Smart Labels: Linking Non-Standard Shapes and Semantics in Built Heritage

The "Grotta del Fauno" case study at Villa d'Este in Tivoli

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In the built heritage domains, formalizing fact and knowledge for conservation, valorisation, and enhancement of historical artifacts has attracted a growing research community. Various methodologies are employed to objectively reproduce and depict the features of a heritage building, including both its morphological and conceptual complexity. Although traditional 3D virtual reconstruction is relatively mature, semantic enrichment and annotation approaches constitute a promising investigation path. The primary scientific challenge lies in analysing and effectively reusing large amounts of heterogeneous data across multiple disciplines beyond mere geometry. Heritage and archaeological buildings, characterized by irregular geometries, intricate ornamentation, and non-standard components, pose significant challenges to mainstream Heritage Building Information Modelling (H-BIM). Workflows typically rely on point cloud data and mesh-based modeling to capture complex geometries; however, translating these into structured BIM models is resource intensive due to the diversity of architectural elements. To address this, the paper introduces "smart labels"—virtual BIM instances that act as connectors between high-fidelity meshes and established ontological frameworks (Built Cultural Heritage - BCH ontology) by linking pseudo-BIM databases (IFC) with semantic knowledge bases (OWL) including topological information for a multidisciplinary, systemic analysis of phenomena. The case study of "Grotta del Fauno" inside the 16th-century Villa d'Este in Tivoli illustrates the potential of enriched data querying to support decision-making in conservation, restoration, and structural analysis.

Keywords: *Built Heritage Modelling, Ontology, Data Management, Semantic Annotation, Digital Twin.*

INTRODUCTION

The preservation and analysis of built heritage demand methodologies that extend beyond conventional geometric modeling. Historical artifacts and structures are repositories of cultural, social, and technical information, yet their complex, non-standard geometries challenge standard documentation approaches. Digital technologies, such as 3D scanning and point cloud processing, have revolutionized heritage documentation, but the subsequent integration of semantic information remains a significant hurdle.

This paper addresses these challenges by proposing an innovative framework that leverages what we called "smart labels" to connect high-fidelity 3D representations with an ontological knowledge base. By fusing point cloud data, mesh segmentation, and semantic enrichment, our approach not only documents the physical state of heritage structures but also captures their historical, material, and conservation-related metadata. The application to Villa d'Este in Tivoli serves as a concrete demonstration of the framework's capability to support interdisciplinary decision-making in heritage conservation.

RESEARCH BACKGROUND

In the built heritage domains, formalizing fact and knowledge for conservation, valorisation, and enhancement of historical artifacts has attracted a growing research community.

Various methodologies are employed to objectively reproduce and depict the features of a heritage building, including both its morphological and conceptual complexity.

To support the multidisciplinary design process oriented to documentation and restoration of Cultural Heritage (CH) manufacts, buildings and infrastructures, early digital approaches relied heavily on 3D virtual reconstructions, while recent advances have seen the integration of semantic annotation to enrich these models (Kiryakov, 2005).

BIM limitations for Cultural Heritage

Heritage Building Information Modelling (HBIM) has evolved as a critical tool for documenting, analysing, and preserving historical buildings, since the BIM standard, based on IFC families offers a basic structure for representing and managing a certain level of semantic information.

BIM relies on a model that was conceived for typical discrete physical building elements like walls, doors, or windows, drawn in 3D, including certain given specific properties (geometry, thermal properties, cost, etc.).

The BIM standard, namely Industry Foundation Classes (IFC), is organized on a centralized structure and coded using Express language; it is important to highlight that it is a generic product data modelling language that can be defined textually and graphically, inherited from the automotive engineering industry and formalized for the exchange of product models (ISO Standard for the STEP (ISO 10303), standardized as ISO 10303-11 (EXPRESS Language Foundation, n.d.).

Unlike modern constructions, heritage buildings are typified by irregular geometries and ornamentation that defy conventional parametric modeling. As discussed by Yang et al. (2019), traditional BIM struggles to accommodate free-form surfaces, necessitating mesh-based models and advanced segmentation techniques. Furthermore, as highlighted by Previtali et al. (2020), the lack of standardized classification for near-unique components in heritage sites makes the creation of bespoke BIM families an inefficient and resource-intensive task.

The recent scientific literature together with the most relevant best-case reviews demonstrated that, at the moment, the attempt to apply BIM in CH and archaeological buildings, most likely does not work. Many challenges to mainstream must be addressed by further research: for instance, workflows typically rely on point cloud data and mesh-based modeling to capture complex geometries; however, translating these into structured BIM models is resource intensive due to the diversity of architectural elements.

Challenges of 3D Semantic Annotation

In the CH domain, the typical process of annotation of project data on iconographic sources like images, constitutes the fundaments for the comprehension of a building by providing semantic information.

Although traditional 3D virtual reconstruction is relatively mature, semantic enrichment and annotation approaches constitute an urgent and promising investigation path. The primary scientific challenge lies in analysing and effectively reusing large amounts of heterogeneous data across multiple disciplines beyond mere geometry.

Semantic annotation according to Kiryakov et al. (2005) involves attaching metadata—such as historical context, material properties, and conservation status—to geometric entities in a digital model. This process transforms raw data into actionable knowledge, facilitating enhanced data querying and supporting decision-making processes.

As reviewed by Messaudi et al. (2018) we can identify three basic approaches to add a note to a 2D source:

- manual (e.g., annotation related to a tag or a term from a taxonomy, or a class of an ontology);

- automatic (e.g., by an image or a shape recognition);

- semi-automatic (e.g., validation of a keyword suggested by the system).

At the moment, most of case study implementations are based on two-dimensional information. In the context of 3D model annotations, data may be associated with points, segments, surfaces, or objects within the digital mock-up. Recent studies indicate a growing attention in incorporating 3D entities into the process of image semantic annotation.

Ontological Frameworks for Built Cultural Heritage

Ontology technologies offer a structured approach to encapsulate semantics, counting on an existing and always evolving generation of software tools, such as editors, inference engines, reasoning algorithms, and query applications.

The general idea eliciting this investigation is to define a framework for implementing an ontology commitment on the built cultural heritage field, to support restoration and exploitation goals.

An ontology - in computer science domain and knowledge-based engineering - is used to describe, share and reuse knowledge and data between software and humans: this conceptual model is used in many information systems relying on semantic web technology (Messaoudi et al., 2018).

The current web is characterized by the fact that, in most of the cases, it is "machine-readable" but not "machine-understandable".

The term "semantic", or "which has to do with meaning", therefore takes on the value of "machine-processable". The semantic web will therefore be an environment in which it will be possible to publish and trace documents and information in a format suitable for querying, interpreting and automatic processing: a web characterized by the presence of more expressive connection structures than the current ones.

A basic statement of this research, elaborated from authors' previous works, is that an ontological framework for Cultural Heritage buildings and/or archaeological manufacts can offer a viable software technology to include various forms of complexity, according to the required level of expressivity (formality). Contents formalization relies on basic catalogues to glossaries, from a collection of taxonomies, represented by frames, toward a formal definition of a structured set of building entities (abstract, physical, etc.), qualified by means of relational connections and logical constraints, in a specific domain context, oriented to the goal of representing a heritage manufact.

This kind of formal representation allows for automated recognition, querying and automatic reasoning.

STATE OF THE ART AND RELATED WORKS

At the present there are different research works oriented to define ontologies in the field of

Cultural Heritage, and to develop frameworks and tools for automation of support to actors (designers, scholars, stakeholders, users, etc.).

Museolan Ontologia – MAO interconnects content generated by an extensive domain set encompassing painting, sculpting, and drawing arts, as well as data from web pages pertaining to locations, historical events, cultural landmarks, and more (Hyvönen, 2012).

MONument Damage Information System – MONDIS regards building conservation ontology, as well as alteration phenomena management oriented to diagnosis and the intervention for possible restorations (Cacciotti, 2015).

More recent Built Cultural Heritage – BCH – ontology, as presented by Zalamea and García (2020), integrates multiple heritage models (e.g., CIDOC-CRM, CityGML, and MONDIS) to support interoperability and enriched data annotation.

Several recent studies have contributed to the field of metadata annotation, reviewed as a key inspiration reference for this paper as discussed in the following section. Messaoudi et al. (2018) provide an ontological model for the 3D annotation of conservation states based on a comprehensive integration of various metadata types.

In a similar attitude, Colucci et al. (2021) proposes an innovative approach to linking point cloud raw data with semantic frameworks, providing a foundational basis for generating structured models.

Keyvanfar et al. (2022) critically examine interoperability challenges in 3D reconstruction, reinforcing the necessity for solutions that can bridge different digital domains.

Puerto et al. (2024) review most recent literature illustrating how BIM with complementary technologies favours the digitalization of heritage buildings.

To summarize, the previous works provided a relevant contribution to both theoretical and applied aspects of semantic enrichment, including specific connection to HBIM. Their findings collectively justify the need for an integrated framework and, at the same time acknowledge about some general limitations across all investigation results:

- Irregularity handling: historical and archaeological buildings have complex, non-standardized geometries, making the segmentation itself a difficult task.
- Computational issues: most approaches struggle with large or highly detailed heritage structures, computationally expensive, requiring powerful hardware and to address scalability.
- Automation gaps: while AI has been successfully introduced, full automation of BIM family recognition, contents querying, reasoning, etc. are still a challenge.

A SYSTEMIC APPROACH FOR SEMANTIC RICHNESS

The goal of an integrative platform, such as the one described below, is to optimize the design process thanks to an effective and explicit interaction among actors (and software) at a higher semantic representation layer .

To express their intentions, communicate and verify them (testing their validity inside and outside their domain of specialization), actors should be enabled both:

– to explicit and model their tacit design knowledge through an appropriate format and structure;
– to manage their design knowledge and increase it in the design process.

For the representation of a historicized state of a CH manufact and its state of conservation, there are four level of technologies for formalization, increasing according to the semantic richness (Andrews, 2012):

– by tags (keywords),
– by attributes (object features),
– by relationships (between provided resources),

– by ontologies ("an explicit specification of a shared conceptualization".

Focusing on the last one, it is clear that the formalization of an ontology in the CH domain is a large-scale complex task - including several domain experts, such as architects, conservation scientists and material experts, building and structural engineers, etc. - necessarily oriented towards the solution of conservation and enhancement problems.

The objective here is not to provide a comprehensive account of this extension, as it would necessitate a wide-ranging technical analysis and viewpoint that exceeds the thematic boundaries of this paper. Instead, we define how the existing CH ontology can be enhanced in terms of semantic richness.

Hierarchical and Topological Relationships

Almost all the problems of degradation, whether they are cracks, infiltrations, deterioration of the material, etc., although they manifest themselves with punctual episodes, more or less extensive, they are actually the result of phenomena that affect one or more building components of the artifact.

This implies the need for an analysis with retrieval, filtering and interrogation of the systemic evidence of the building model.

In other words, if we approach the CH investigation starting from the building entity directly observed, in order to understand its relationship with the other building entities it is necessary that the latter are characterized by an explicit hierarchical and topological relationship, belonging or inclusion to super/sub-ordinate construction systems.

Authors approach to implement this breakdown systemic relationships, is to start from already existing and tested ontologies, such as the one developed by Messaudi et al. (2018), mapping the CIDOC-CRM Model (Vassilakaki, 2015) extending it with a multidisciplinary semantic information by adding more terms, inference rules, constraints, and axioms to represent the topological organization (including reciprocal dualism of environmental and technological systems (Figure 1).

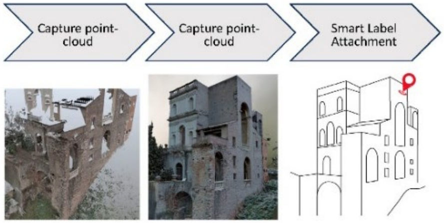

Fig. 1.
From a Point cloud representation to a semantic one enriched by a Smart Labe,

The classes of building objects/concepts will be characterized by relationships and constraints of inheritance, generalization, aggregation, cardinality in order to represent functional or topological or geometric characteristics. Example: "*that arch is a type of opening that belongs to that specific bearing wall – having superficial decoration pattern - which is an internal partition that divides those two rooms belonging to contiguous environmental units with the same visitors' activities but with different exposure to the outside*".

Inheritance constraints follow the hierarchy defined through relationships:

– "*is_a*" which establishes inheritance relationships between the class and the instances that depend on it;
– "*ako*" (a kind of) in turn establishes hierarchical relationships between classes of the knowledge structure (sub-class).
– Aggregation constraints define topological relationships;
– "*part_of*" which provides the means to associate individual objects into a set of related parts;
– "*has_a*" which represents the inverse relationship of inclusion.

From a mathematical point of view, such an organization is equivalent to an ordering of the elements based on the reflexive, anti-symmetrical and transitive order relation "being part of" (*semi-lattice*).

Assemblages are very common and useful, because they take on specific meanings and valences: a building is an assembly of environments, walls, and so on. Associating parts in a set endows the assembly with properties that go beyond the sum of its parts' properties and allows its parts to share common properties.

For example, Villa d'Este's property of constituting "a historic residence" is not a deliberate property of one of its parts, but rather of their global assembly.

The definition of such a structure on the set of building objects allows to express and evaluate characteristics related to spaces and their conformation through the physical objects that make up the building organism.

The topology of building objects is constituted by the set of relations of reciprocal arrangement between spatial and environmental units. It is therefore useful for describing the methods of conservation and enhancement of the organism by identifying the relationships between the individual entities of ontology.

The "Smart Label" solution

In the professional practice, there is an urgent need to connect efficiently heterogeneous databases, starting from the 3D model: it is evident that HBIM, intended as a computer-aided architectural design (CAAD) tool, have been created using a space-components product strategy. This method has shown to be effective in facilitating the flow of data and ensuring compatibility of information between different software programs together with, according to the current diffusion, the existing building and its Digital Tween.

BIM, and its standard IFC, offers an available solution, which already includes the possibility of representing a basic semantic level, the so-called "low level ontologies".

In CH domain, we can define two solutions according to the two edges between standard and non-standard classification of semantemes, namely the CH entities assuming a meaning.

So, where the artifact can be break down in typical building components, using a basic low detail level 3D representation, BIM can be the platform to able to enrich design entities linking them to design ontologies.

Differently, for instance in the archaeological context, this parametric system would have to geometrically represent non-standard elements, like e.g., a broken vault, artefacts of a partly broken stone wall, a column or a landscape with potential historic findings.

A standard BIM system typically is not able to model this kind complexity. Also due to missing information, e.g., if parts of the artefacts are not excavated yet. Furthermore, a substantial part of information about the archaeological artefacts are given in different representations like text, historic images, or as a link to an external website.

To overcome these restrictions, a layer of abstraction is applied.

Rather than directly representing non-standard elements within the BIM system, a "Smart Label" (conceived as a specific Revit family) is employed. The "Smart Label," characterized by its simplistic visual representation, is positioned near the artefact by specialists, either in 2D or in 3D on the point cloud/mesh. This can be accomplished within the BIM software or in the VR environment. The label is subsequently linked to the inventory identifier of the archaeological artefact and augmented with various domain-specific information, along with connections to additional external information sources (Figure 2). Consequently, the "Smart Label" serves as a repository for all pertinent and diverse information, which can then be extracted using standard and advanced BIM methodologies, facilitating calculations, and serving as a foundation for visual analysis.

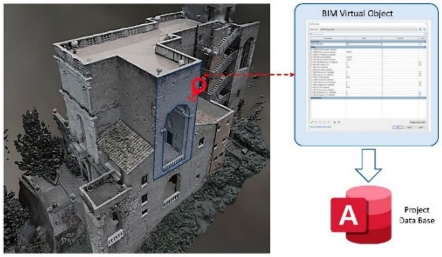

Fig. 2.
Link from a Virtual Object to the Project Data Base.

The "Smart label" is organized as the inventory identifier of the artefact, and includes DB links to the various domain specific KBs: when linked to Ontology allow for the use of filters, search-engines, inference, or analytic algorithms, etc.

METHODOLOGY

Data Acquisition and Pre-processing

The first step in our framework involves acquiring high-resolution point cloud data through laser scanning and photogrammetry. For Villa d'Este, multiple scans were performed to capture the intricate details of its architectural features. The raw data are then processed to create high-fidelity meshes that accurately represent the building's irregular geometries.

The 3D model was generated by aerial photogrammetric survey using reconstruction software. Using a *249g DJI mini2* drone with a 4K camera, a manual aerial photogrammetric survey was carried out following the guidelines for 3D photographic reconstruction and the need for detail of the work. The photos were inserted into the opensource software *Meshroom* to be aligned and used in the reconstruction of the 3D model using special algorithms. The result, typical of best practices, is an accurate 3D model, with high-detail textures.

The architectural survey, in colour and reflectance, was carried out with *Faro S70* Laser scanner. A series of *LiDAR* scans were carried out from terrestrial locations aimed at covering the need for intervention on the work and which were then, using *Faro SCENE* software, aligned, and used for the extrapolation of sensitive data to each area of interest.

Mesh Generation and Segmentation

Using advanced software (e.g., *Autodesk Meshmixer*), the point clouds are converted into meshes. Subsequent segmentation isolates key architectural components - walls, columns, decorative elements, and spatial partitions. Fragmentation processes further refine these segments, ensuring that even near-unique objects are captured with precision in order to be subsequently linked to basic, low level of detail, BIM building entities (Manuel et al., 2024).

This process has been partially (but can be further) automated by using existing software and algorithms for mesh segmentation:

– *Autodesk ReCap + Revit*: used in workflows to convert point clouds to HBIM models.
– *CloudCompare*: Allowed for manual and automatic mesh segmentation.
– *Rhino + Grasshopper* (with plugins like *Ladybug, Kangaroo, and Volvox*): can be used for algorithmic segmentation.
– *Geomagic Wrap*: Advanced for heritage mesh processing and conversion.
– *Deep Learning Frameworks* (e.g., *TensorFlow, PyTorch*): Applied for automated recognition.

Semantic Segmentation Approaches

For semantic segmentation, apart from operating manually for the case of study, the workflow can be further automated by using the following methods.

Rule-Based Methods:

Research has explored using geometric heuristics (e.g., normal vectors, curvature) to separate elements then classified in HBIM components by means rule-based algorithms.

Machine Learning & Deep Learning:

PointNet++ and *CNN-based methods* are increasingly used for automating the recognition of HBIM components from point cloud-derived meshes.

Graph-Based Segmentation:

Studies explore graph-cut algorithms to detect repeating architectural features (e.g., vaults, arches, decorative motifs).

Ontological Framework and Smart Labels

The core of our methodology is the introduction of the "smart labels"- virtual BIM instances that serve as a bridge between the 3D geometric database (using IFC standards) and the semantic domain (represented through the semantically enriched BCH ontology in OWL). Each smart label is a data container that includes:

- Geometric Data: Information about shape, dimensions, and spatial relationships.
- Semantic Metadata: Annotations derived from the BCH ontology, such as historical context, material properties, and conservation status.
- Relational Data: Links between different components, enabling hierarchical and topological analyses.

A graph-based approach is employed where building components and spaces are nodes, and their interrelationships (e.g., adjacency, connectivity, belonging, inheritance) are edges. This model not only supports enriched querying but also facilitates the visualization of structural dependencies and historical correlations (Gros et al. 2025).

Integration with BIM and Knowledge Bases

The smart labels are integrated into a BIM environment via a dedicated DB Link mechanism. This integration enables seamless access to both geometric and semantic data, providing a unified interface for heritage professionals.

Revit Database Link allows us to maintain a relationship between *Revit* "virtual objects", such as Smart Labels and a *Microsoft Access*, or ODBC (relational database) (Trento et al., 2022).

Alternatively, data can be exported to a graphic DB (Simeone et al. 2021).

Anyways, these entities are mapped to domain specific Ontologies, i.e., CIDOC-CRM. So, it is possible to make changes to these entities, and to import them back into the project *Revit* data.

We used *Revit* DB Link to export *Revit* project data to the Ontology knowledge database, to make changes to the data, and to import it back into the project.

By linking the IFC-based 3D model with the OWL-based knowledge, users can perform complex queries on the ontologies that are addressed to both physical and historical aspects of the heritage site.

CASE STUDY: VILLA D'ESTE IN TIVOLI

Follows a short description of the implementation steps that we processed, most of the time with very low level of automation:

Context and Data Collection

Villa d'Este in Tivoli is a prime example of 16th-century historical architecture with rich cultural significance. The building's intricate facades, irregular spatial layouts, and decorative elements present ideal conditions for testing our smart label framework. Detailed point cloud data were collected across multiple zones, focusing particularly on the Grotta del Fauno - a space renowned for its ornate design and historical narratives.

Application of the Smart Label Framework

In applying our framework to Villa d'Este, the following steps were executed:

1. *Mesh Segmentation*: The complex geometry of the Grotta del Fauno was segmented into

individual components representing architectural features such as vaults, frescoed surfaces, and ornamental columns.
2. *Smart Label Attachment*: Virtual BIM instances (smart labels) were assigned to each segmented component. At the same time, where viable, typical building components belonging to the HBIM libraries have been modelled using a basic low detail level of representation. The entities identified by smart labels (virtual BIM families), together with BIM instances, were enriched with metadata, linking each component to the corresponding entries in the BCH ontology.
3. *Ontology Integration*: The enriched data were merged with the existing IFC database, ensuring that both the geometric and semantic information were readily accessible. This integration enabled enriched data queries - such as retrieving historical maintenance records or material degradation reports - thus facilitating informed conservation strategies.

Outcomes, Benefits and Limits

The deployment of smart labels in Villa d'Este, although early and partially implemented just for investigation, to understand the potentials of the proposed technological pipeline, demonstrated several advantages:

Enhanced Data Querying: users could perform multidisciplinary queries that combined geometric, historical, and material data.

Improved Decision-Making: conservation and restoration experts were better equipped to assess structural conditions and historical significance, leading to more informed restoration and adaptive reuse planning.

Interoperability: The approach bridged the gap between traditional BIM data and semantic knowledge bases, ensuring that both technical and contextual information were preserved and accessible.

The smart label concept could represent a simple but significant advancement in the digital documentation of heritage sites. By acting as intermediaries between IFC and BCH ontology, these virtual BIM instances enable the effective fusion, in a relational database, of geometric and semantic data. This is particularly crucial for heritage buildings where irregularities and unique features are the norm rather than the exception.
However, the approach is not without its challenges. The integration process demands rigorous data pre-processing and robust segmentation algorithms to ensure that the smart labels accurately reflect both geometry and context. Moreover, the scalability of the approach to larger or more complex heritage sites requires further investigation.

CONCLUSIONS

This paper has introduced a novel framework for linking non-standard shapes and semantic representations in built heritage artifacts using smart labels. By integrating high-fidelity 3D mesh data with a robust ontological framework, our approach facilitates enriched data querying and supports informed decision-making in heritage conservation. The application to Villa d'Este demonstrates the feasibility and benefits of this methodology, particularly in addressing the challenges posed by irregular geometries and heterogeneous data.

This work underscores the importance, addressing the early feasibility, of a robust ontological foundation that can bridge the gap between raw geometric data and structured semantic knowledge.

While the smart label approach shows promise, further research is needed to optimize data processing, workflow automation and ensure scalability across diverse heritage contexts.

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