12 records were excluded at this stage, comprising ten papers deemed out of scope and two with no substantial correlation to the research objectives. Ultimately, a total of 95 publications were included for bibliometric analysis. These selected papers provided the basis for spatial-temporal analysis, the classification of application scenarios, and the evaluation of technical approaches, as detailed in Appendix A.

To facilitate both statistical and qualitative analyses, a structured paper coding process was conducted, drawing on established approaches from qualitative research (Onwuegbuzie et al., 2012; Onwuegbuzie and Weinbaum, 2016). Informed by the taxonomic and thematic analysis frameworks proposed by Onwuegbuzie et al. (2012), we developed a customized classification scheme tailored to the scope of HBIM-related literature. The coding system focused on five key dimensions: article type, heritage-related category ("H" category), explicit definition or conceptualization of HBIM, integration technologies involved, and presence of case studies. Each paper was systematically deconstructed along these dimensions to allow for organized categorization and in-depth analysis. Using thematic analysis, recurring themes and patterns were extracted across the dataset and subjected to constant comparison to identify conceptual similarities. The resulting thematic clusters were then synthesized into categorical headings, which served as analytical units for subsequent interpretation and visualization.

2.1.3. Literature analysis

VOSviewer, a widely used software tool for bibliometric analysis and visualization, was employed to examine connectivity and clustering relationships among the selected publications (Ding and Yang, 2022). A comprehensive literature database was created for subsequent analysis. Developed in Java, VOSviewer enables the generation of color-coded bibliometric maps that visually represent relationships such as co-authorship, keyword co-occurrence, and citation linkages (Bukar et al., 2023). Through co-occurrence and co-citation mapping, the tool facilitated the identification of high-frequency keywords, thematic clusters, and emerging trends within the HBIM research domain.

2.2. UML modeling methodology

Following the literature-based analysis, this paper develops a UML class diagram to formalize the core concepts and semantic structures embedded in HBIM workflows. The model focuses on key heritage data categories—structural, material, historical, cultural, and conservation—and establishes their relationships to various types of 3D representations, including Smart Point Cloud, BIM (IFC), and 3DGS.

The modeling process adopts a layered approach. At the core is the HeritageObject class, which serves as the anchor for both geometric and semantic entities. Semantic information is modularized into distinct but interoperable classes, allowing flexible association at both object and component levels. Geometry is abstracted through a unified 3DRepresentation structure, enabling multiple formats to coexist under a shared semantic logic.

This approach supports hierarchical annotation and integration from multiple data sources, with semantic properties systematically encoded through controlled vocabularies and reference lists. The resulting UML schema enables both machine-readable interoperability and conceptual clarity, providing a structural foundation for the proposed AHII framework.

3. Results

3.1. Preliminary findings

The following review summarizes literature on the role of HBIM in heritage conservation, highlighting bibliographic characteristics, key research focuses, temporal trends, and research methods utilized in this field.

Since 2013, HBIM-related publications have shown a clear upward trend, indicating growing academic interest (Fig. 4(a)). The annual publication volume remained low between 2013 and 2016 (1–2 papers per year), followed by a sharp increase beginning in 2017. Research output peaked in 2018 and 2019 (12 and 11 papers, respectively), then reached a new high in 2022 and 2023 with 15 publications each year. Despite minor fluctuations, overall publication activity remains strong, with the low count in 2025 (1 paper) reflecting the ongoing status of the publication year. This inconsistency may reflect the complex and interdisciplinary nature of HBIM, as well as practical challenges in its implementation, such as data integration, standardization, and interoperability.

The international collaboration network in HBIM research reveals a core–periphery structure, with Italy and China serving as the primary hubs. Italy exhibits extensive cooperation with European and North American countries, while China plays a pivotal role in fostering regional collaboration within Asia, particularly with Malaysia, Singapore, and Thailand (Fig. 4(b)). The color gradient ranging from blue (earlier studies) to yellow (recent studies), indicates temporal trends in research activity. Emerging contributions from Southeast Asian and Middle Eastern countries—such as Malaysia and Saudi Arabia—are increasingly evident in recent years. The temporal gradient indicates an expansion from initial concentrations in Europe and North America to include Southeast Asian and Middle Eastern regions, suggesting increased global engagement with HBIM.

Publications on HBIM are concentrated primarily in journals and conference proceedings, with *ISPRS Archives*

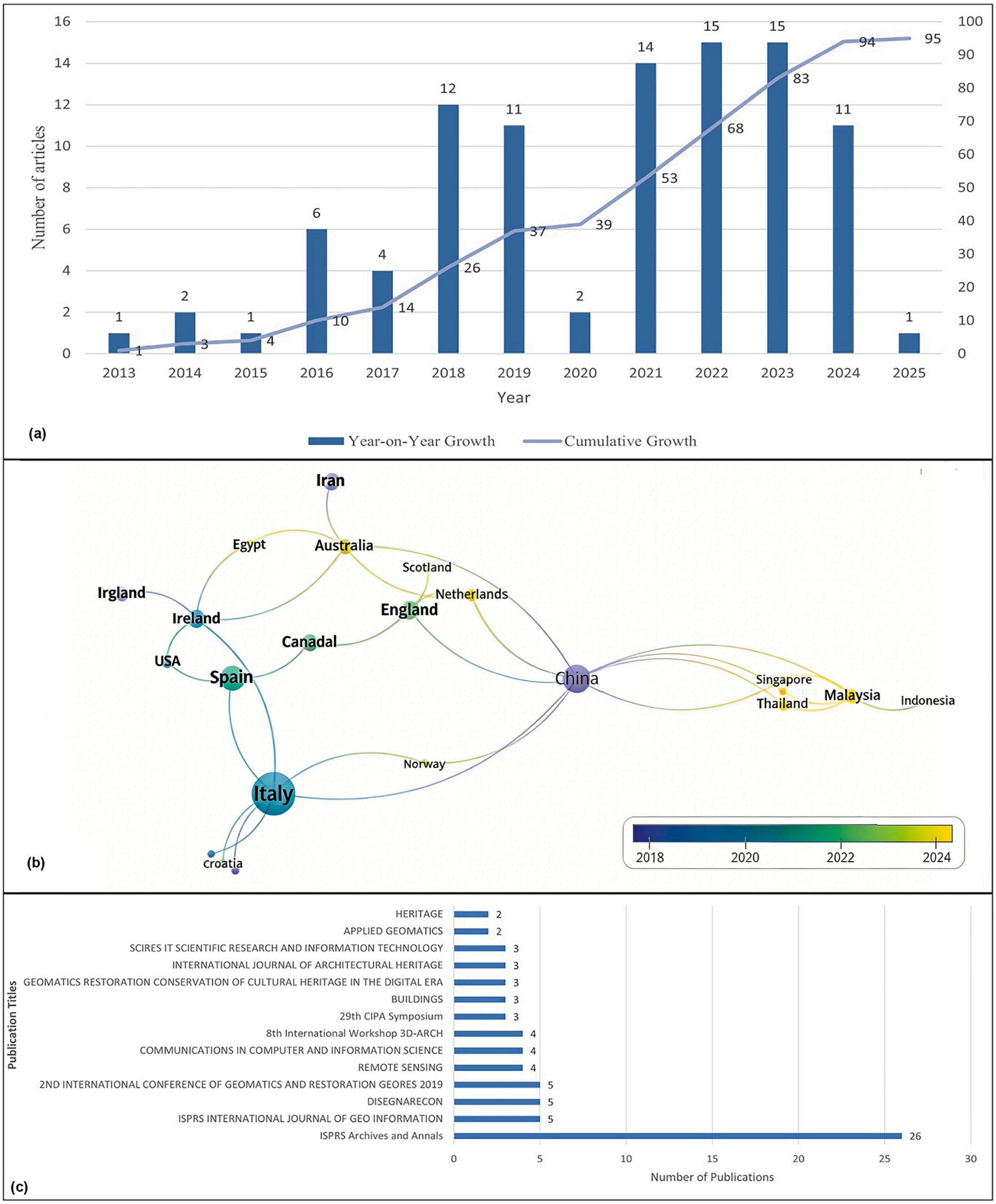

Fig. 4 Results for bibliographic characteristics analysis: (a) number of publications and publication timeline; (b) publications by country/region, timeline, and volume; (c) number of publications by journal and conference.

and Annals (26 articles) as the leading venue. In addition to this, specialized journals including *ISPRS International Journal of Geo-Information*, *DISEGNARECON*, *Remote Sensing*, and *Buildings*, each account for between three and five publications (more journals can be found in Fig. 4(c)). Overall, the dissemination of HBIM research predominantly occurs through international conferences and journals with a strong focus on remote sensing, imaging technologies, and digitized representations of heritage. This reflects the interdisciplinary nature of the field, which lies at the intersection of geomatics, computer science, and cultural heritage conservation.

3.2. Network analysis with VOSviewer: research focus and trends

This section reveals trends and focal points regarding the application of HBIM in heritage conservation, showcasing the field's evolving trajectory and the diverse directions of current research.

3.2.1. Research focus

The size of the circles representing the keywords indicates the volume of publications associated with each keyword, while the lines connecting the keywords reflect the strength of the relationships between them (McAllister et al., 2022). Therefore, it can be observed that the six key research focuses identified through the keyword network each correspond to a distinct thematic cluster (Fig. 5(a)):

- **Cluster 1 (Red):** This cluster centers on HBIM and cultural heritage, representing the conceptual and methodological core of the field. HBIM is strongly associated with keywords such as *digital twin*, *LOD (Level of Detail)*, and *augmented reality*, reflecting its role in digital representation, documentation, and interpretation of heritage assets.
- **Cluster 2 (Green):** Focused on BIM and photogrammetry, this cluster emphasizes technologies related to data acquisition and documentation. Terms like *LiDAR*, *laser scanning*, and *close-range photogrammetry* suggest that accurate 3D data capture is foundational to HBIM workflows.
- **Cluster 3 (Blue):** This group highlights themes related to management, survey, and preventive conservation, suggesting the application of HBIM for monitoring, risk assessment, and long-term heritage site management.
- **Cluster 4 (Yellow):** Centered around point cloud and restoration, this cluster reflects the technical aspects of converting raw spatial data into HBIM models. Topics such as *scan-to-HBIM*, *digital documentation*, and *data management* are prominent here.
- **Cluster 5 (Purple):** This emerging cluster includes machine learning, artificial intelligence, and classification, indicating a growing interest in automated processing, semantic segmentation, and intelligent analysis within the HBIM domain.

These clusters collectively illustrate the interdisciplinary nature of HBIM research, spanning from conceptual frameworks and heritage theory to cutting-edge technologies in data capture, model management, and artificial intelligence.

3.2.2. Keywords with high relevance to architectural heritage

In the HBIM-themed keyword network, "cultural heritage" emerges is central, bridging diverse research dimensions from data acquisition and modeling (e.g., point cloud, photogrammetry) to management and interoperability (e.g., data management, survey, management), as well as the integration of emerging technologies (e.g., AI, machine learning, digital twin). At the same time, as a key subset of cultural heritage, architectural heritage plays a pivotal role in anchoring these technological and methodological developments, reinforcing the multidisciplinary nature of heritage digitization and conservation research (Fig. 5(b)).

3.2.3. Keyword co-occurrence comparison for heritage/historic/historical-BIM

The comparative analysis of keyword co-occurrence reveals that although Historic BIM and Heritage-BIM share strong associations with field data acquisition techniques (e.g., photogrammetry, terrestrial laser scanning, FEM structural analysis), their research emphases diverge significantly (Fig. 5(c) and 5(d)). Historic BIM demonstrates stronger linkages with digital visualization tools (e.g., digital twins, AR, VR), reflecting its orientation toward technology-driven preservation of historic structures. In contrast, Heritage-BIM shows tighter integration with conservation workflows (e.g., scan-to-HBIM) and cultural value preservation, highlighting its process-oriented approach to heritage management. The absence of "Historical BIM" in co-occurrence networks suggests that while the concept may exist in literature, it hasn't gained wide adoption or standardization. This terminological preference underscores the field's emphasis on comprehensive heritage conservation over narrowly defined historical building applications.

3.2.4. Clustering and publication timeline analysis results of keywords in the field

In the paper on HBIM, the color gradient from blue to yellow in the graph represents the timeline of publication from early to more recent works (Fig. 5(e)). This gradient reveals the evolution of research focus and interest, highlighting how certain topics have become increasingly important over time. For instance, earlier studies (shown in blue) primarily concentrated on documentation, conservation, and modeling of heritage buildings, reflecting the foundational phase of HBIM development. As the field evolved, mid-phase research (blue to green) started to integrate GIS, semantic modeling, and interoperability, indicating a shift towards broader applications and technical improvements. More recent studies (indicated in yellow) show a growing interest in artificial intelligence, automation, digital twin technology, and damage assessment, suggesting a clear trend towards data-driven, real-time, and predictive applications of HBIM. This shift also aligns with the increasing need for resilience, risk management, and sustainable heritage preservation in response to environmental and societal challenges.

3.3. Analysis results for paper coding

After coding, our analysis centers on three key categories: "H" Category, which explores how the "H" in HBIM is defined and interpreted across different papers; HBIM Definition, focusing on the overall conceptualization and scope of HBIM; and Integration Technology, which examines the tools, methods, and interdisciplinary techniques involved.

3.3.1. "H" category

Analysis reveals nuanced distinctions between the terms "Heritage", "Historic", and "Historical" in HBIM-related

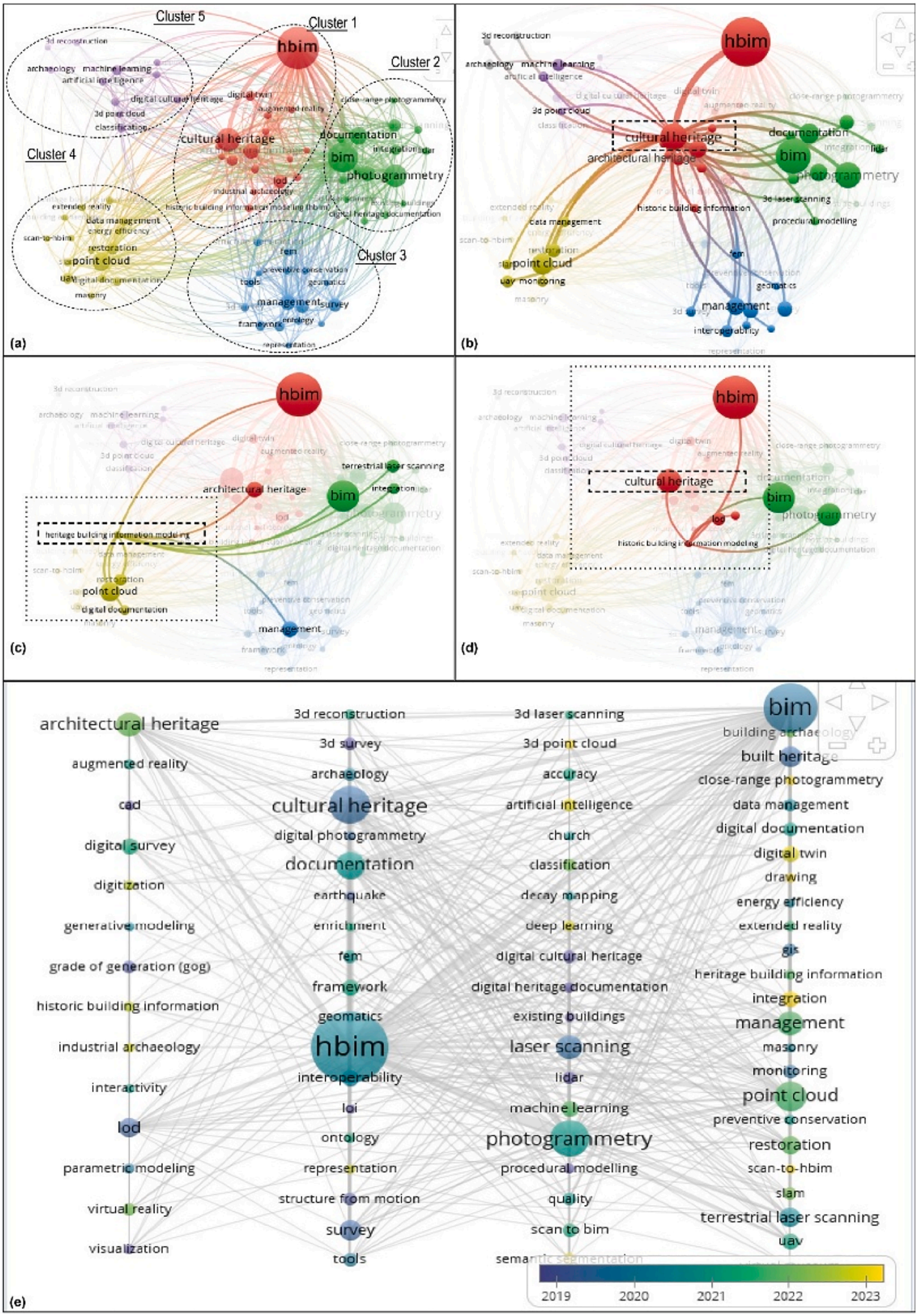

Fig. 5 Network analysis with Vosviewer: (a) clustering analysis results of keywords in this field of research; (b) keywords with high relevance to architectural heritage; (c) keywords with high relevance to historic BIM; (d) keywords with high relevance to Heritage-BIM; (e) clustering and publication timeline analysis results of keywords in the field.

Table 1 HBIM "H" Category Statistics (see Appendix A for details).

Category	Count	Percentage (%)	Numbers
Heritage	48	50.53	1, 5, 8, 10, 11, 14, 15, 16, 17, 19, 21, 23, 27, 28, 29, 36, 37, 38, 39, 40, 41, 42, 44, 46, 47, 49, 50, 51, 52, 53, 54, 55, 56, 58, 61, 66, 68, 69, 71, 75, 77, 78, 81, 86, 87, 90, 91, 94
Historic	23	24.21	2, 6, 13, 18, 22, 25, 26, 30, 32, 34, 35, 48, 59, 60, 63, 67, 73, 79, 82, 83, 85, 88, 95
Historical	13	13.68	7, 9, 12, 20, 31, 33, 45, 57, 62, 70, 80, 92, 93
Heritage/Historic	6	6.32	3, 4, 24, 43, 76, 89
Heritage/Historical	2	2.3	64, 84
N/A	3	3.45	65, 72, 74

literature (Table 1). Among them, *"Heritage"* emerges as the most prominent and frequently occurring term, signifying its central role in framing the conceptual foundation and objectives of HBIM research. In contrast, *"Historic"* is commonly associated with physical or spatial attributes, such as *historic buildings* or *historic urban areas*, emphasizing typological and morphological characteristics of the built environment. Meanwhile, *"Historical"* appears less frequently but is often linked to aspects of documentation, archival practices, and the temporal significance of heritage assets. The overlapping yet contextually specific usage of these terms suggests a layered interpretation of the "H" in HBIM, encompassing both tangible materiality and intangible aspects such as historical value and cultural meaning. This semantic variation reflects the interdisciplinary nature of HBIM and highlights the evolving discourse around heritage representation in digital environments.

In addition to these discrete definitions, some publications explicitly define the "H" in HBIM as "heritage/historic" or "heritage/historical," indicating a hybrid or dual emphasis. This suggests a general consensus on the foundational role of *heritage* as the conceptual core of HBIM, while simultaneously acknowledging the relevance of *historic* or *historical* dimensions in supporting different research and practice objectives. The coexistence of such composite terms also reflects the relative ambiguity surrounding the definition of "H", pointing to an ongoing lack of conceptual clarity in the field's terminological usage.

3.3.2. The broad definition of "H" and its domain in HBIM

Building upon the conceptual mapping presented in Fig. 4, the relative positioning of the terms *"Historical"*, *"Historic"*, and *"Heritage"* can be further clarified through a two-dimensional quadrant typology. The horizontal axis (*x*-axis) represents the degree of historic importance, ranging from low to high, while the vertical axis (*y*-axis) reflects the level of traditional or cultural legacy recognition, also ranging from low to high. Together, these axes construct a semantic landscape in which the meaning and usage of each term can be spatially situated.

In the broader definitional context, the term *"historical"* serves as an umbrella concept encompassing both *"historic"* and *"heritage"* (Fig. 6). While *historical* refers broadly to anything related to the past or to the study of history, it does not inherently convey significance or value. Within this typology, *historic* typically denotes entities, such as buildings, events, or figures, that have great and lasting importance in history, often associated with pivotal societal developments. *Heritage*, on the other hand, emphasizes the legacy of tangible and intangible assets inherited from the past, recognized as culturally or socially valuable and worth preserving for future generations. Notably, *historic* and *heritage* are not mutually exclusive; they intersect where buildings or places are both historically significant and culturally recognized as heritage assets.

The review of current literature on HBIM (which may stand for Historical, Historic, or Heritage Building Information Modeling) reveals a discernible trend: regardless of the terminology adopted, research in this domain overwhelmingly aligns with the *heritage* paradigm. That is, scholarly and practical efforts predominantly focus on the conservation, documentation, and management of built cultural heritage. Even when labeled as *Historical-BIM* or *Historic-BIM*, the underlying intention often centers on heritage-related values such as authenticity, cultural continuity, and adaptive reuse. This suggests that, in practice, the "H" in H-BIM has increasingly come to signify *Heritage*, underscoring the field's orientation toward the safeguarding of cultural heritage rather than merely referencing historical data or commemorating significant events.

3.3.3. Heritage & Heritage-BIM categorization of heritage-related information

According to the latest UNESCO classifications, *heritage* encompasses three primary domains: cultural heritage, natural heritage, and mixed heritage (Labadi, 2013). Within cultural heritage, a further distinction is made between tangible cultural heritage—including movable, immovable, and underwater heritage (such as artworks, monuments, sites, and submerged archaeological remains)—and intangible cultural heritage, which includes traditions, rituals, craftsmanship, and oral expressions. These categories collectively reflect a multidimensional understanding of heritage that integrates material presence, symbolic meaning, and intergenerational transmission of values (Fig. 7).

Within this broader typology, HBIM (Heritage Building Information Modeling) is specifically developed for the documentation and management of cultural heritage, with a particular emphasis on tangible immovable heritage, especially historic buildings, architectural ensembles, and archaeological sites. As indicated in the diagram, HBIM's "H" is situated within the *cultural heritage* domain, and more precisely, within the subset of tangible and immovable assets recognized for their architectural, historical, or typological significance.

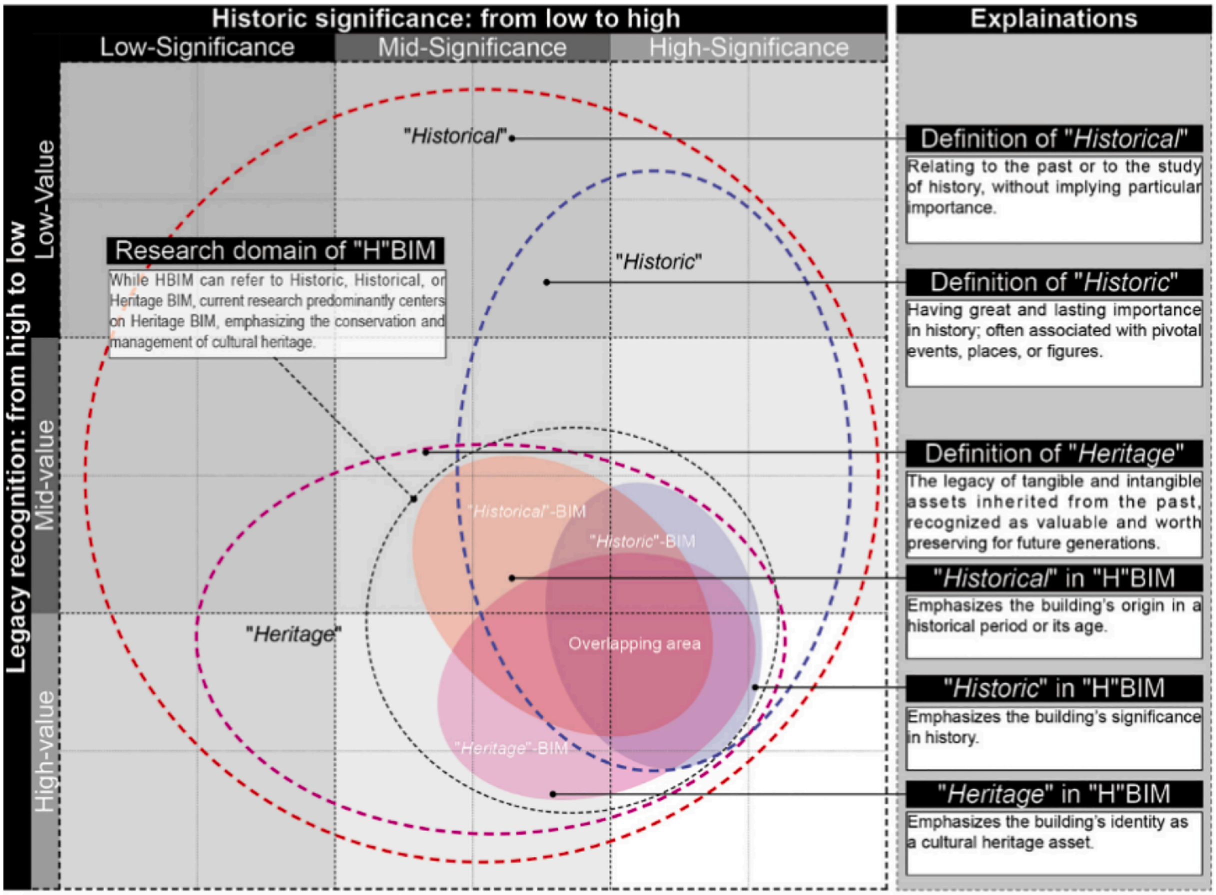

Fig. 6 Conceptual relationships between "Historical", "Historic", and "Heritage" in the context of HBIM.

However, when comparing the focus of current HBIM research with the broader scope of *cultural heritage* as defined by UNESCO, certain discrepancies become apparent. Most notably, while HBIM excels in the geometric documentation, material characterization, and structural analysis of built heritage, it often falls short in capturing intangible values such as social practices, symbolic meanings, and community-based heritage values. Moreover, aspects like cultural significance assessment, stakeholder participation, and the representation of non-material narratives are frequently underrepresented in current HBIM-based methodologies.

This gap suggests that although HBIM positions itself within the cultural heritage domain, its practical application tends to privilege the technical and physical dimensions of heritage over its experiential, performative, and sociocultural components. Bridging the divide between current HBIM practice (focusing primarily on physical heritage documentation) and UNESCO's broader heritage definitions (including intangible cultural dimensions) requires the integration of value-based approaches into HBIM workflows.

3.3.4. Attribute Hierarchies in integrated HBIM systems

Based on the coding and classification of 95 reviewed publications, HBIM-related research can be organized into five major attribute domains: **Structural Information** (60 publications, 35.93%), **Material Information** (15 publications, 9.6%), **Historical Information** (25 publications, 15.0%), **Cultural & Artistic Information** (16 publications, 9.6%), and **Restoration & Conservation Information** (48 publications, 30.5%). Each domain represents a distinct dimension of heritage information embedded in HBIM workflows and is supported by a set of methodological approaches and modeling priorities. The detailed findings for each attribute category are as follows (Table 2).

(i) *Structural Information:* This category includes 60 papers—over half of the total—and represents the most emphasized domain in HBIM literature. Research in this area focuses on the geometric and morphological modeling of architectural elements, structural behavior, and construction typologies. Structural attributes are often the foundation for scan-to-BIM workflows and parametric modeling. Common themes include vault reconstruction, facade articulation, and structural damage assessment. However, integration with non-physical semantic layers remains relatively underdeveloped.

(ii) *Material Information:* Comprising 15 publications (9.6%), this category addresses the representation and analysis of construction materials, including physical composition, aging, and deterioration patterns. Studies often rely on diagnostic surveys, photogrammetry, or

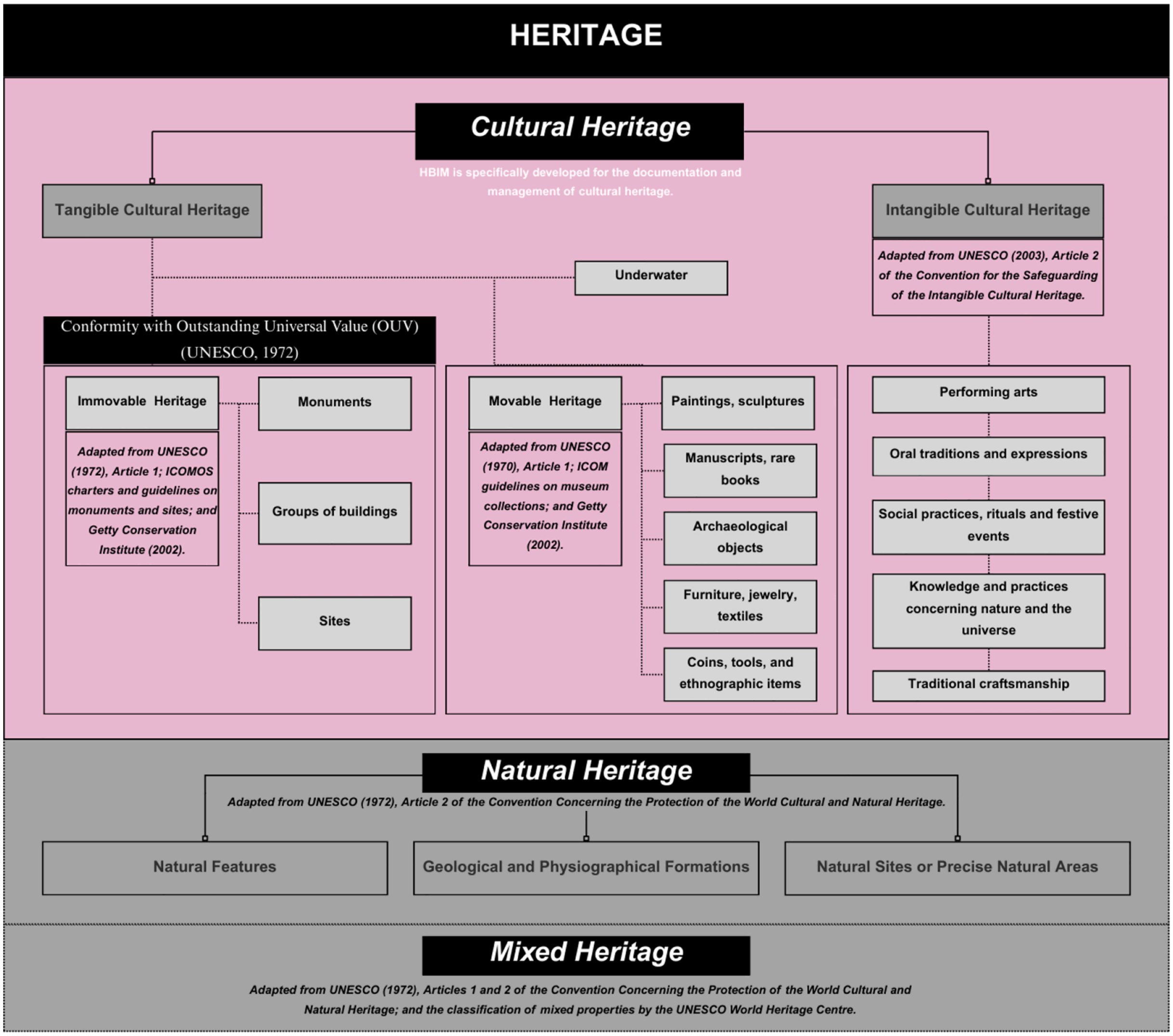

Fig. 7 Classification of Heritage based on UNESCO and International Charters.

Table 2 Attribute Hierarchies in integrated HBIM systems.

HBIM attribute presence	Count	Percentage (%)	Numbers
Structural	60	35.93%	1; 2; 3; 4; 5; 6; 7; 8; 11; 12; 14; 16; 18; 19; 20; 21; 22; 23; 25; 26; 27; 28; 29; 30; 32; 33; 35; 36; 39; 41; 42; 43; 45; 46; 47; 48; 52; 53; 54; 56; 57; 58; 59; 60; 63; 70; 71; 72; 74; 76; 77; 78; 80; 83; 84; 88; 91; 92; 93; 95
Material	15	9.58%	1; 28; 37; 38; 41; 43; 45; 46; 48; 50; 56; 58; 64; 71; 83
Historical	25	14.97%	1; 2; 10; 12; 23; 26; 28; 30; 32; 36; 41; 45; 46; 47; 56; 57; 59; 60; 62; 63; 71; 72; 83; 87; 94
Cultural & artistic	16	9.58%	1; 9; 26; 31; 46; 48; 50; 57; 60; 66; 68; 73; 75; 83; 86; 87;
Restoration & conservation	51	30.54%	1; 5; 7; 8; 12; 13; 14; 17; 19; 21; 22; 23; 25; 26; 28; 29; 30; 32; 33; 36; 37; 38; 39; 41; 43; 44; 45; 46; 48; 49; 50; 52; 54; 56; 57; 58; 59; 62; 66; 67; 69; 71; 74; 76; 80; 82; 83; 85; 91; 93; 95

multispectral analysis to inform HBIM material components. Despite its relevance to conservation, material information remains sparsely embedded in most models, often serving as secondary data annotations rather than central modeling elements.

(iii) *Historical Information:* This category is represented by 25 publications (15.0%) and focuses on documenting the temporal evolution of heritage assets, including construction phases, archival records, and historical semantics. Many papers in this group

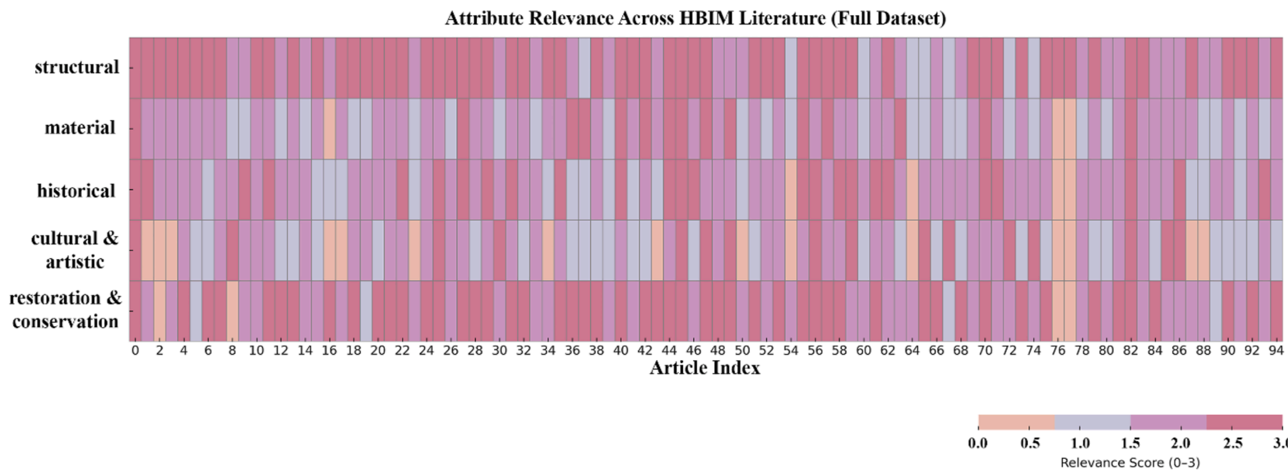

Fig. 8 Heatmap analysis about HBIM's attribute categories.

emphasize the integration of documentary sources into HBIM environments to support interpretative modeling and historical reconstructions. However, challenges persist in formalizing historical stratification and uncertainty within current modeling platforms.

(IV) *Cultural & Artistic Information:* Accounting for only 16 publications (9.6%), this domain is the least represented in HBIM research. It includes symbolic, iconographic, stylistic, and spatial narrative elements of built heritage. Artistic attributes such as frescoes, religious iconography, and architectural ornaments are occasionally modeled or visualized through textured meshes, but rarely embedded semantically within HBIM environments. This indicates a clear underrepresentation of intangible and aesthetic values.

(V) *Restoration & Conservation Information:* With 48 publications (30.5%), this category ranks second in representation. Studies in this group primarily concern deterioration mapping, documentation of past interventions, and predictive or preventive conservation strategies. HBIM is frequently positioned as a tool for supporting heritage management workflows, including maintenance planning and risk assessment. This domain shows strong integration with monitoring technologies and AI-enhanced diagnostic tools.

To further interpret the degree of emphasis attributed to each HBIM information category, a four-tiered relevance rating—comprising *** (high relevance), ** (moderate relevance), * (limited mention), and - (not addressed)—was applied. This classification allows for a nuanced assessment of how comprehensively each attribute is integrated into HBIM workflows (Appendix B).

Across the five attribute categories, a consistent trend emerges: while a limited number of studies demonstrate deep integration of specific attributes, a substantial portion falls into the mid-range categories of "***" and "*". These middle tiers often represent studies where an attribute is acknowledged, either through conceptual framing or minor references, but lacks technical implementation, semantic structuring, or in-depth modeling. In particular, attributes such as Material, Historical, and Cultural & Artistic are frequently referenced in narrative terms or as background context, yet are rarely developed into fully integrated HBIM components.

The heatmap in Fig. 8 illustrates the relevance distribution of five key HBIM attribute categories. The color intensity represents the degree of integration. The analysis reveals a pronounced disparity in the degree of attention assigned to different attributes. Structural and Restoration & Conservation show higher relevance scores across the reviewed studies, whereas Material, Historical, and Cultural & Artistic display lower and more heterogeneous relevance levels. Cultural & Artistic shows the highest concentration of minimal relevance ratings.

The asymmetry in relevance distribution captured in the heatmap highlights a structural bias within current HBIM implementations, favoring tangible, static data types over dynamic, interpretive, or value-based heritage dimensions.

Overall, these findings point to a structural imbalance in HBIM attribute modeling, underscoring the need for advanced methodologies and interdisciplinary collaboration to elevate underrepresented attributes from marginal annotations to core components of heritage modeling systems.

3.3.5. Overview of technologies integrated with HBIM

The technology integration analysis of the papers revealed a diverse but hierarchical adoption of digital tools and methods. Excluding N/A (where technology integration was not specifically identified), a total of 14 different integration techniques were identified, each reflecting a specific functional role in the heritage modeling workflow (Table 3).

An analysis of the technological integration across 95 reviewed HBIM papers reveals a clear pattern of preference toward certain data acquisition and processing tools. The most commonly adopted technologies include **Terrestrial Laser Scanning (TLS),** appearing in 34 papers (20.99%). TLS, as a mature and accurate 3D data acquisition method, remains the dominant approach in heritage modeling, particularly for complex architectural geometries and structural surveys (Liu et al., 2023; Quattrini et al., 2015).

Table 3 HBIM integration technical Statistics.

Integration technology	Count	Percentage (%)	Numbers
TLS	34	20.99	2, 3, 11, 12, 16, 18, 21, 22, 25, 26, 27, 28, 30, 32, 39, 44, 45, 46, 52, 58, 63, 67, 70, 71, 76, 78, 79, 80, 82, 89, 92, 93, 94, 95
N/A	30	18.52	7, 8, 10, 13, 14, 15, 19, 20, 23, 24, 31, 33, 35, 36, 37, 40, 41, 43, 47, 48, 53, 59, 61, 64, 65, 66, 68, 69, 77, 90
Digital photogrammetry	21	12.96	2, 3, 12, 16, 18, 22, 26, 27, 28, 30, 32, 44, 45, 46, 63, 67, 71, 80, 82, 89, 92
AI	11	6.79	4, 5, 17, 38, 49, 50, 51, 54, 55, 74, 91
UAV photogrammetry	12	7.41	11, 21, 25, 39, 52, 58, 70, 76, 78, 79, 93, 94
VR	9	5.56	1, 5, 25, 56, 60, 73, 83, 84, 91
GIS	9	5.56	6, 9, 29, 34, 54, 62, 72, 81, 95
DT	9	5.56	5, 17, 38, 49, 50, 54, 55, 86, 92
AR	6	3.70	5, 25, 60, 73, 84, 91
DL	6	3.70	42, 75, 83, 85, 87, 88
ML	6	3.70	42, 75, 83, 85, 87, 88
IoT	5	3.09	17, 38, 49, 50, 55
XR	2	1.23	60, 91
MR	1	0.62	86
Mobile mapping	1	0.62	57

This is followed by **Digital Photogrammetry** (21 papers, 12.96%), which remains a cost-effective and flexible approach for both close-range and UAV-based documentation (Shakeri et al., 2019). Notably, **UAV Photogrammetry** (12 papers, 7.41%) and **Artificial Intelligence** (AI, 11 papers, 6.79%) are also gaining traction. UAVs are commonly employed for large-scale or hard-to-access sites, while AI techniques support semantic segmentation (Cao et al., 2022; Ulku and and Akagündüz, 2022), damage detection (Barbhuiya and Das, 2025; Zhang and Yuen, 2022), and feature recognition (Matter and Gado, 2024), highlighting a computational turn in HBIM workflows.

Other technologies such as **GIS**, **Digital Twin (DT)**, and **Augmented Reality (AR)** each appear in 5–9 papers (5.56%–6.34%), typically in domain-specific applications such as spatial analytics, interactive interfaces, or heritage simulation (Kalantari et al., 2024). Meanwhile, emerging tools like **Internet of Things (IoT)**, **Deep Learning (DL)**, and **Machine Learning (ML)** remain underrepresented, each adopted in 6 papers (3.70%), indicating a growing but still limited integration. **Mixed Reality (MR), Extended Reality (XR)**, and Mobile Mapping are the least adopted technologies, each appearing only once.

4. Discussion

4.1. Reframing the "H" in HBIM

The letter "H" in HBIM, commonly interpreted as "Historic", s "Historical", or s "Heritage", is rarely unpacked in depth within current literature. However, as this paper shows, the "H" encompasses a wide spectrum of values, including tangible elements such as historical stratification and materials, as well as intangible components such as cultural narratives and artistic symbolism. A critical redefinition of "H" is essential, as it moves HBIM beyond the geometric representation of historical buildings toward a more inclusive and interdisciplinary model of cultural heritage documentation and management.

4.2. Persistent gaps between cultural heritage and HBIM

While the four-category structure of HBIM provides a foundational structure for heritage data organization, the distribution of scholarly attention among these categories remains uneven. As revealed in this review, **Structural** and **Restoration & Conservation** attributes dominate current HBIM research, both in terms of modeling depth and frequency of integration. These domains benefit from the availability of mature survey technologies, standardized workflows, and clear technical parameters for digital representation (Dore and Murphy, 2017). This tendency suggests that while the scholarly community increasingly recognizes the value of multidimensional heritage information, technical and methodological barriers persist in translating conceptual importance into modeling practice. As a result, many attributes remain in a peripheral position, present in discourse but not structurally embedded in the data logic or modeling outputs of HBIM systems.

In contrast, **Material**, **Historical**, and **Cultural & Artistic** attributes receive significantly less focus. Material information is often referenced superficially, such as in relation to deterioration mapping, but rarely encoded with detailed typologies or material science data. Historical aspects, while frequently mentioned in narrative form, are seldom formalized in modeling logic or stratigraphic layers. Cultural and artistic dimensions, including ornamentation, iconography, or symbolic interpretations, are notably underrepresented and often treated as visual embellishments rather than semantically meaningful components.

Despite the increasing adoption of digital tools in heritage practice, gaps persist between the epistemologies of cultural heritage and the logic of BIM-based environments (Mansuri et al., 2022). This imbalance is particularly striking when compared with the broader definition of cultural heritage as articulated by UNESCO and ICOMOS (Fig. 9). These structures emphasize not only the tangible fabric of heritage, but also the **historical depth, symbolic meaning,**

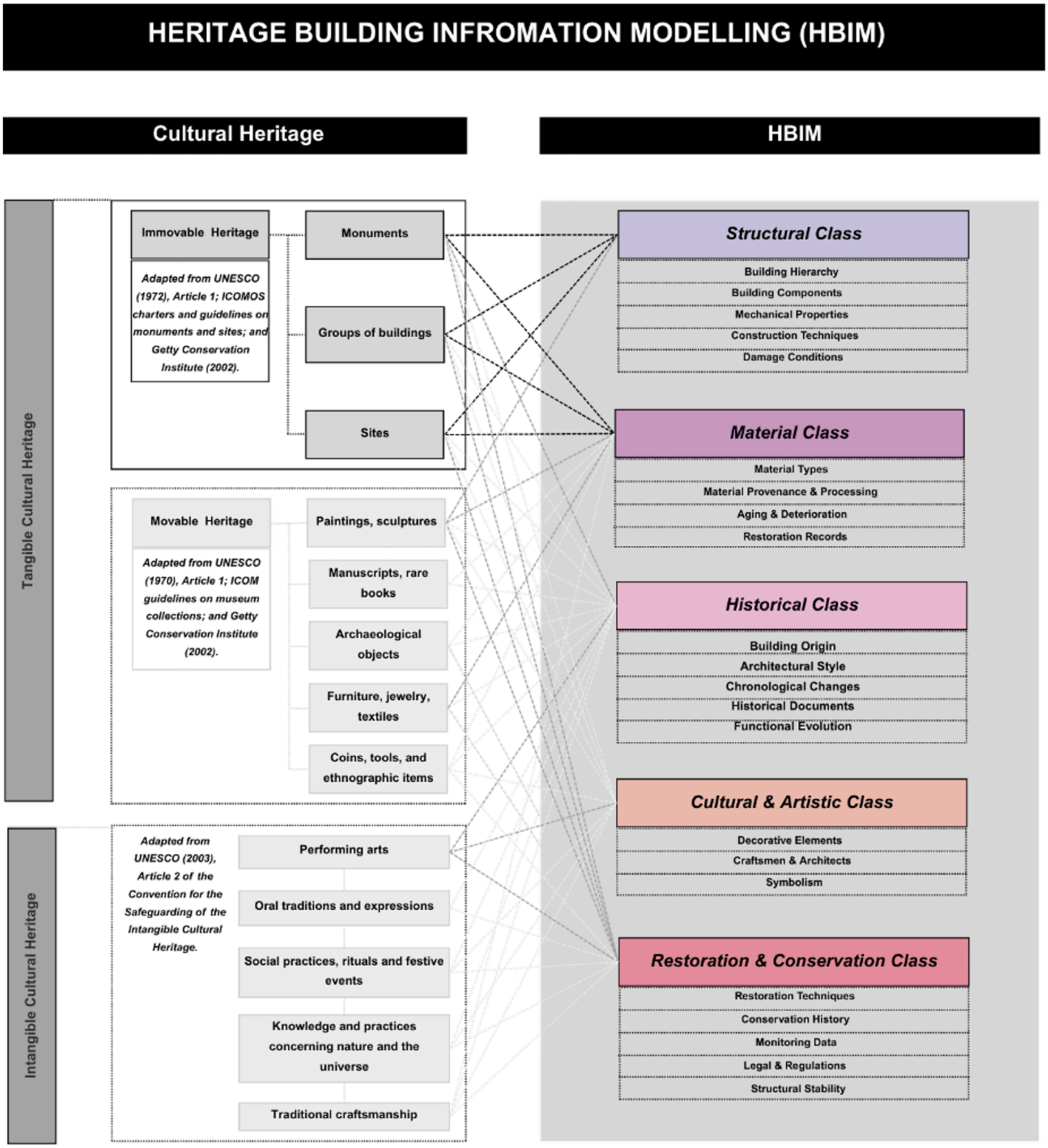

Fig. 9 Hbim classifications with broader heritage typologies.

and cultural values that imbue sites with significance. The current HBIM taxonomy, however, tends to prioritize what can be measured, scanned, or modeled geometrically, while marginalizing aspects that are interpretative, experiential, or socially embedded.

Such a divergence suggests that HBIM remains partially aligned with conservation needs, yet falls short of embodying the **holistic, value-based** understanding of heritage promoted in the heritage papers field. Bridging this gap requires both technical innovation and conceptual expansion, redefining what is considered "modelable" and developing workflows that incorporate qualitative, intangible, and narrative forms of knowledge alongside spatial data.

4.3. Future directions for underrepresented attribute domains

The attribute-based analysis revealed a strong bias toward structural and conservation-related information, with far less attention given to material semantics, historical layering, and especially cultural-artistic attributes. These attributes are often mentioned but rarely modeled, suggesting a state of passive integration. Future research should address this imbalance through the development of ontologies, annotation schemas, and mixed methods that allow for the meaningful encoding of soft heritage data. For instance, linking HBIM with oral histories, archival narratives, or ethnographic mappings may help elevate intangible attributes into operational model elements (Heesom et al., 2021).

4.4. Expanding the integration potential of HBIM with emerging technologies

Beyond its core function as a modeling environment for heritage documentation, HBIM presents significant untapped potential as a central integrative platform for a range of complementary digital technologies. The interoperability of HBIM with systems such as **GIS**, **AI**, **IoT**, and **MR** remains limited in practice, yet offers promising avenues for both research and application.

GIS integration, for instance, enables the spatial contextualization of HBIM models within broader urban or landscape environments, facilitating multi-scalar heritage management, visibility analysis, and risk assessment. While a small number of papers have experimented with GIS-HBIM workflows, full bidirectional data exchange and semantic alignment remain underdeveloped (Brumana et al., 2019; Heesom et al., 2021; Noardo, 2018).

AI can support automated tasks within HBIM environments, including semantic segmentation of point cloud data, material classification, or predictive modeling of degradation processes. The integration of AI improves efficiency and enables deeper interpretative analysis, particularly when paired with annotated historical and diagnostic datasets (Şentürk and Şimşek).

Similarly, **IoT-based sensor networks** offer real-time environmental monitoring, which could be embedded within HBIM to enable dynamic risk analysis, preventive maintenance scheduling, and heritage-responsive design. Although conceptually aligned with HBIM's management potential, such integrations are rarely realized due to interoperability barriers and the absence of standardized protocols (Laohaviraphap and Waroonkun, 2024).

Mixed Reality (MR) applications present another emerging opportunity. When connected to HBIM databases, MR can enhance interpretability and public engagement by visualizing semantic attributes, historical phases, or restoration hypotheses in immersive formats. This integration can transform HBIM from a professional tool into a participatory platform for cultural mediation.

To fully realize this potential, HBIM must evolve from a **static modeling environment into a modular, interoperable ecosystem**. This requires the development of open standards, API-level integration mechanisms, and shared ontologies that allow for the seamless exchange of data and functionalities across platforms. Such advancement would position HBIM as more than a digital documentation tool, it would serve as an operational nucleus within a broader, responsive, and semantic heritage information infrastructure (Bolognesi and Villa, 2021).

4.5. Toward an architectural heritage information infrastructure (AHII)

The insights derived from both the attribute- and technology-focused analyses underscore the need to establish an integrated four-step AHII workflow (Yu et al., 2025b). This infrastructure encompasses: (1) Data Collection, involving archival research, remote/on-site surveys, image capture, and terrestrial laser scanning; (2) Data Processing, where collected data are converted into semantic point clouds, 3D models, and HBIM objects through geometry and data mapping; (3) Data Storing, which focuses on database selection, spatial indexing, and cloud-based infrastructure to ensure long-term accessibility and interoperability; (4) Data Dissemination, leveraging emerging technologies such as 3DGS, VR, and digital twins to enable immersive, lightweight, and semantically rich representations (Fig. 10).

HBIM, within this workflow, serves as a foundational but partial component that must be enhanced through **semantic web technologies, immersive visualization (e.g., VR/AR/MR), digital twin simulation**, and **real-time**

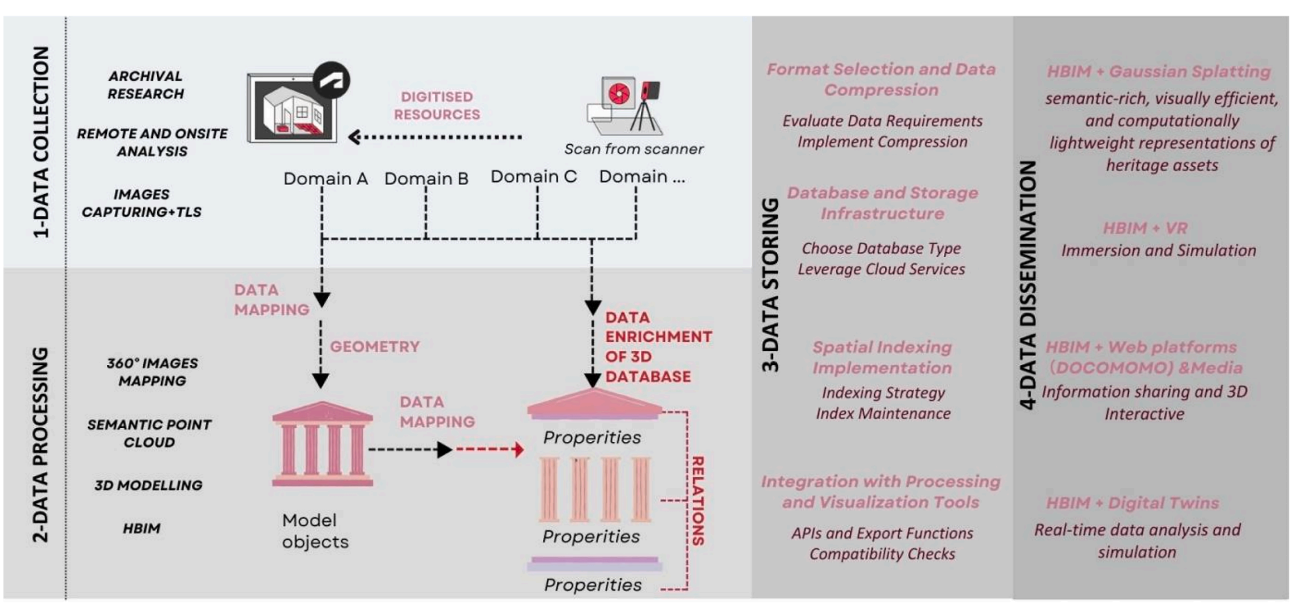

Fig. 10 Overview of AHII.

monitoring via IoT and sensor networks. This evolution transforms static 3D models into a dynamic, interoperable ecosystem, positioning HBIM as a node within a broader, responsive digital heritage network. The realization of AHII not only demands technical innovation but also institutional alignment across shared protocols, data governance models, and interdisciplinary capacity-building.

To support the envisioned integration of HBIM within a broader AHII, a generalized **Unified Modeling Language (UML)** workflow is proposed (Fig. 11). This UML class

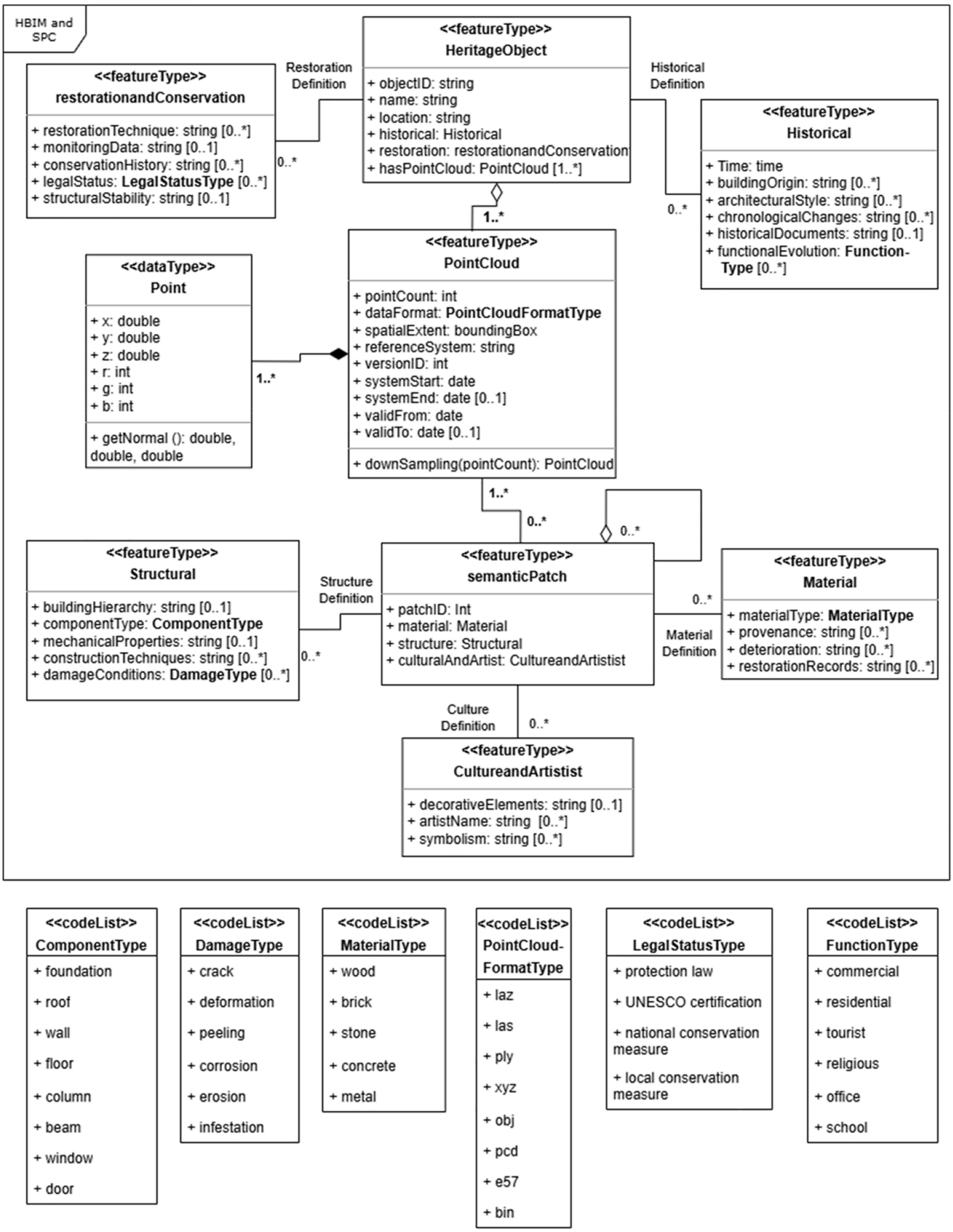

Fig. 11 Uml workflow for HBIM with Smart Point Cloud.

diagram illustrates a comprehensive data structure tailored for Heritage Building Information Modeling (Heritage-BIM) based on point cloud, addressing the complex requirements of documenting, analyzing, and managing historic built environments. At the core of the model is the Heritage Object class, which represents individual heritage assets, described by attributes such as ID, name, location, and textual description. This object-oriented structure integrates both geometric and non-geometric information, beginning with the Representation class, which captures metadata related to the data type and sensor used. From this, the Point Cloud Data class handles raw spatial data, including its format and density, and supports operations like down sampling. The point cloud data is then organized into semantic groupings via the Point Cluster and Semantic Class modules, enabling advanced segmentation and classification. The Point class records spatial coordinates, color information, normal, segmentation IDs, and semantic labels, supporting both accurate 3D reconstruction and meaningful interpretation of historic elements. The diagram thus provides a conceptual foundation for developing HBIM platforms that are semantically aware, historically informed, and conservation-oriented—and offers a schema through which these attributes can be semantically organized and computationally accessible within an extended AHII workflow.

4.5.1. UML schema for HBIM—SPC

To account for the architectural and material specificity inherent in heritage structures, the model includes the Structure Class and Material Class, which captures information about the component type, function, material category, and surface texture, key factors in assessing historical authenticity and decay. Furthermore, the model extends beyond physical attributes to embed rich cultural and temporal context through the Historical Class, Culture and Artist Class, and Restoration and Conservation Class. These classes incorporate stylistic periods, historical documents, artistic features, authorship, restoration interventions, and long-term monitoring data. Subclasses such as Historical Documents and Monitoring Data enable finer-grained documentation of sources and temporal states. This integrated structure facilitates a heritage-centric HBIM workflow that not only supports the technical reconstruction of historical sites but also ensures the preservation of intangible values and knowledge.

A Smart Point Cloud (SPC) refers to a semantically enriched point cloud in which each segmented cluster or patch is annotated with structured information—such as material, structural, and historical attributes—based on a defined ontology. In the context of HBIM, SPC serves as a critical intermediary for linking raw geometric data with high-level heritage semantics, enabling both accurate 3D model reconstruction and information-driven visualization, simulation, and analysis.

As can be seen in Fig. 11, the UML model is centered around the concept of a Heritage Object, which serves as the top-level entity and is defined by both historical and restoration-related information, as well as a collection of associated PointCloud instances. Each PointCloud represents one scan linked to the heritage object, but a heritage object can be consist of more than one scans. This way, it can deal with partial scans for large-sized buildings, as well as the temporal changes of the same point cloud. The PointCloud includes metadata such as ID, format, reference system, and spatial extent. In addition, bi-temporal attributes are introduced to track both the system registration time (systemStart, systemEnd) and the real-world validity period (validFrom, validTo). This enables changes, corrections, or updates to be recorded without overwriting earlier states (Thompson and van Oosterom, 2021).

The classes Historical, and Restoration and Conservation are directly linked to Heritage Object, capturing time-based interpretations and legal-conservation metadata respectively. Historical includes optional fields such as origin date, architectural style(s), functional evolution, and historical documents. Similarly, restorationandConservation covers optional attributes like restoration techniques, monitoring data, legal status, and structural stability, allowing flexibility for objects without formal conservation records.

Each PointCloud comprises basic per-point attributes (coordinates and color), which gain semantic meaning only through association with semanticPatch entities. These patches, identified by unique IDs, encode domain knowledge via links to Structural, Material, and CultureandArtist classes. Patches may overlap across scans and support recursive nesting, enabling hierarchical, multi-scale semantic modeling of complex architectural components.

The Structural class emphasizes component type (e.g., wall, roof), while other properties like mechanical performance or construction methods are optional. Material stores information on material types, provenance, deterioration, and interventions. While Historical connects at the object level, it complements patch-level semantics. CultureandArtist supports narrative content such as decoration, symbolism, and authorship.

Notably, semantic classes can be assigned at either object or patch level depending on their applicability. For instance, consistent restoration across an entire building would be linked to the object, while localized interventions—like a specific sculptural element—would be annotated at the patch level. This dual-level design balances reusability with precision and supports both top-down and bottom-up semantic interpretation in SPC-enhanced HBIM environments.

Critically, all semantic annotations are stored in JSON format, indexed by ClusterID, and linked directly back to the corresponding patch in the point cloud. This allows for dynamic querying, visualization, or updating of structural conditions and historical narratives—positioning SPC as a data-rich backbone for adaptive HBIM systems. This integration also contributes to the broader goals of the AHII.

4.5.2. UML schema for AHII integrating multi-workflow pipelines: HBIM and 3DGS

As heritage digitization evolves beyond conventional mesh-based or parametric modeling approaches, the need for lightweight, photorealistic, and flexible visualization techniques becomes increasingly evident, especially for large, complex, or fragmentary cultural assets. 3DGS, a recent advancement in point-based rendering, offers a compelling alternative to traditional surface reconstruction by enabling high-quality visual output directly from raw or semi-processed spatial data (Clini et al., 2024). Its strengths in real-time visualization, scalability, and adaptability to varying levels of detail make it particularly suitable for integration within heritage information systems. Within the context of the AHII framework, 3DGS complements existing HBIM and SmartPoint Cloud workflows by serving as an efficient visualization layer, capable of delivering semantically annotated, perceptually rich content with minimal computational overhead.

The UML conceptual model developed for the AHII provides a comprehensive integration of heterogeneous data representations and semantic layers within heritage documentation workflows. By combining entities such as SmartPoint Cloud, IfcHBIM, and Gaussian Splatting under a unified 3DRepresentation structure, the model reflects a modular yet interoperable architecture that supports both traditional BIM-based modeling and emerging point-based or image-derived reconstruction methods. Importantly, the model incorporates external Semantic entities, including Historical, Cultural and Artistic, and Restoration and Conservation classes, which can be flexibly referenced across BIM elements, Gaussian patches, and VR representations. This layered semantic integration enables a hybrid documentation strategy that allows both object-level and component-level annotation, addressing the limitations of monolithic BIM or static point cloud approaches. Furthermore, the inclusion of VR-Presentation as a dedicated class extends the usability of HBIM outputs for immersive engagement, simultaneously formalizing the linkage between digital representations and experiential narratives. The model's extensibility, supported by well-structured code lists (e.g., VR-Format Type, Document Type), demonstrates its potential for broad adoption across heritage digitization contexts. In sum, this AHII schema establishes a semantically rich, visualization-ready information framework that bridges geometric fidelity with interpretive depth, aligning with both scholarly and practical demands in digital heritage management.

In summary, the proposed integration of HBIM into an AHII workflow (Fig. 12) underscores the need for scalable, interoperable, and semantically enriched data environments. By formalizing workflows through UML representations and incorporating emerging technologies such as 3DGS, HBIM can evolve from a model-centric documentation tool to a central node within a dynamic heritage information ecosystem. Such a shift not only enhances heritage data usability across disciplines and platforms but also lays the groundwork for intelligent, real-time heritage management.

4.6. Trends and limitations in technological integration

This section summarizes key trends and highlights critical limitations related to technological integration, semantic segmentation, and scalability within current HBIM practices.

4.6.1. Technological integration

The technological landscape of HBIM research is currently dominated by mature tools such as TLS and photogrammetry, which offer high-fidelity geometric capture. However, integration of advanced technologies, including AI, MR, and IoT, remains limited. These technologies, though underutilized, hold transformative potential for semantic enrichment, real-time monitoring, stakeholder engagement, and predictive maintenance. The relatively low representation of these tools indicates systemic barriers, such as software interoperability, the lack of shared standards, and limited cross-domain skillsets. To move forward, HBIM practice must embrace modular, interoperable toolchains that enable cross-functional integration from data acquisition to interpretation.

4.6.2. Segmentation and semantic scalability

Although this paper does not focus on advancing segmentation algorithms, semantic segmentation remains essential in SPC-enhanced HBIM pipelines. Current approaches, often rule-based or supervised, depend on annotated data or specific rules, limiting their scalability and generalizability across diverse heritage contexts. Moreover, geometric features alone may inadequately represent semantics, as identical materials can vary in shape, and similar geometries might represent different functions. Deep learning methods such as simultaneous identification of structural, material, and functional attributes. The concurrent segmentation of structure, material, and function remains an open challenge, highlighting the need for more scalable, semantically comprehensive approaches.

5. Conclusion

This paper provides a critical reappraisal of HBIM by interrogating its definitional boundaries and technological integrations. It demonstrates that while HBIM has become an essential tool in heritage documentation and conservation, its conceptual underpinnings remain inconsistently defined, particularly concerning the meaning of the "H", whether Historic, Historical, or Heritage. The literature analysis shows a prevailing inclination toward the "Heritage" paradigm, underscoring the need to extend HBIM beyond geometric and physical modeling toward a value-based, multidimensional representation of heritage.

The attribute analysis further highlights a structural imbalance in current HBIM practices, with strong emphasis on structural and conservation data and minimal integration of cultural, historical, and artistic dimensions. Similarly, the technological landscape is dominated by traditional tools like TLS and photogrammetry, while more advanced technologies such as AI, IoT, and MR remain underutilized. To address these gaps, the paper proposes an extended UML framework and introduces 3DGS to enhance semantic richness, visual efficiency, and real-time interactivity.

Ultimately, this paper advocates for the evolution of HBIM into a modular, interoperable, and semantically enriched system embedded within a broader AHII. Such a transformation bridges the epistemological divide between cultural heritage and BIM logic while aligning HBIM practices with global heritage values, enabling more intelligent, inclusive, and sustainable heritage management.

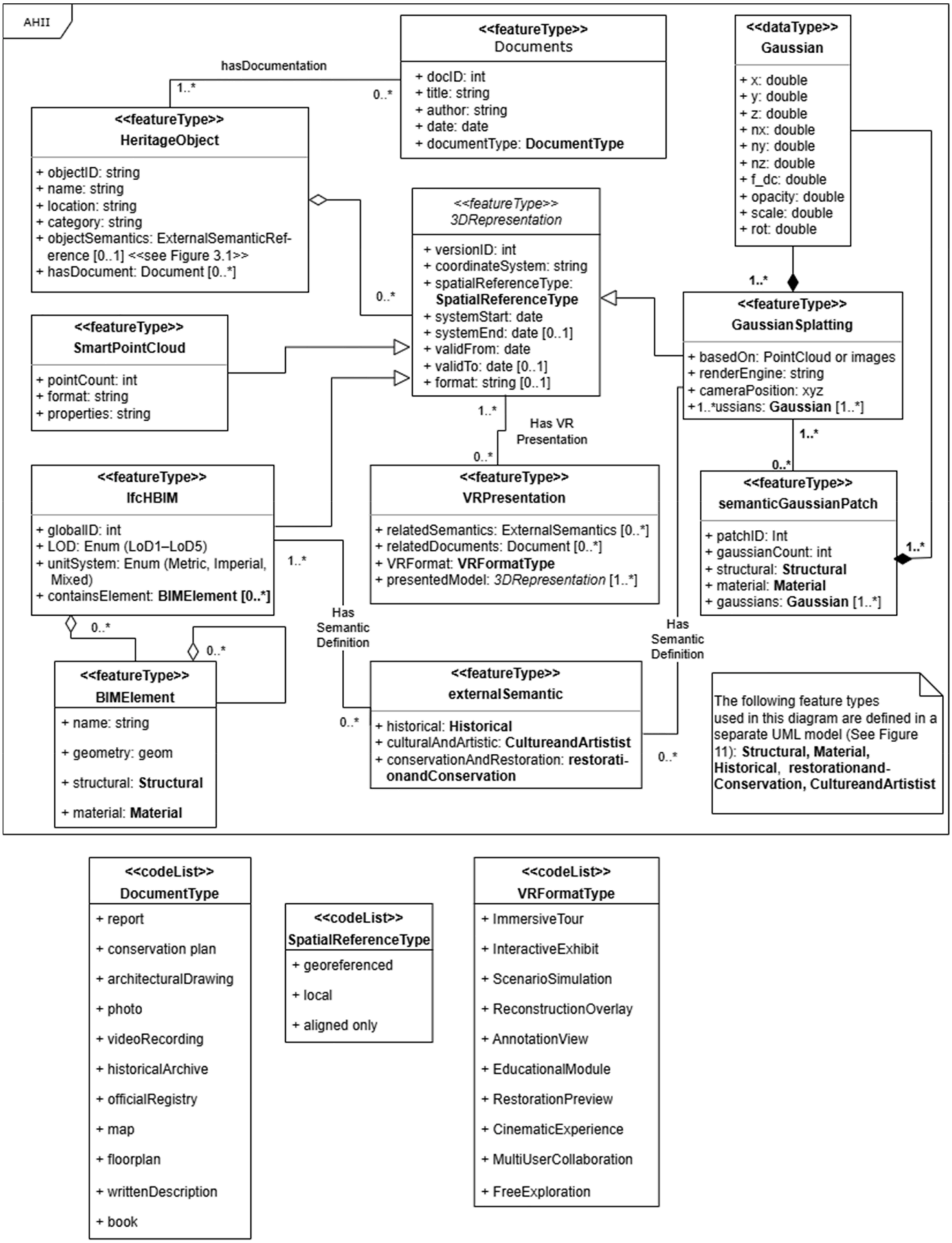

Fig. 12 Uml workflow for AHII.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foar.2026.02.007.

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