# Toward IFC-Compatible HBIM Semantics for Component-Level Representation of Architectural Heritage

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**Abstract**

The growing use of artificial intelligence (AI) and data-driven methods in architectural heritage research requires structured and reusable semantic units to support consistent modelling, annotation, and knowledge alignment. In this context, Historic Building Information Modelling (HBIM) can serve as a semantic anchor by linking surveyed geometry with object-based representations and non-geometric information. However, current HBIM workflows remain semantically fragmented: point cloud segmentation often relies on project-specific labels, object modelling adopts inconsistent decomposition and naming logics, and semantic enrichment is frequently implemented through custom parameters without a shared component-level framework. Although Industry Foundation Classes (IFC) provide the most widely adopted canonical structure for interoperability, their standard entities are often too coarse to represent heritage-specific subcomponents. To address this gap, this study proposes an IFC-compatible semantic framework for component-level representation in HBIM. The framework combines a canonical IFC-aligned layer with a heritage extension layer and introduces a mapping strategy for representing semantically meaningful subcomponents without modifying the core IFC schema. A Serliana arch on the church of SS. Paolo e Barnaba in Milan is used as a case study to illustrate the implementation of the proposed approach. The study establishes a preliminary semantic foundation for component-level heritage representation in HBIM, providing both a conceptual basis for structuring heritage subcomponents and an operational basis for their IFC-compatible implementation. This foundation may also support future developments in ontology alignment and cross-modal AI applications, where stable semantic anchors are required for data integration and annotation.

## 1. Introduction

The growing interest in multimodal artificial intelligence (AI) and foundation models in cultural heritage demands a fundamental need for structured, consistent, and interoperable semantic structures and representations (Pierdicca et al., 2020, Réby et al., 2023). Current datasets derived from image collections, point clouds, historical drawings, and textual sources are typically heterogeneous and lack component-level annotation standards. This makes cross-modal alignment nearly impossible and limits the integration of heritage information into emerging AI workflows. The presence of structured, stable, and reusable semantic units that can support consistent annotation, cross-project comparison, and machine-readable knowledge alignment is urgently needed.

This challenge is particularly evident at the level of architectural components and subcomponents. Unlike conventional building elements in contemporary construction, heritage elements often contain internally differentiated parts with distinct morphological, constructive, and semantic significance. For example, a historic column cannot be adequately understood as a single undivided object, since its base, shaft, and capital may each carry different formal, historical, or conservation-related information. Similar conditions apply to windows, vaults, portals, and decorative assemblies. Therefore, if heritage-oriented AI workflows are expected to move beyond coarse object recognition toward meaningful semantic alignment, a component-level and, where necessary, subcomponent-level representation becomes essential.

Within this context, Historic Building Information Modelling (HBIM) offers a particularly suitable environment to act as a semantic anchor. By linking survey-based geometry with object hierarchy, attributes, and documentation layers, HBIM provides a structured modelling framework in which physical building elements can be associated with machine-readable information. This makes HBIM a promising bridge between geometric acquisition and semantic formalization, especially for future workflows involving intelligent annotation, knowledge graphs, ontology alignment, and foundation-model-based reasoning over heritage assets.

However, to fulfil this role effectively, HBIM representations must remain interoperable and compatible with established data standards. In this respect, Industry Foundation Classes (IFC) constitute the most widely adopted open standard for building information exchange. Yet IFC was primarily developed for modern construction practice and does not directly provide sufficient semantic granularity for many heritage-specific subcomponents (Salah et al., 2025). In current HBIM workflows, such information is often simplified into coarse canonical entities or encoded through ad hoc parameters and project-specific naming systems, limiting interoperability, semantic consistency, and reuse across datasets and platforms.

To address this gap, this paper proposes an IFC-compatible semantic foundation for the representation of heritage architectural components and subcomponents. The proposed framework is based on a two-layer logic:

- a canonical layer aligned with standard IFC entities,
- a heritage extension layer designed to represent finer-grained semantic units required by architectural heritage.

Through a mapping strategy that combines hierarchical decomposition and semantic property assignment, the framework aims to support structured subcomponent representation without altering the core IFC schema. In this way, it establishes a semantic basis for component-level alignment in

HBIM environments while preserving interoperability with standard BIM practices.

## 2. Related work

### 2.1 From segmentation to properties: semantic inconsistency in HBIM practice

Mainstream HBIM workflows generally comprise three stages: data collection, Scan-to-HBIM, and information mapping. This workflow connects multiple modalities, ranging from point clouds and HBIM models to photographs, drawings, textual records, and documentation describing historical, material, stratigraphic, archaeological, and pathological information (Banfi, 2023; Banfi and Liu, 2026). However, in current practice, semantic implementation across the HBIM workflow remains highly inconsistent. From point cloud segmentation to object modelling and property definition, the representation of heritage information is often fragmented, project-dependent, and insufficiently standardized (Figure 1).

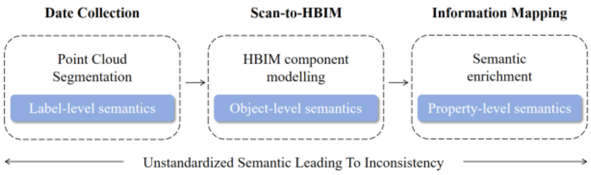


Figure 1. Semantic representations across the current HBIM workflow.

**2.1.1 Point cloud segmentation**: The ongoing pursuit of automation and semi-automation has accelerated the integration of deep learning (DL) and machine learning (ML) into point cloud segmentation. Semantic labels are the basic part of this work, however, they are rarely based on a shared and reusable classification logic.
Several studies have investigated AI-based segmentation methods for identifying architectural components in heritage point clouds. Grilli et al. (2019) employed manually annotated labels to train ML and DL models, including classes such as “shaft”, “capital”, “architrave”, “abacus”, and “frieze”. Pierdicca et al. (2020) applied a DL framework for cultural heritage point cloud segmentation using labels such as “arc”, “dec”, “door”, and “window”. Moyano et al. (2024) also used semantic tags like “vault”, “attached arch”, “perpend arch”, “capital”, and “abacus” in segmentation tasks.
The semantic classes adopted in these studies are typically bespoke, ad-hoc, or project-specific taxonomies without a canonical semantic backbone. In most cases, they are primarily designed to support segmentation performance evaluation rather than interoperability with subsequent HBIM modelling and information management processes.
To align segmentation with formalized information management frameworks, Gil and Arayici (2025) selected the Uniclass Element/Function (EF) table as the primary classification ontology. This taxonomy is derived from an industry-standard hierarchical system in the UK, enabling ontology-aligned HBIM integration. However, Uniclass mainly represents functional groupings rather than explicit geometric building components. Furthermore, its application remains largely regional, whereas internationally recognized standards such as the IFC provide a globally adopted, object-oriented schema that more directly supports HBIM modelling and semantic interoperability.
Consequently, the absence of a shared semantic framework for component-level labeling remains a critical limitation in current heritage point cloud segmentation workflows. A purely geometric evaluation of segmentation is insufficient without semantic alignment capable of supporting conservation interpretation and long-term heritage stewardship.

**2.1.2 HBIM component modelling**: This inconsistency continues in the modelling phase. HBIM object modelling has long been driven more by the accuracy and efficiency of geometric reconstruction than by the development of shared and interoperable semantic structures (Lovell et al., 2023). When segmented or surveyed data are translated into HBIM objects, the level of decomposition and the naming of components are often determined by modelling convenience or project-specific interpretation rather than by a formal semantic structure. In this regard, Scandurra et al. (2024) highlighted that HBIM requires a more rigorous definition of breakdown structures, including the formal recognition of semantically significant elements and the adoption of standardized nomenclatures to ensure data consistency across different digital platforms.
A representative example is provided by Malinverni et al. (2019), who proposed a preliminary decomposition of the building into classes and subclasses before modelling. Their approach organized the building as a tree structure, beginning with the whole building and branching into major domains such as interior and exterior, followed by architectural element categories and finer parts. To identify each entity, they assigned unique hierarchical ID codes, so that naming directly reflected the component’s position within the decomposition structure. However, this hierarchy does not follow a single, clearly defined decomposition principle. It combines spatial zones, functional areas, architectural elements, subcomponents, and decorative features within the same tree structure, resulting in mixed semantic relations and uneven levels of granularity. Consequently, the assigned ID codes function mainly as positional references within a project database rather than as reusable semantic identifiers grounded in a transferable architectural taxonomy.
As a result, although subcomponent modelling enables richer information mapping, it does not guarantee semantic consistency across different cases. The absence of explicit rules governing the level of decomposition and the definition of components further reinforces the variability of HBIM object structures, limiting their interoperability and reuse beyond the original project context.
As a result, the same heritage element may be represented as a single canonical object in one model, but as several subcomponents in another. Even where detailed decomposition is adopted, naming conventions may remain unstable, alternating between typological, morphological, and arbitrary modelling labels. This weakens semantic consistency across models and limits the comparability of heritage components at the object level.

**2.1.3 Semantic enrichment**: Most HBIM studies leverage the property function to store heritage data, since BIM’s robust information-carrying capacity is one of its primary advantages over other modelling environments. This is a native feature of BIM, in which data enrichment is handled internally within the model hierarchy.
Recent HBIM studies still predominantly rely on project-specific custom parameters attached to BIM objects to encode heritage information, including descriptive, historical, material, stratigraphic, and diagnostic data (Brumana et al., 2018), largely because no widely adopted standard or controlled vocabulary currently exists to define such terminology. Lovell et al. (2023) note that, although HBIM is widely used for non-geometric information management, the field still lacks clearly

standardized information requirements and consistent implementation strategies.

However, some recent studies have begun to move toward more reusable and standardized parameter structures. Oostwegel et al. (2022) proposed six heritage-oriented IFC property sets for cultural heritage assets, including CHPeriod, CHSignificance, CHElement, CHType, CHSpace, and CHMaterial, representing an explicit shift from project-specific parameterization toward interoperable semantic structures.

This trend is even clearer in dictionary-based approaches. Argasiński et al. (2025) used the buildingSMART Data Dictionary (bSDD) to transform a heritage classification system into reusable thesauri for components, materials, and monument types, aiming to improve the consistency, accuracy, and cross-platform usability of heritage BIM data.

Even so, these efforts remain emerging rather than mainstream. Recent reviews continue to identify interoperability, shared standards, and structured knowledge representation as open challenges in HBIM research and practice. Such attempts have not yet resulted in a widely adopted component-level semantic parameter framework for HBIM, and most implementations still depend on project-specific property definitions.

Therefore, despite the information-rich promise of HBIM, current workflows still lack a coherent semantic foundation spanning labels, components, and properties. This fragmentation reduces the reusability and machine-readability of heritage data, and it limits the potential of HBIM to function as a stable semantic anchor for interoperability, ontology alignment, and future AI-driven applications.

## 2.2 IFC limitations

The semantic inconsistency observed across labels, modelled objects, and properties is closely related to the limits of the standard structures used to organize HBIM data. IFC remains the most important open standard for BIM interoperability, as it provides a canonical object-oriented framework for representing building elements, spatial hierarchies, relationships, and properties. For this reason, it remains an essential anchor for structuring heritage information in a reusable and exchangeable way.

However, both IFC and existing BIM naming and classification standards, such as ISO 12006-2, UniClass, and OmniClass, were developed for the general construction industry rather than for heritage-specific semantic representation. While contemporary construction typically relies on relatively standardized and modular components, historic buildings often contain irregular, non-standard, and highly articulated elements, such as arches, capitals, mouldings, and deformed masonry. As noted by Parente et al. (2025), the application of IFC schema and international classification standards to historic buildings is therefore not straightforward.

As a result, the semantic granularity of standard IFC representation is often insufficient for heritage-oriented modelling. A historic column may be represented as an IfcColumn, yet its base, shaft, and capital are not directly formalized as semantically explicit heritage subcomponents within the canonical schema. In practice, such information is often simplified or only partially formalized through custom properties, loosely defined object types, or project-specific modelling conventions. This makes it difficult to represent heritage-specific aspects such as material decay, stratigraphic complexity, and structural pathologies consistently.

Therefore, the problem is not that IFC lacks interoperability, but that it lacks a heritage-specific semantic foundation for fine-grained component representation. The challenge is not to replace IFC, but to develop an IFC-compatible framework capable of bridging canonical BIM entities and heritage-specific semantic units.

## 2.3 Ontology-based approaches for heritage semantic interoperability

To improve semantic consistency and interoperability in HBIM, several studies have explored ontology-based approaches and semantic web technologies. In this context, IFC serves as the main canonical backbone for structuring building information, while ontology models are used to capture richer historical meanings, contextual knowledge, and interpretative relations that are difficult to represent through BIM schemas alone. Within the cultural heritage domain, CIDOC CRM is widely adopted as an ISO-standardized ontological framework for representing heritage knowledge and is often linked to RDF-based environments for semantic integration.

Accordingly, IFC-to-OWL and IFC-to-RDF transformations have been increasingly adopted as strategies for connecting BIM environments with higher-level semantic representation. Quattrini et al. (2017), for example, proposed a knowledge-based HBIM enrichment workflow in which a domain ontology was used to structure information needs at building, macro-area, and element levels, and then translated into shared parameters for HBIM enrichment. The enriched model was subsequently exported to IFC, converted into IFC-OWL/RDF, and mapped into a simplified ontology for semantic querying and faceted browsing. Similarly, Yang et al. (2019) linked Revit-based HBIM elements with an ontology environment through IFC-to-RDF conversion and identifier-based association, using CIDOC CRM as the broader semantic context for integrating heterogeneous historical knowledge.

These studies demonstrate the value of ontology mapping for improving interoperability, semantic querying, and external knowledge linking. However, their main contribution lies in schema-level alignment and metadata enrichment rather than in the construction of reusable component-level semantic structures. In most cases, the ontology functions as an external enrichment layer built on top of IFC, rather than as an IFC-native mechanism for defining architectural subcomponents and their semantic relations. Moreover, existing ontology mappings rarely provide a practical label design that can directly support point-cloud segmentation, image annotation, or multimodal AI-oriented heritage workflows.

Therefore, although ontology-based HBIM enrichment has significantly expanded the descriptive and relational capacity of heritage information systems, it has not yet established a reusable semantic framework capable of bridging canonical IFC entities and heritage-specific component categories. This reveals the need for an IFC-compatible semantic structure that operates not only at the level of metadata and knowledge graphs, but also at the level of component representation and annotation.

## 2.4 Research gap

Recent studies have expanded HBIM from geometric reconstruction toward richer information modelling and semantic enrichment. However, three limitations remain. First, many HBIM workflows still rely on coarse object categories and project-specific parameterization rather than explicit semantic formalization. Second, although IFC provides an interoperable canonical structure, it does not directly support the fine-grained representation of many heritage-specific subcomponents. Third, ontology- and vocabulary-based approaches improve heritage knowledge description, but they do not fully establish an operational modelling bridge between canonical BIM entities and heritage semantic units. Therefore, a need remains for an IFC-compatible semantic foundation capable of supporting component-level and subcomponent-level alignment in HBIM environments.

## 3. Proposed Framework

### 3.1 Canonical Component Layer

The proposed framework begins with the definition of a Canonical Component Layer, which establishes a standardized set of architectural elements serving as the structural backbone for semantic enrichment and heritage-oriented extensions.

The IFC 4.3 schema provides a comprehensive object-based data model for representing building components within BIM environments. IFC entities such as IfcWall, IfcColumn, and IfcBeam represent physically existing elements that form the structural or enclosure system of a built facility. These elements are categorized under the superclass IfcBuiltElement, which generalizes the primary construction components of buildings and infrastructure.

While IFC provides a broad set of entities for representing built elements, many of these classes are designed for general-purpose BIM applications and infrastructure domains, including transportation and MEP systems. As a result, not all IFC entities are suitable for representing the component structure of historical architecture.

To establish a canonical component taxonomy suitable for heritage modelling, this study performs a systematic filtering of the IfcBuiltElement subclasses. The selection focuses on architectural components that are:

- structurally meaningful in historic buildings
- commonly represented in HBIM workflows
- relevant for architectural segmentation and semantic annotation

Entities related to infrastructure systems, mechanical devices, and transportation elements were excluded, as they are rarely applicable to architectural heritage documentation.

Based on this filtering process, the canonical component layer retains the following IFC entities (Table 1) as the core architectural primitives:

| Category | IFC Entities |
|---|---|
| Structural elements | IfcWall, IfcColumn, IfcBeam, IfcSlab, IfcRoof |
| Openings | IfcDoor, IfcWindow |
| Circulation elements | IfcStair, IfcStairFlight, IfcRailing |
| Architectural accessories | IfcPlate, IfcMember, IfcBearing, IfcCovering, IfcCourse, IfcChimney |

Table 1. Canonical IFC components selected for heritage building modelling.

These entities collectively represent the primary structural, enclosure, and architectural components of historic buildings and form the canonical vocabulary for the proposed framework.

### 3.2 Heritage Extension Layer

While the canonical component layer establishes a standardized set of architectural primitives based on native IFC entities, these components for architectural heritage remain relatively coarse in their semantic granularity. Historic buildings often contain complex architectural details, decorative elements, and stratified construction features that cannot be adequately represented using only the standard IFC component hierarchy.

For example, an IfcColumn in IFC typically represents the entire column as a single object, whereas architectural heritage documentation often requires a more detailed decomposition into subcomponents such as the base, shaft, and capital. Similarly, wall-related elements may contain architectural features including cornices, moldings, pilasters, or decorative frames, which are significant for historical interpretation, conservation, and architectural analysis.

To address this limitation, the proposed framework introduces a Heritage Extension Layer, which enriches the canonical IFC components with heritage-specific subcomponents and semantic properties. Rather than replacing the IFC schema, the heritage extension layer operates as a hierarchical semantic expansion anchored to the canonical components defined in Section 3.1. In this way, each canonical component may be further decomposed into a set of heritage-oriented subcomponents, forming a structured heritage component taxonomy for the semantic representation of architectural details that are typically absent from standard BIM schemas.

The proposed subcomponents are derived from commonly accepted architectural decomposition principles used in architectural history, heritage documentation, and conservation practices. For instance, the base, shaft, and capital represent well-established morphological parts of a classical column, while the architrave, frieze, and cornice together constitute the classical entablature. Figure 2 illustrates an IFC-compatible semantic decomposition of classical column and entablature elements.

The selection of subcomponents follows three criteria:

1. architectural meaningfulness in historic buildings,
2. geometric separability enabling explicit modelling in HBIM environments,
3. relevance for semantic segmentation and fine-grained annotation of heritage structures.

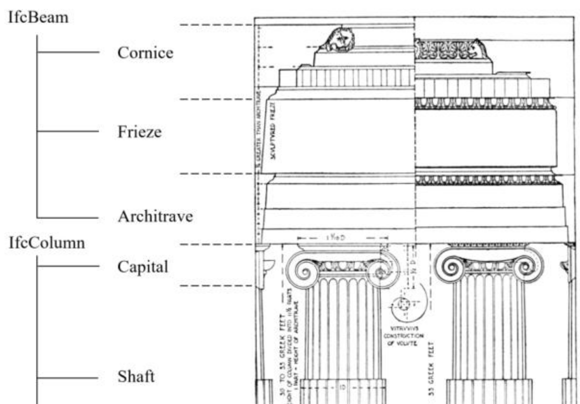


Figure 2. IFC-compatible semantic decomposition of classical column and entablature elements.

At the same time, stylistic, typological, or interpretative distinctions are not always modeled as independent geometric subcomponents. Instead, such information may be represented through semantic properties or type-level descriptors. For example, not every historic beam corresponds to an entablature. When an entablature is represented through IfcBeam for IFC compatibility, the designation entablature should be encoded as a semantic type label (e.g., through ObjectType, classification, or property-based annotation), rather than treated as a generic synonym for beam.

Within this framework, the Minimum Semantic Unit (MSU) defines the operative level of semantic granularity. An MSU is the smallest architecturally meaningful and semantically distinguishable architectural component that can be explicitly identified, represented, and reused within an HBIM environment.

It should be noted that semantic decomposition in HBIM does not necessarily correspond to actual construction units. In historical architecture, elements that are semantically distinguishable may be physically realized as a single piece. For example, a capital and shaft may be carved as one monolithic element, while remaining separable at the semantic level. Therefore, the MSU is defined according to architectural meaning and semantic reusability rather than strict construction logic.

Additionally, the definition of an MSU is operational rather than absolute, and may vary depending on modelling purpose, documentation scale, and annotation requirements.

This hierarchical structure allows heritage features to be systematically linked to canonical IFC components while maintaining interoperability with existing BIM platforms. Furthermore, the explicit decomposition of architectural elements provides a reusable semantic foundation for fine-grained segmentation, annotation, and documentation in digital heritage workflows. Accordingly, MSUs may also function as segmentation labels, supporting distinctions such as IfcBeam_Cornice and IfcWall_Cornice.

### 3.3 Mapping Strategy

To integrate heritage-specific subcomponents into an IFC-compatible data structure, this study proposes a mapping strategy (Figure 3) that links the Heritage Extension Layer to canonical IFC entities. The strategy operates at two levels: hierarchical mapping, and semantic property mapping.

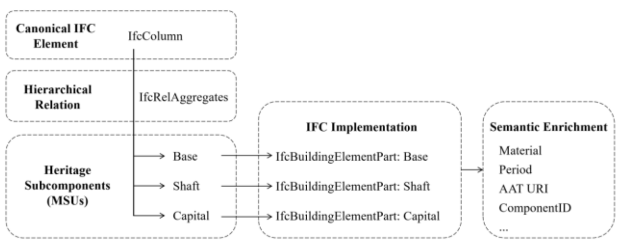


Figure 3. IFC-compatible mapping strategy linking a canonical IFC element to heritage subcomponents (MSUs), illustrated through an ancient column.

At the structural level, heritage subcomponents are associated with canonical IFC entities through whole-part relationships. Within the proposed framework, canonical IFC elements function as parent entities, while MSUs are represented as subordinate semantic parts. In IFC, such decomposition can be modeled through IfcRelAggregates, which links a parent element to its constituent components. This allows heritage-specific subcomponents to be represented as aggregated parts of canonical IFC elements without modifying the native IFC schema. In this way, the proposed framework preserves interoperability while enabling a finer semantic granularity for heritage representation.

At the semantic property level, property-based enrichment therefore complements hierarchical decomposition by capturing non-geometric heritage knowledge essential for interpretation and documentation, including stylistic, typological, material, chronological, and interpretative information that does not require explicit geometric decomposition.

A fully standardized system of heritage-oriented property sets would be desirable. Existing studies have proposed reusable categories such as CHPeriod, CHSignificance, CHElement, CHType, CHSpace, and CHMaterial. However, the full specification of such property templates lies beyond the scope of this paper and is identified as a direction for future work.

To improve semantic interoperability, the names of heritage subcomponents should be aligned with established controlled vocabularies, such as the Getty Art & Architecture Thesaurus (AAT). Where applicable, the corresponding AAT URI may also be recorded as a semantic reference through properties or classification fields. Such alignment supports terminological consistency across projects and facilitates future integration with external heritage knowledge bases.

In addition, each subcomponent instance may be assigned a ComponentID as a stable and human-readable identifier for semantic annotation, documentation, and cross-platform referencing. Although IFC already provides a GlobalId for each entity, this identifier is system-generated and not optimized for manual interpretation or reuse in annotation workflows. By contrast, the proposed ComponentID serves as an operational semantic identifier linking HBIM objects, segmentation labels, and external knowledge records, rather than replacing the native IFC identifier.

The exact syntax may vary depending on project requirements, but the identifier should minimally encode the parent canonical element, the subcomponent category, and an instance index. This distinction between reusable type labels (e.g., Column_Base, Beam_Cornice) and instance-level identifiers (e.g., CH01_COL_03_CAP_01) supports both standardization and practical implementation. Type labels ensure consistency in semantic classification across different heritage sites, while ComponentIDs enable traceable referencing of individual subcomponent instances in HBIM models, annotation tasks, and linked documentation environments.

## 4. Case study

### 4.1 The church of SS. Paolo e Barnaba in Milan

The case study focuses on the church of SS. Paolo e Barnaba in Milan (known as S. Barnaba), whose construction began in 1545 near a former hospital and convent complex. The building is historically significant as one of the earliest Milanese churches designed according to the principles of the Counter-Reformation. In 1561, the architect Galeazzo Alessi intervened in the design, establishing a layout that became influential for later religious architecture in Milan: however, the project by Galeazzo Alessi was grounded in a prior phase of architectural renovation initiated in 1545 on the pre-existing small church of San Barnaba in Brolio, of which numerous remains are still visible in the underground level. The distinctive configuration of the choir and the presbytery derives precisely from the adaptation of these earlier masonry structures, to which Alessi added a spacious nave, ultimately establishing a unified architectural design.

The church is characterized by a single-nave plan with a raised presbytery and choir intended to accommodate the monastic community, while the nave was used by the congregation. Structurally, the nave is covered by a barrel vault, whereas the presbytery is defined by a rectangular pavilion vault. The façade reflects the decorative richness typical of Mannerist architecture. The upper order of the façade displays a pronounced ornamental density, while the lower part appears simpler due to restoration works carried out under the direction of Luca Beltrami, in October 1890 (Premoli, 1904; Premoli, 1913; Houghton Brown, 1964).

A second intervention on the façade, initiated in December 1904, entailed modifications to the materials and the replacement of certain architectural elements. In this phase, Candoglia marble, supplied by the Veneranda Fabbrica, was effectively used for the plinth, portions of the portal, and the columns of the Serliana window in the main façade; Nembro marble (from Verona), by contrast, was employed to clad the four pilasters of the lower level (Premoli, 1905).
Due to its historical relevance, architectural complexity, and presence of articulated decorative and structural components, the church represents a suitable case study for testing semantic structuring and component-level classification approaches within HBIM environments (Figure 4).

Figure 4. Main façade and view of the single nave of SS. Paolo and Barnaba church.

The façade includes a Serliana-type window composition consisting of a central arched opening flanked by two rectangular openings supported by columns and pilasters (Figure 5). The stone frame of this composition is also known as a Serliana arch.
Serliana arches are characteristic of Renaissance and later classicizing styles. They consist of a large central opening beneath a semicircular arch, flanked by two smaller rectangular openings. This motif was illustrated in Sebastiano Serlio’s Architettura and became a hallmark of Palladian architecture. It is named after the Veneto architect Andrea Palladio, or in reference to Sebastiano Serlio, who documented similar arched forms from ancient Roman architecture (Getty Research Institute, n.d.).
The complex semantic structure of the Serliana stone frame makes it particularly suitable for validating the proposed framework, because its composite configuration brings together multiple canonical architectural elements and their subcomponents within a single integrated structure.

### 4.2 Geometric and semantic decomposition

Following the proposed framework, the Serliana stone frame (also known as the Serliana arch or Palladian motif) is decomposed into five main structural groups: columns, pilasters, wall, entablature, and arch (Figure 6).
Columns and pilasters, which provide vertical support, are further subdivided into three primary components: base, shaft, and capital. The entablature, serving as the horizontal superstructure, is decomposed into cornice, frieze, and architrave. The central arch, which forms the dominant visual and structural element of the Serliana, is represented through its key components: archivolts (the ornamental moldings framing the arch), voussoirs (the wedge-shaped stones forming the arch ring), and intrados (the inner curved surface of the arch).


Figure 5. (a) Photo of the Serliana window in façade. (b) point cloud of the Serliana window: stone frame and glass window.

**Serliana stone frame**

- Column (4)
  - Base
  - Shaft
  - Capital
- Pilaster (2)
  - Base
  - Shaft
  - Capital
- Wall (2)
- Entablature (2)
  - Cornice
  - Frieze
  - Architrave
- Arch (1)
  - Archivolts
  - Voussoirs
  - Intrados

Figure 6. Semantic decomposition of the Serliana stone frame.

### 4.3 Mapping strategy to the IFC-compatible framework

In this study, the Serliana stone frame is modeled as an IfcElementAssembly representing a semantic unit composed of multiple building elements. Through IfcRelAggregates relationships, the assembly organizes main architectural components such as columns, pilasters, walls, entablature, and arch elements. Selected parent elements, such as IfcColumn, are further decomposed into heritage-specific subcomponents (e.g., base, shaft, and capital) using IfcBuildingElementPart. This hierarchical structure enables component-level semantic representation while remaining compatible with the IFC schema (Figure 7).

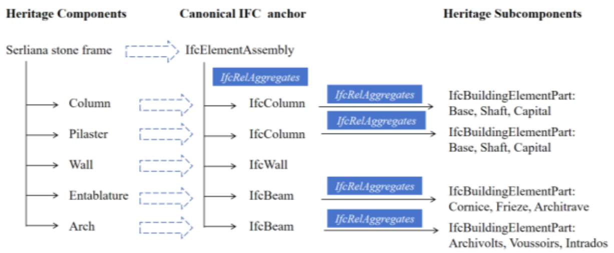


Figure 7. IFC-compatible mapping diagram

### 4.4 HBIM implementation

To operationalize the IFC-compatible framework shown in Figure 7, the Serliana stone frame was implemented in Autodesk Revit through a nested family strategy.

In order to fulfill the structure of Figure 7, MSUs are modeled separately as individual families and then nested into a parent family. Meanwhile, all MSUs must keep the “Shared” option activated, in order to preserve their individual identities during the export process and allow them to be recognized as independent entities in the IFC schema rather than being merged into a single geometry.

From an IFC mapping perspective, each MSU is assigned a specific IFC class through the Export Type to IFC As parameter. In this study, MSUs are mapped to IfcBuildingElementPart, which enables the representation of subcomponents within a hierarchical structure. At the same time, the Type IFC Predefined Type is set to USERDEFINED, allowing the introduction of heritage-specific semantic labels (e.g., Column_Base, Column_Shaft, Column_Capital) that are not covered by standard IFC predefined types.

This configuration ensures that, during IFC export, the parent element (e.g., column as IfcColumn) maintains a decomposition relationship with its MSUs through IfcRelAggregates, while each MSU retains its semantic role as an identifiable subcomponent (Figure 8).

Figure 9 presents the final MSU-based semantic decomposition of the Serliana stone frame in the HBIM model. Different architectural subcomponents are instantiated as distinct semantic units and visually differentiated by color, demonstrating how the proposed semantic framework can be translated into an operational HBIM representation. As a result, the HBIM model supports geometric decomposition and semantic extensibility at component level, and provides a structured basis for consistent annotation and further interoperability testing in downstream applications.

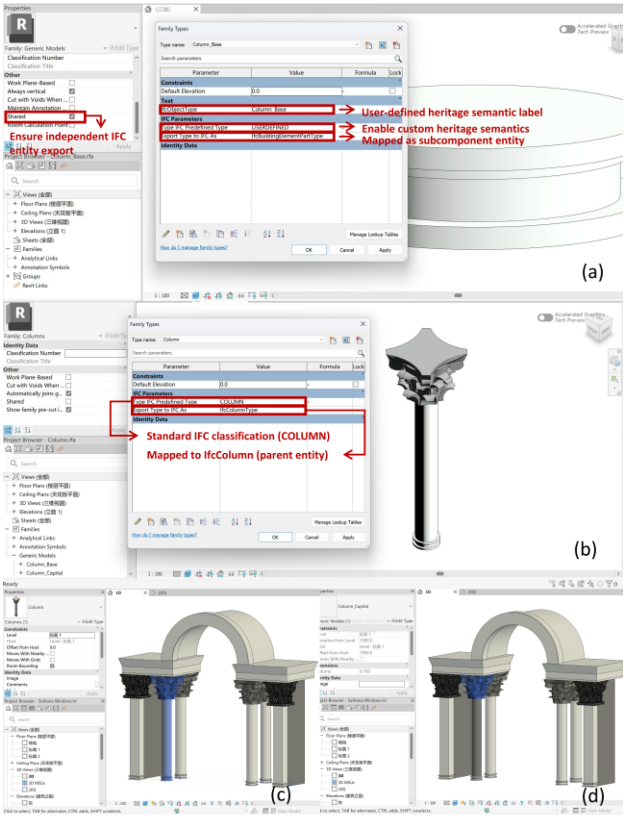


Figure 8. Revit-based implementation of hierarchical IFC mapping (a) IFC mapping of an MSU as IfcBuildingElementPart with user-defined semantic labels: Column_Base; (b) Mapping of the parent element as IfcColumn; (c) Column as a parent element in HBIM; (d) Column_Capital as an MSU within the parent element in HBIM.

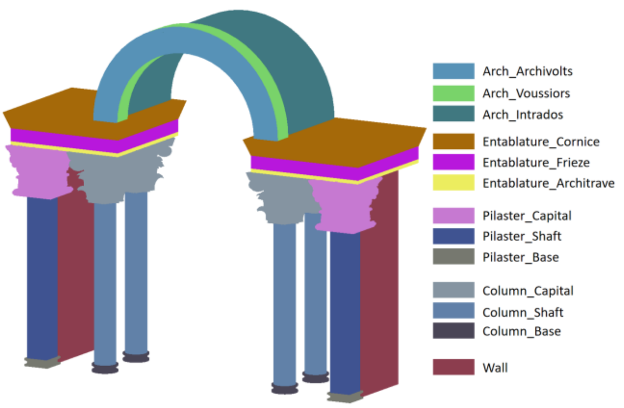


Figure 9. Final MSU-based semantic decomposition of the Serliana stone frame in the HBIM model.

## 5. Results and Discussion

### 5.1 Case study application and IFC-oriented implementation

The proposed framework was applied to a selected Serliana stone frame extracted from the church of SS. Paolo e Barnaba in Milan. The architectural composition was decomposed into a set of heritage subcomponents, which were interpreted as MSUs, thereby enabling a finer semantic resolution than that provided by conventional IFC object categories alone. The case study demonstrates that a heritage architectural element can be reorganized into a structured semantic hierarchy, in which canonical IFC entities act as stable parent elements while finer-grained subcomponents form a reusable heritage extension layer. From an IFC-oriented perspective, the proposed mapping strategy identifies IfcBuildingElementPart as the most suitable representation for heritage subcomponents, while heritage-specific information can be attached through property sets. In this way, the framework preserves compatibility with the IFC schema without introducing new core classes, while still supporting a more explicit semantic description of architecturally meaningful parts. This is particularly relevant in heritage contexts, where elements such as bases, shafts, capitals, cornices, or decorative frames often carry distinct formal, historical, and conservation-related meanings that cannot be adequately represented through coarse object categories alone.

The HBIM modelling experiment further confirmed that this hierarchical decomposition can be implemented at the modelling level. However, the implementation also revealed an important limitation. Although IfcRelAggregates was identified as the most appropriate IFC-compliant mechanism for expressing part-whole relations between canonical elements and heritage subcomponents, the tested authoring and export workflow did not explicitly preserve this relation in the exported IFC model. This indicates that a gap still exists between the semantic requirements of heritage representation and the current capabilities of standard HBIM-to-IFC workflows. Such a limitation is not only a technical issue of model export, but also a constraint on the development of interoperable and reusable semantic datasets, since stable hierarchical relations are essential for preserving semantic consistency across modelling, exchange, and downstream annotation workflows.

### 5.2 Interpretation of semantic stability and reuse

The present study does not argue against project-specific semantic subdivision in HBIM. On the contrary, such decompositions are often fully justified by the analytical objectives of a given project. For example, the subdivision of a wall into stratigraphic layers may be highly meaningful in conservation-oriented workflows, where material sequences, construction phases, or decay patterns need to be documented in detail (Banfi et al., 2023). In this sense, project-specific decomposition remains a valid and often necessary strategy for heritage analysis.

However, these subdivisions are inherently dependent on particular research goals and therefore do not always provide stable semantic units for reuse across projects. The same heritage element may be divided according to stratigraphy in one study, according to structural behaviour in another, or represented as a single object in a more general HBIM model. Such variability does not invalidate project-specific modelling, but it limits semantic consistency, interoperability, and comparability at the component level.

From this perspective, the architectural component-based framework proposed in this study should be understood not as a replacement for project-oriented semantic enrichment, but as a more stable semantic infrastructure. It aims to define reusable component-level anchors that remain sufficiently consistent across modelling contexts, while still allowing additional layers of task-specific information to be attached when required. In this sense, the framework contributes primarily at the level of semantic stability and component-level reuse across modelling contexts.

### 5.3 Toward ontology-ready heritage semantic modelling

Beyond the specific HBIM implementation, the case study highlights the role of the proposed framework as a semantic infrastructure for future heritage knowledge organization. By decomposing architectural compositions into stable and reusable MSUs, the framework provides potential annotation anchors that can be shared across heterogeneous data sources, including point clouds, images, technical drawings, and textual documentation. In this sense, the contribution of the framework is not limited to IFC-compatible representation, but extends to the establishment of a component-level semantic basis for future ontology alignment, knowledge-graph construction, cross-modal alignment, and broader forms of machine-readable heritage knowledge organisation.

In an ontology-oriented perspective, canonical architectural entities such as Column, Wall, or Window may be interpreted as higher-level semantic classes, while finer subcomponents such as Base, Shaft, and Capital can be formalised as more specific classes within a heritage extension layer. Part-whole relations between these entities, currently discussed in IFC through mechanisms such as IfcRelAggregates, may in future semantic web implementations be reformulated as explicit object properties, such as partOf and hasPart. In this way, canonical IFC concepts remain relevant as alignment anchors, while the proposed framework enables a finer and more reusable semantic articulation for heritage-specific architectural knowledge.

Accordingly, the proposed framework should not be understood as a complete ontology in itself, but rather as an ontology-ready semantic structure. It establishes a conceptual bridge between HBIM-based modelling environments and future semantic web representations, in which component-level classes, hierarchical relations, and instance-level identifiers may be progressively transformed into machine-readable knowledge structures.

## 6. Conclusion and Future Direction

This study proposes a component-level semantic framework for architectural heritage modelling that enables fine-grained decomposition of historic building elements while remaining compatible with the IFC data model. Its main contribution is to reposition heritage semantic modelling as a foundational requirement for future interoperable, knowledge-driven, and AI-oriented workflows, rather than as a secondary issue of object description.

The framework provides both a conceptual and an operational basis for heritage representation. Conceptually, it defines stable architectural subcomponents and MSUs as reusable semantic anchors for heritage documentation. Operationally, it demonstrates how these units can be implemented in HBIM and mapped to IFC-compatible entities, allowing hierarchical and semantically explicit representation of heritage components.

The proposed structure also opens new perspectives for ontology alignment, linked data integration, and multimodal AI applications. In particular, persistent component-level identifiers can support the connection of HBIM elements with point clouds, images, historical drawings, textual archives, and external knowledge bases, thus enabling consistent annotation and cross-modal alignment.

Future work will focus on four main directions. First, the extension and standardization of heritage component taxonomies will be further developed beyond the limited set of elements addressed in this case study, in order to support broader applicability across different architectural typologies and heritage contexts. Second, persistent ComponentID rules will be formalized to provide stable and traceable identifiers for heritage elements and subcomponents across HBIM, annotation, and external data environments. Third, heritage-oriented property sets will be further developed to enrich the proposed semantic framework with structured attributes, allowing component-level information such as material, morphology, condition, chronology, and documentation links to be represented more systematically. Fourth, the alignment of the proposed semantic framework with heritage ontologies will be explored, enabling formal semantic definitions and interoperability with broader knowledge representation systems. In the longer term, these developments may contribute to HBIM-based knowledge graphs and support emerging AI-driven applications.

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**References**

Argasiński, K., Tomczak, A., 2025. Enhancing Semantic Interoperability of Heritage BIM-Based Asset Preservation. Heritage, 8(10), 410. doi.org/10.3390/heritage8100410.

Banfi, F., 2023. Virtual Heritage | From 3D Modelling to HBIM and Extended Reality. Maggioli Editore. https://www.maggiolieditore.it/virtual-heritage.html?srsltid=AfmBOorIS4oOfdP8xX1v_mBoxkQgUWH4uQOe3qzM4yBWii6oL28Ysu_d (10 November 2025).

Banfi, F., Liu, W., 2026. The State of HBIM in Digital Heritage: A Critical and Bibliometric Assessment of Six Emerging Frontiers (2015–2025). Applied Sciences, 16(2), 906. doi.org/10.3390/app16020906.

Banfi, F., Stanga, C., Landi, A.G., 2023. Virtual access to heritage through scientific drawing, semantic models and VR-experience of the Stronghold of Arquata del Tronto after the earthquake. SCIRES-IT: SCIentific RESearch and Information Technology, 13(1), 83–100.

Brumana, R., Della Torre, S., Previtali, M., Barazzetti, L., Cantini, L., Oreni, D., Banfi, F., 2018. Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): Surveying, preservation, site intervention—the Basilica di Collemaggio (L’Aquila). Applied Geomatics, 10(4), 545–567. doi.org/10.1007/s12518-018-0233-3.

Getty Research Institute, n.d. Serliana (arches). Art & Architecture Thesaurus. The J. Paul Getty Trust. https://www.getty.edu/vow/AATFullDisplay?find=Serliana&logic=AND&note=&english=N&prev_page=1&subjectid=300311053 (10 March 2026).

Gil, A., Arayici, Y., 2025. Point Cloud Segmentation Based on the Uniclass Classification System with Random Forest Algorithm for Cultural Heritage Buildings in the UK. Heritage, 8(5), 147. doi.org/10.3390/heritage8050147.

Grilli, E., Özdemir, E., Remondino, F., 2019. Application of machine and deep learning strategies for the classification of heritage point clouds. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W15, 447–454. doi.org/10.5194/isprs-archives-XLII-4-W18-447-2019.

Houghton Brown, N., 1964. The church of San Barnaba in Milan. Arte Lombarda, 9(2), 62–93.

Lovell, L.J., Davies, R.J., Hunt, D.V.L., 2023. The Application of Historic Building Information Modelling (HBIM) to Cultural Heritage: A Review. Heritage, 6(10), 6691–6717. doi.org/10.3390/heritage6100350.

Malinverni, E.S., Mariano, F., Di Stefano, F., Petetta, L., Onori, F., 2019. Modelling in HBIM to document materials decay by a thematic mapping to manage the cultural heritage: The case of “Chiesa della Pietà” in Fermo. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W11, 777–784. doi.org/10.5194/isprs-archives-XLII-2-W11-777-2019.

Moyano, J., Musicco, A., Nieto-Julián, J.E., Domínguez-Morales, J.P., 2024. Geometric characterization and segmentation of historic buildings using classification algorithms and convolutional networks in HBIM. Automation in Construction, 167, 105728. doi.org/10.1016/j.autcon.2024.105728.

Oostwegel, L.J.N., Jaud, Š., Muhič, S., Malovrh Rebec, K., 2022. Digitalization of culturally significant buildings: Ensuring high-quality data exchanges in the heritage domain using OpenBIM. Heritage Science, 10(1), 10. doi.org/10.1186/s40494-021-00640-y.

Parente, M., Bruno, N., Ottoni, F., 2025. HBIM and information management for knowledge and conservation of architectural heritage: a review. Heritage, 8(8), 306. doi.org/10.3390/heritage8080306.

Pierdicca, R., Paolanti, M., Matrone, F., Martini, M., Morbidoni, C., Malinverni, E.S., Frontoni, E., Lingua, A.M., 2020. Point Cloud Semantic Segmentation Using a Deep Learning Framework for Cultural Heritage. Remote Sensing, 12(6), 1005. doi.org/10.3390/rs12061005.

Premoli, O.M., 1904. Vita illustrata di S. Alessandro Sauli barnabita. A. Bertarelli & C., Milano.

Premoli, O.M., 1905. Il restauro della facciata di S. Barnaba. Bollettino degli Ascritti al Consorzio di St. Antonio M. Zaccaria, V, 186–193.

Premoli, O.M., 1913. Storia dei Barnabiti nel Cinquecento. Desclée & C. ed., Roma.

Quattrini, R., Pierdicca, R., Morbidoni, C., 2017. Knowledge-based data enrichment for HBIM: Exploring high-quality models using the semantic-web. Journal of Cultural Heritage, 28, 129–139. doi.org/10.1016/j.culher.2017.05.004.

Réby, K., Guilhelm, A., De Luca, L., 2023. Semantic segmentation using foundation models for cultural heritage: An experimental study on Notre-Dame de Paris. In: Proceedings of the IEEE/CVF International Conference on Computer Vision, 1689–1697.

Salah, R., Károlyfi, K.A., Szép, J., Géczy, N., 2025. A Structured Framework for HBIM Standardization: Integrating Scan-to-BIM Methodologies and Heritage Conservation Standards. Digital Applications in Archaeology and Cultural Heritage, e00420.

Scandurra, S., Lanzara, E., Improta, I., Lo Pilato, A., Itri, F., 2024. bSDD for artworks in HBIM open and standard-oriented documentation. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVIII-2/W4, 397–404. doi.org/10.5194/isprs-archives-XLVIII-2-W4-2024-397-2024.

Yang, X., Lu, Y.C., Murtiyoso, A., Koehl, M., Grussenmeyer, P., 2019. HBIM modeling from the surface mesh and its extended capability of knowledge representation. ISPRS Int. J. Geo-Inf., 8(7), 301. doi.org/10.3390/ijgi8070301.