




# From HBIM to Digital Twins: An Interoperable Framework for Semantic Knowledge Integration and Dynamic Monitoring of Historic Buildings

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## Abstract

*Historic Building Information Modeling (HBIM) has established itself as a promising approach for the digital documentation and management of cultural heritage. However, there remain fundamental challenges in terms of semantic depth, interoperability, and the dynamic updatability of such models. This paper proposes a multi-layered framework that integrates a geometry-based HBIM model with ontological knowledge representation, external linked data sources, and sensor-based monitoring. Based on open standards such as IFC, ifcOWL, and CIDOC CRM, a concept for a semantically enriched digital twin is developed, which processes both static information and dynamic environmental and condition data. The framework enables context-based analyses, predictive conservation strategies, and promotes interdisciplinary collaboration. Using a prototype framework, methodological advantages, technological challenges, and future development fields are discussed. The paper thus contributes an integrative impulse to the further development of data-driven, sustainable heritage conservation within the context of digital cultural heritage infrastructures.*

*Software and its engineering → Interoperability; Information systems → Information integration; Computing methodologies → Knowledge representation and reasoning*

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## 1. Introduction

In recent years, the concept of Historic Building Information Modeling (HBIM) has developed into a central instrument in digital heritage conservation. The aim is not only to capture the geometric structure of historical buildings but to digitally represent them holistically by integrating semantic, historical, and conservation-related information ([MMP13]; [Bar16]). Nonetheless, significant challenges remain: the fragmentation of existing HBIM approaches, the lack of semantic standardization, and the limited integration of dynamic operational data all restrict the potential of sustainable, interoperable, and knowledge-based cultural heritage information systems ([PVD\*11]; [QMC\*15]).

Recent research thus calls for an extension of traditional BIM methods through ontologies, linked data technologies, and sensor integration in order to model historic buildings not merely as static 3D models, but as semantically interconnected, dynamic knowledge objects in the spirit of a "Digital Twin" ([DH22]). While individual components—such as ifcOWL, CIDOC CRM, or SSN/SOSA—have already been used in case studies, a coherent,

multi-layered framework that systematically integrates these components and is based on open standards has been lacking.

Accordingly, this paper proposes a conceptual approach toward an interoperable, ontology-based HBIM framework can be developed to integrate semantic knowledge networking and dynamic monitoring of historic buildings in support of data-driven conservation strategies.

To this end, it presents a multi-layered framework that connects a geometry-based HBIM model with a semantic knowledge graph, linked data, and IoT monitoring based on a synthesis of the state-of-the-art literature. It addresses current shortcomings in terms of interoperability, standardization, and semantic depth and contributes to the development of adaptive, networked information systems for digital heritage conservation.

## 2. Related Work

Since the introduction of the HBIM concept over a decade ago, numerous studies have been conducted to advance digital methods for the documentation and management of cultural heritage. Murphy et al. (2013) [MMP13] laid early foundations by

demonstrating how laser scan data and photographs can be used to generate parametric 3D models of historical buildings enriched with attribute information. These efforts developed libraries of component objects (e.g., vaults, window shapes) to digitally reproduce the often complex architectural elements of historical structures. Murphy et al. [MMP13] thus established a workflow from point cloud to HBIM model, which has been widely adopted in later projects.

Early approaches to Historic BIM modeling show that historical buildings pose specific requirements in terms of geometry and information structure. The HBIM concept was introduced to adapt BIM methodologies to existing buildings—recognizing that heritage structures require a different modeling logic than new constructions ([MMP09]). A key strategy was the development of parameterized object libraries for historical motifs, such as classical columns, vaults, or ornamentation, which are not found in standard BIM libraries. These libraries were usually created based on laser scans or photogrammetry and manually remodeled—a process now known as “Scan-to-HBIM.” In this process, point clouds from terrestrial laser scanning (TLS) or photogrammetric images are converted into 3D BIM models by tracing geometries and adapting building elements ([QMC\*15]).

Research has refined this workflow through methods for automated detection of point cloud data, increased accuracy, and dealing with uncertainties in the existing fabric, such as tilted or non-vertical elements ([Bar16]). Despite technological progress, many studies emphasize that irregular, complex structures require human interpretation and cannot be fully automated ([MMP09]). Occluded areas (data occlusions) also lead to gaps in the model, which must be supplemented with archival materials or plausible assumptions ([BOB\*20]).

A central deficit in current HBIM practice is the lack of standardization. Many projects develop their own modeling guidelines since no universally accepted standards for HBIM objects and their attributes currently exist. Researchers therefore call for extensions of existing exchange formats such as IFC in order to consistently represent historic building fabric and conservation data ([PBH24]).

Building on these semantic approaches, the role of standardized ontologies for cultural heritage is increasingly emphasized. A key standard is ifcOWL, an Web Ontology Language (OWL)-based representation of the IFC format, which converts BIM data into RDF triples and thus makes them machine-readable ([PVD\*11]). In addition, the Building Topology Ontology (BOT) supports the structured modeling of spatial and hierarchical relationships within a building—for example, defining rooms, zones, and component affiliations ([PT16]; [RLS21]). For the integration of sensor time-series data, the SSN (Semantic Sensor Network) and SOSA (Sensor, Observation, Sample, and Actuator) ontologies have been developed. These enable formal, unambiguous links between sensor data and specific building components and allow contextual evaluation ([CBB\*12]; [JHC\*19]). These semantic standards form the basis for linking static model information with dynamic environmental observations—creating what is known as a “living digital twin.”

Building on this, Di Stefano et al. (2020) [DGM20] propose combining ontology-based semantic models with the BIM geometry model. In their study, a parallel coupling of an OWL ontology model with a BIM model is developed to cover both non-geometric knowledge content (e.g., damage classifications, historical events) and the building logic. This synchronization of two model worlds—the knowledge graph on one hand and object-oriented BIM on the other—significantly improves interdisciplinary collaboration and dataset interoperability.

A related research line focuses on deeper integration of HBIM into the Semantic Web to address interoperability issues and explicitly model knowledge. The aim is to consider HBIM not just as a geometric model with attributes but as part of a distributed knowledge graph linked to external ontologies and datasets. Pauwels et al. (2016) [PT16] developed a semantic enrichment pipeline in which BIM data is linked with an ontology-based web repository. Their method includes defining a cultural heritage ontology, mapping BIM data to this ontology, and publishing the enriched data in a triplestore. With SPARQL queries, users could, for instance, search for components with certain historical properties or analyze relationships between decorative elements and archival sources.

Studies also show that HBIM data can be linked with existing cultural heritage ontologies such as CIDOC CRM, for example, to embed restoration histories, historical contexts, or archival metadata ([IGE\*24]). Building on these foundations, another active research area aims to expand the semantic spectrum of HBIM models—especially by incorporating externally defined vocabularies and cultural heritage ontologies. While many current HBIM models contain geometric information and some attributes, they often lack rich contextual knowledge about the building—such as historical events, architectural styles, or material provenance. Ontologies such as CIDOC CRM and controlled vocabularies like the Getty Art & Architecture Thesaurus (AAT) address this gap. They enable formal, standardized descriptions of cultural heritage information that can be linked to BIM models ([PVD\*11]; [PBH24]).

In a widely recognized approach, building information was modeled using ifcOWL and CIDOC CRM to systematically and structurally incorporate historical data into HBIM. This allows not only physical properties but also construction phases, styles, or restoration measures to be represented as linked, queryable objects in the knowledge graph. On this basis, a knowledge-based HBIM can emerge that goes beyond geometric representation and integrates historical, cultural, and conservation-related information. ([PT16], [CMP\*22])

An increasingly important aspect of current research is the integration of heterogeneous data sources into comprehensive information systems for heritage. Data on historic buildings is often decentralized and in different formats—for example, as text documents in archives, photographs in museums, GIS maps from heritage authorities, or live sensor data from monitoring systems. New approaches aim to embed HBIM models as central platforms within such federated data spaces. Initiatives like the “Culture Data Space” aim to connect BIM with external collections to create a shared, cross-institutional knowledge base ([RLV24]).

A third important research area concerns the use of artificial intelligence (AI) in heritage preservation—particularly in computer vision and machine learning. The goal is to support or replace tasks previously performed manually with automated analysis techniques. A noteworthy contribution comes from Seo et al. (2023) [SDC23], who present a deep-learning-based Scan-to-HBIM method in which high-resolution orthophotos of historic facades are segmented using convolutional neural networks (CNNs) to automatically detect various types of weathering and material damage.

Manual modeling of complex historic buildings remains time- and labor-intensive despite modern tools. Therefore, AI-based methods are increasingly coming into focus to support and objectify this process. In addition to object detection, recent studies have also explored hybrid approaches combining predefined ontologies with machine learning to segment point clouds in a targeted way.

### 3. Framework Requirements

The analysis of the current state of research shows that existing HBIM approaches remain fragmented and face major challenges in dealing with complex, heterogeneous, and semantically rich cultural heritage data. In particular, there is a lack of unified standards for modeling historical objects, interoperable data formats, and sustainable mechanisms for integrating external knowledge sources and dynamic operational data. Numerous studies emphasize the need to systematically link geometric, historical, and conservation information and convert it into a formalized, queryable structure. Furthermore, the integration of current sensor data and the feedback of model-based insights into operational decision-making and communication processes is gaining increasing importance.

Against this background, the following functional and technical requirements can be identified for a forward-looking framework for digital heritage conservation:

- Structured integration of diverse data sources (geometry, historical documentation, damage records, environmental data);
- Semantic enrichment of the model through domain-specific ontologies to formalize expert knowledge;
- Connection to external knowledge resources using Linked Data technologies to enable interoperability and context expansion;
- Capability to integrate and query dynamic condition data via IoT and monitoring systems for real-time and predictive analysis;
- Provision of user-friendly, interactive interfaces for analysis, visualization, and decision support, adapted to different user groups and professional disciplines.

These requirements form the conceptual foundation for the multi-layered framework introduced in the following chapter.

### 4. Conceptual Framework

To meet the outlined requirements, we propose a multi-layered framework that integrates an HBIM model with a Semantic Web knowledge graph, Linked Data, and IoT-based monitoring. Figure 1 illustrates the five interconnected layers of the proposed framework.

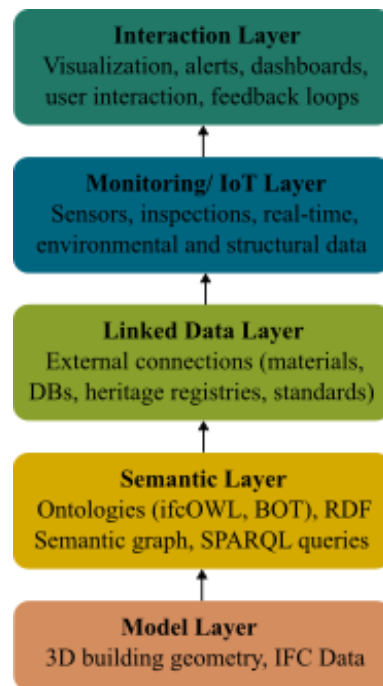


Figure 1: HBIM Conceptual Framework.

Each layer is described in detail below.

#### 4.1 Model Layer (Geometric and Base Data Model)

The foundation is a basic HBIM model of the heritage asset that includes the geometry and fundamental attributes of all building components. The structure is digitally documented using appropriate methods—typically terrestrial laser scanning and photogrammetry to generate detailed point clouds ([MMP13]). From this data, a parametric 3D building model is created, usually via manual modeling in BIM authoring software. More recent workflows also involve (semi-)automated scan-to-BIM tools and AI algorithms that can extract elements like walls, vaults, and columns directly from point clouds ([CCP\*23]).

The process begins with a comprehensive survey of relevant data, integrating multiple sources:

- Geometric data (e.g., via TLS, drone-based photogrammetry, LiDAR),

- Historical records (e.g., archive documents, drawings, material analyses),
- Condition data (e.g., inspection reports, photos, sensor readings).

A “semantic-first” approach is used from the beginning: survey teams and historians apply standardized identifiers, metadata templates, and terminologies aligned with existing ontologies ([QMC\*15]). This early semantic structuring facilitates later integration into the knowledge graph and promotes consistency across all layers.

Regardless of the modeling method, the resulting HBIM should contain as-built geometry and key physical properties of the structure. The use of open exchange formats, especially IFC (Industry Foundation Classes), is essential for ensuring interoperability. Each building element is assigned a Globally Unique Identifier (GUID), which serves as a critical reference point for linking across semantic and data layers.

The HBIM layer thus provides the spatial and object-based foundation: a digital representation of the structure with defined components (walls, roofs, windows, etc.) and base attributes (dimensions, materials, construction period, etc.).

#### 4.2 Semantic Layer (Ontological Knowledge Model)

On top of the geometric HBIM model, a semantic layer is introduced that represents the building and its components as a structured knowledge graph. The goal is to enrich the geometric HBIM model with meaningful, domain-specific concepts relevant to heritage conservation. This is achieved through the use of ontologies and Semantic Web technologies ([PVD\*11]).

Specifically, the IFC-based HBIM model is converted into the Resource Description Framework (RDF). RDF enables the representation of statements in the form of triples (subject – predicate – object), resulting in a graph-based structure where individual components are modeled as nodes with typed relationships. The transformation uses established ontology standards such as:

- ifcOWL, which maps IFC classes and properties to the Web Ontology Language (OWL) ([PVD\*11]),
- and BOT (Building Topology Ontology), which models spatial and hierarchical relationships within buildings ([RLS21]).

The objects in the HBIM—e.g., a wooden beam with a unique GUID—are transferred to the semantic graph as individuals and linked via predicates to additional information. For example, a beam object can be connected to its material class (e.g., oak), load-bearing capacity, historical construction phases, restoration events, or environmental exposure. This type of representation allows for far richer descriptions than what traditional BIM tools typically support, where such metadata is often proprietary or unstructured.

The ontology-based semantic model significantly expands the informational depth of the BIM model. It enables the formal description and querying of conditions, damage types, actors,

historical contexts, or conservation measures. By explicitly representing expert knowledge in a logically traceable structure, a coherent digital knowledge repository of the asset is created.

One core advantage of the semantic layer is the ability to perform semantic queries via SPARQL. Complex queries like: “Which timber beams in section X have a load-bearing capacity < 3 kN and are located in zones with consistently high humidity?” can be answered only through the structured linking of physical, structural, and environmental data via semantic concepts. Additionally, the semantic model supports logical inference. For example, a combination of properties—such as “wooden element”, “load-bearing”, and “high moisture exposure”—can be used to automatically classify a component as a risk object, even if that status was not explicitly assigned.

A key aspect of the semantic layer is its permanent linkage to the geometric HBIM model: Each semantic instance in the graph references a corresponding object in the 3D model through the shared GUID. This follows the approach by Di Stefano et al. [DGM20], who propose a synchronized dual-model system: ontology on one side, BIM on the other. This setup allows updates to either model while maintaining a consistent mapping and synchronization logic.

Overall, this semantic layer results in a model-based information system that extends beyond geometry to include rich, non-geometric knowledge structures—such as historical relationships, actor roles, or regulatory contexts. This ontological approach is foundational for advanced querying, analysis, and decision-making capabilities in digital heritage management.

#### 4.3 Linked Data Layer (External Knowledge Integration)

The Linked Data Layer extends the semantic HBIM knowledge graph beyond the boundaries of a single project by incorporating external data sources, regulatory frameworks, and semantic knowledge bases. While the Semantic Layer focuses on the formal representation of internal project data, the Linked Data Layer enables interconnection with globally available reference data in the Semantic Web.

Technically, this is achieved by assigning persistent, dereferenceable URI identifiers to concepts and objects that link to external Linked Open Data sources ([PVD\*11]).

A typical use case is the integration of material information. For instance, a building material referenced in the HBIM—such as oak wood, sandstone, or lime mortar—can be linked via a URI to an external dataset, like the Getty Art & Architecture Thesaurus (AAT) or a certified material database. A beam object in the RDF knowledge graph might, for example, have the property :hasMaterial :oakWood, where :oakWood links to an external URI containing additional data such as density, weathering characteristics, or susceptibility to pests.

The same principle applies to the inclusion of technical regulations: building elements can be linked via URIs to specific sections of national or international standards (e.g., DIN, EN, ICOMOS guidelines). Historical sources can also be incorporated—e.g., through links to entries in Wikidata, digital archives, or cultural heritage registries ([CMP\*22]).

This type of external referencing increases the informational value of the HBIM model significantly—without duplicating data. Instead, the semantic model refers to the respective authoritative source, ensuring reliability. A prerequisite is the use of compatible ontologies and shared data models. If external sources also employ ontologies (e.g., for materials, construction phases, or stakeholder roles), ontology mapping or alignment techniques are required to ensure semantic consistency ([PVD\*11]).

In the literature, two primary approaches for external data integration are distinguished:

- a relational approach that connects to external relational databases (e.g., via APIs or tools like Revit DBLink), especially suitable for large, dynamic datasets such as maintenance logs or environmental sensor values;
- and an ontological approach, which links directly at the semantic level using RDF/OWL structures.

Studies (e.g., [CMP\*22]) show that these approaches serve different goals: relational methods offer operational flexibility and performance, while ontological methods enable greater expressiveness, long-term interoperability, and deep semantic reasoning.

This paper adopts a primarily ontological Linked Data approach to enable seamless integration into federated cultural heritage knowledge networks. However, relational integrations remain valuable, particularly for efficiently managing real-time sensor data.

By introducing this Linked Data Layer, the HBIM model becomes part of the Semantic Web, allowing SPARQL-based queries that extend beyond the model itself—for example, incorporating external knowledge on material behavior, conservation techniques, or legal regulations. Moreover, the open structure promotes reusability: academic institutions, monument registries, or museum systems could automatically access model-linked information.

In sum, the Linked Data Layer forms the backbone of an interoperable, extensible, and future-proof information ecosystem for digital heritage conservation.

#### 4.4 Monitoring/IoT Layer (Dynamic Data Integration)

The Monitoring/IoT Layer extends the framework by incorporating dynamic, time-dependent data from the operational and environmental monitoring of the heritage asset. While the previous layers primarily model static or structured descriptive information—such as geometry, material properties, or historical contexts—this layer introduces real-time or periodic condition data, continuously collected and updated. As a result, the HBIM model becomes the foundation of a “living digital twin”—a digital representation of the building that evolves alongside its real-world conservation state ([NA21]).

Historic buildings are exposed to a wide range of variable influences, such as climatic fluctuations, moisture exposure, mechanical stress, or chemical aging. To monitor these factors,

sensor systems are installed at critical components or areas. These include:

- Temperature and humidity sensors inside rooms or within structural elements,
- Structural sensors, such as strain gauges or tilt sensors for detecting deformation,
- And environmental sensors to monitor air quality, vibrations, or weather conditions ([USC25]).

These sensors generate time-series data at regular intervals (e.g., minutes, hours, or days), which are transmitted to a central IoT platform for processing and storage. Integration of this sensor data into the HBIM system can occur via two pathways:

1. Direct embedding into the semantic knowledge graph, using ontologies like SSN (Semantic Sensor Network) and SOSA (Sensor, Observation, Sample, and Actuator Ontology), which provide formal representations of sensors, observations, and measurement values ([CBB\*12]; [JHC\*19]).
2. Or by maintaining the data in an external time-series database and referencing it semantically via URIs, following the same principle as the Linked Data Layer.

Both methods aim to unambiguously associate sensor readings with specific building components. A critical element here is the assignment between a sensor instance and the corresponding building element. For example, “Humidity Sensor #42” might measure moisture levels in the wooden beam with GUID 1234. This relationship is semantically modeled so that SPARQL queries can retrieve, for example, the latest humidity values for all load-bearing wooden elements in a specific building zone.

In addition, dashboards and visualization tools can automatically generate alerts if thresholds are exceeded. Manually collected inspection data—such as maintenance reports, damage logs, or photo documentation—can also be modeled semantically. Each finding is recorded as an event with a timestamp, classification, and affected object, and integrated into the knowledge graph ([NA21]).

Thus, the Monitoring/IoT Layer transforms the HBIM from a static documentation system into a dynamic, condition-aware digital twin. This not only supports retrospective analyses but also enables predictive maintenance strategies. For example, the system can detect prolonged high moisture exposure and issue proactive recommendations—such as initiating preventive conservation work.

In research, such integrated systems are increasingly referred to as “Smart Heritage Systems” or “Reactive Digital Twins” ([DMP23]) and are considered pivotal for sustainable, data-driven heritage conservation, especially in light of climate change challenges.

However, technical challenges remain, such as:

- Ensuring interoperability among diverse data formats (e.g., IFC, JSON, CSV),

- Guaranteeing the robustness and durability of sensor hardware,
- And efficiently managing large volumes of time-series data.

The framework addresses these issues with a layered architecture: the geometric core model remains stable and independent, while condition data can be flexibly linked and updated without compromising the integrity of the HBIM.

#### 4.5 Interaction Layer (Feedback and Interaction Layer)

The Interaction Layer constitutes the top layer of the conceptual framework and represents the systematic feedback loop between the HBIM model and its operational, strategic, and communicative applications. It acts as the interface between the digital knowledge system and its various user groups, reflecting the “interaction” of model-based information in real-world decisions, actions, and stakeholder interactions ([BBS19]; [BRA\*20]).

A central element of this layer is the provision of interactive visualization and user interfaces. Technologies such as:

- Web-based 3D viewers,
- Virtual Reality (VR) and Augmented Reality (AR) applications,
- and dashboard interfaces,

enable access to the semantically enriched model in diverse usage contexts. For example:

- Damage conditions can be visually highlighted using color coding.
- Condition reports can be accessed directly through the model.
- Environmental influences can be visualized in real time.

Immersive visualizations not only support technical analysis but also enhance stakeholder engagement and interdisciplinary communication. For instance, a virtual HBIM model can be used in VR settings to allow restorers, public authorities, or external experts to collaboratively assess the condition of a monument ([BRA\*20]).

This layer can also connect to external simulation tools—for instance, structural stress analysis, energy behaviour simulations, or moisture migration models. Their outputs can be fed back into the semantic model and integrated into the knowledge structure ([BBS19]).

Another key feature is the adaptive feedback mechanism. Real-world interventions—such as restorations, material replacements, or maintenance actions—are documented in the HBIM model and thereby change its data foundation. These actions leave “digital traces” in the system, which can influence the interpretation of future data. ([NA21]).

In summary, the Interaction Layer ensures that the semantically enhanced HBIM model is not a static data repository,

but rather an active tool for heritage conservation. It transforms the model into a decision-support system, a knowledge-sharing platform, and a strategic planning instrument. Only through this feedback loop does the full operational value of the framework become apparent, positioning it as a cornerstone of sustainable, data-driven heritage management.

## 5. Discussion

The proposed multi-layered framework for a semantically enriched HBIM model makes a significant contribution to the advancement of digital infrastructures for cultural heritage. Rather than delivering only geometric representations of historic buildings, the system connects information from various domains—including ontologies, linked data, and dynamic sensor inputs—into a coherent and interoperable architecture. As such, this discussion shifts away from reiterating existing challenges and instead focuses on the scientific value and forward-looking implications of the approach.

A key innovation lies in the operationalized integration of geometric modeling data with formal semantic knowledge representation. By employing open ontology standards such as ifcOWL, CIDOC CRM, and BOT, the framework creates a semantic model capable of expressing not only static physical properties, but also historical, conservation-related, and operational contexts. This conceptual depth allows for:

- Complex semantic queries,
- Cross-domain knowledge linking,
- And automated reasoning—capabilities far beyond the reach of traditional HBIM systems.

The integration of monitoring data via the SSN/SOSA standard represents another strategic strength of the framework. This dynamic extension transforms the model into a “living digital twin” that not only supports retrospective documentation, but also enables forward-looking capabilities such as predictive maintenance ([FAM\*15]).

Another notable advantage is the framework’s potential to enhance interdisciplinary collaboration. By semantically harmonizing domain-specific terminology and aligning knowledge structures across fields, it facilitates cooperation between architects, heritage scientists, conservators, and data specialists ([OBG14]). The HBIM model becomes not just a technical platform but a shared cognitive environment, capable of integrating external knowledge bases and standards through Linked Data ([PBB\*18]; [CMP\*22]).

The technical realization of the framework shows that existing semantic technologies can be embedded into practical workflows—thanks to features like persistent URIs, standardized mapping routines, and modular architectures. The structured semantic approach supports both human interaction (via visualization interfaces) and machine interpretation (through rule-based reasoning and inferencing). This paves the way toward automated decision support and adaptive maintenance planning, as envisioned in the concept of “smart heritage systems” ([DMP23]).

While the initial effort for modeling, ontology development, and data curation remains considerable, the study shows that methodical structuring and standardization can lead to significant long-term efficiency gains. The field is thus moving from overcoming isolated technical barriers to shaping intelligent, semantically structured heritage ecosystems.

Ultimately, this framework is not simply a technical construct—it functions as a strategic bridge between digital modeling, semantic knowledge processing, and sustainable heritage conservation. Its contribution lies not in solving individual technical issues, but in charting a cohesive, future-ready path for the digital transformation of cultural heritage.

## 6. Outlook & Future Work

This study lays the conceptual foundation for a multi-layered, semantically enriched HBIM framework, which integrates geometric, historical, semantic, and sensor-based information into a cohesive system architecture. However, for broad practical implementation, several interdependent research and development steps are required.

First, the development of user-friendly tools is essential. These tools should allow integration of semantic data models into BIM environments without requiring in-depth knowledge of RDF or SPARQL (see [QMC\*15]; [CMP\*22]).

This includes:

- Ontology editors as plug-ins for standard BIM software,
- And automated converters from IFC to RDF/OWL, bridging the gap between geometric modeling and semantic knowledge representation (see [PVD\*11]; [TŠ15]).

Second, there is a pressing need for shared, domain-specific standards for the semantic description of historical buildings. Although numerous project-specific ontologies exist today, there is still no widely accepted reference structure for materials, damage types, restoration actions, or historical architectural features (see [IGE\*24]; [PBB\*18]). A “Historic-BIM Ontology” based on ifcOWL, BOT, and CIDOC CRM could serve as a unifying semantic backbone.

Third, the application of artificial intelligence (AI) offers promising approaches to enhance the efficiency of semantic enrichment. For example:

- Deep learning methods such as convolutional neural networks (CNNs) can automatically segment laser scan data or detect common damage patterns (e.g., cracks, moisture, biological growth) in image material (see [SDC23]).
- Additionally, natural language processing (NLP) could be used to extract relevant information from text sources like restoration reports and semantically link it to building elements (see [DdGM25]).
- In the field of monitoring, predictive maintenance concepts based on time-series data and machine

learning can help detect early warning signs and generate actionable recommendations (see [USC25]).

These approaches are intended to be explored in the context of the proposed framework during subsequent development phases. Rather than focusing on the creation of new AI algorithms, the objective is to assess the applicability of existing, proven methods and to integrate them meaningfully into workflows for semantic enrichment and condition monitoring in heritage building contexts.

Fourth, the integration of external data repositories should be further strengthened. For instance, linking HBIM with GIS systems enables analysis of spatial contexts, microclimate zones, or traffic exposure (see [RLV24]). The integration of climate scenario models can also help assess risks related to temperature or humidity fluctuations—a critical factor in the era of climate change (see [NA21]). While highly relevant, indoor and outdoor climate variations will not be differentiated in the initial test phase. Instead, general environmental data (e.g. humidity and temperature) will be used to validate system architecture and integration. Detailed analysis is planned for later stages.

Fifth, extensive and typologically diverse case studies are necessary to empirically validate the scalability, adaptability, and practical utility of the framework (see [OBG14]; [FAM\*15]). Examples should range from small-scale objects (e.g., wells) to complex structures like castles or churches. These studies can help identify reusable standard modules, test modular flexibility, and reveal adjustment needs. Quantitative metrics should also be included—such as:

- Time savings in information retrieval,
- Extension of maintenance intervals via monitoring,
- Or reduction in on-site visits thanks to remote analytics.

As an initial step toward implementation, the framework will be tested on a small-scale heritage element. This pilot will serve to validate the full architecture—including geometric modeling, semantic integration, linked data connectivity, and user interaction—in a controlled and measurable setting. Rather than isolating specific technologies, the emphasis will be on assessing the coherence and operational viability of the framework as a unified system. This strategy ensures a structured transition from theoretical design to practical application and will provide a solid foundation for its progressive deployment in diverse heritage conservation scenarios, ultimately contributing to the realization of sustainable, data-driven digital heritage infrastructures.

## 7. Conclusion

This study introduces a conceptual framework that explores how the integration of semantic technologies into HBIM could significantly enhance digital heritage conservation. The framework theorizes an extension of traditional HBIM models through ontology-based knowledge structures, Linked Data mechanisms, and the inclusion of dynamic monitoring layers—enabling the modeling of heritage assets as rich, semantically connected information systems.

The multi-layered framework presented in this paper enables not only the formalized documentation of physical properties and historical contexts, but also their continuous updating based on sensor data—in the spirit of a "living digital twin".

Moreover, it has become clear that semantically enriched HBIM models can significantly improve interdisciplinary collaboration between architects, conservationists, historians, and engineers. The use of standardized ontologies such as ifcOWL, BOT, or CIDOC CRM allows for unambiguous description of objects, properties, and relationships, simplifying cross-disciplinary queries and analyses (cf. [PVD\*11]; [BMT08]). The systematic linking of external knowledge sources—such as archival documents or normative material databases—is also supported by Linked Data technologies (cf. [QPM17]).

At the same time, the study highlights the significant challenges involved in implementing such systems. These include:

- High initial modeling effort,
- Lack of standardized ontologies in the heritage domain,
- Interoperability issues between proprietary BIM tools and open RDF structures,
- And limited usability for non-technical users (cf. [Bar16]).

These challenges emphasize the need for future work in tool development, standardization, and methodological simplification.

In summary, this work contributes to the evolution of the HBIM paradigm toward an open, semantically enriched information system for built cultural heritage. The proposed framework shows how technical, semantic, and operational data can be connected in a coherent, queryable digital model that serves not only documentation, but also preventive conservation strategies, scientific research, and interactive knowledge dissemination.

Thus, it lays the groundwork for sustainable, data-driven heritage preservation in the 21st century.

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