3D Point Cloud Annotation through an ontology model: the case-study of San Giovanni a Porta Latina, Rome

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Abstract

Ontologies play a crucial role in the semantic enrichment of 3D models, enabling structured knowledge representation and interoperability in the digital documentation of built heritage. This study presents a multi-layered semantic segmentation workflow for point clouds that integrates spatial classification with formal ontological modelling. The proposed method is applied to the Church of San Giovanni a Porta Latina in Rome, where the point cloud was manually segmented using the open-source software CloudCompare according to five thematic layers: constructive element, construction technique, material, chronological reference, and decay. Semantic labels were assigned through the Cloud Layers plugin and embedded into the ASCII-exported point cloud, forming the basis for conversion into RDF and integration into a semantic web framework. This structure supports querying via SPARQL, allowing for the extraction and analysis of complex relationships within the dataset. By working directly on the point cloud his approach surpasses the limitations of traditional 2D documentation, offering a more holistic understanding of architectural complexity. The proposed methodology provides a scalable and interoperable approach to cultural heritage documentation, enabling spatial reasoning and data-driven decision-making directly on digital twins of historic structures.

1. Introduction

The conservation and restoration of historical monuments require thorough diagnostic analysis conducted by multidisciplinary team. The results of these investigations include data acquired through different techniques and protocols, which are essential for conservation specialists in assessing the condition of built heritage.

In recent years, advancements in digital technologies have significantly improved the collection, visualization, and indexing of digital resources. These developments have introduced innovative tools that are transforming documentation practices in the cultural heritage domain. However, managing multidimensional data in heterogeneous formats presents new challenges, such as the need to develop effective methods for data analysis and interpretation, facilitate data sharing across different stakeholders and contexts, and establish a centralized archive to ensure the long-term preservation of documentary results.

One of the key challenges faced by the scientific community in cultural heritage is integrating data from various sources into a unified information model. This model should comprehensively represent the conservation state of a building while allowing for future updates. It is crucial that these data are spatially correlated to provide heritage experts with an intuitive and efficient system for exploring the information used in their assessments. At the same time, such a system should enable the recording and sharing of observations within the scientific community.

2. State of the Art

2.1 Ontologies and Vocabularies

The digitization of cultural heritage is characterized by complex challenges due to its heterogeneity, as well as the relationships and interconnections that arise within it. Throughout the digitization process, each scholarly community has created—and unfortunately continues to create—databases structured according to different descriptors, metadata, methodologies, and architectures. As a result, despite the enhancements and innovations made possible by digital technologies, most of the knowledge produced is isolated and rarely reusable. In addition, the 3D representation process increasingly used, and the massive amount of data produced, pose significant challenges related to the passage from the raw model acquisition to meaningful data interrogation and interpretation. In order to overcome such obstacles, data curation, knowledge graphs and semantic representation are of significant help. In particular, standardized vocabularies and thesauri are necessary for guaranteeing implemented representation knowledge whereas ontological modelling and data enrichment make information interoperable between humans and machines (Guillem et al., 2025) as well as among humans themselves.

Ontologies are meant as a synonym of 'conceptualization' (Gruber, 1995), in opposition to what is defined in philosophy where it is the science of what exists, of types and structures of objects, properties, events, processes and relations in every dimension of the reality (Smith, 2003). Thus, ontologies provide a formal, structured framework to represent knowledge from different domains in a unified way and to address the challenges posed by fragmented and heterogeneous data especially when using formal, structured, standardized models. Ontology-based data integration offers a promising solution by providing a unified way for linking and analysing diverse datasets as those produced by 3D object representation and diagnostics.

The CIDOC CRM model is one of the main international systems for documentation of cultural heritage and it has been Standard ISO since 2006. Due to that, it was chosen as *top level* reference for the mappings. Nonetheless, the specificity of certain domains to be represented sometimes requires the use of specializations, understood as in-depth extensions of the general ontology, which operate as vertical expansions that comfortably adapt and extend the generic models defined at the highest level. For achieving the modelling purposes, the CIDOC CRMsci and

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CRMinf extensions were used for describing the inferential processes, analyses and interpretation of information obtained from diagnostics results. For the description and contextualization of the architectures analysed, instead, it was used the CPM, a formal ontology under development since 2015 by the research group of Sapienza University of Rome within the Department of History, Representation and Restoration of Architecture, coordinated by Professor Donatella Fiorani. The CPM is intended as an extension of CIDOC CRMbase for comprehensive representation of historical architecture and the complex interrelations between different aspects concerning cultural heritage: its knowledge, analysis, description, maintenance and conservation (Acierno and Fiorani, 2025).

What was done at a conceptual level of formalization was then completed by working with thesauri and controlled vocabularies (Zeng and Mayr, 2019) to deal with the complexity and granularity of reality. Vocabularies, in fact, support linking related data across the web by providing common reference points for data descriptions (Garijo and Poveda-Villalón, 2020); enable different systems and datasets to understand and integrate information meaningfully, even if they were developed independently; avoid confusion caused by ambiguous or varied terminology and help formalize domain knowledge so that it can be processed by machines. Furthermore, they provide a common language for cataloguing and documentation, facilitating the integration of information from different sources. It also enables the use of data by both users and computer systems allowing the exploitation of data via embedding, clustering and data mining.

2.2 Semantic Annotation ad Segmentation

This kind of data, produced by various specialists through graphical, textual materials or other processes, is generally not spatially structured. Even though this data refers to the same physical object —such as a historical building— or specific areas of it —like a deteriorated wall section— their connection is often based solely on a conceptual description of the building, without explicit references to their spatial relationships.

Research in this field primarily focuses on architectural heritage and aims to integrate semantic descriptions of morphology within multiple geometric representations. This is achieved through segmentation and classification processes (Grilli et al., 2017; Croce et al., 2021; Réby et al., 2023) or parametric reconstruction, combining reality-based models with structured knowledge models (Gros et al., 2019).

These studies have primarily focused on the potential for automatic segmentation of images or point clouds using machine learning processes. In such cases, the classification process can follow different approaches, based either on the radiometric data of the model textures (texture-based approach) or on the analysis of the geometric properties of point clouds (geometry-based approach). In texture-based approaches, segmentation is mainly driven by color data, which can be extracted from a textured mesh model (pixel-based classification). In contrast, geometry-based classification relies primarily on the geometric properties of the digital model using specific features (3D points classification).

Despite the significance of these approaches, the unstructured nature of semantic descriptions limits their practical application. In the geomatics community, numerous benchmark datasets have been proposed (Niemeyer et al., 2014; Özdemir and Remondino, 2019), providing labelled terrestrial and aerial data on which users can test and validate their algorithms. Most of the available datasets offer classified natural, urban, and road scenes, such as Semantic3D (Hackel et al., 2017) or The Cityscapes Dataset (Cordts et al., 2016).

While in these scenarios object classes and labels are well defined (mainly ground, roads, trees, and buildings), identifying precise categories in the field of cultural heritage is much more complex. This is because, for the same case study, multiple classes can be identified depending on different purposes and a semantic architectural class is not always associated with a specific shape or colour.

However, beyond the geometric and visual representation of forms, a significant amount of data is typically gathered, organized, and analysed in the study of cultural heritage artefacts. Some studies (Amat et al., 2013) focus on data management within heritage investigations, integrating information derived from different techniques into a unified spatial reference system and proposing various analytical tools, including annotation features.

Further studies on semantic annotation applied to 1D and 2D data led to the development of multiple digital heritage research platforms that allow users to store digital heritage content and perform semantic queries on multimodal cultural heritage data archives (Fabiani et al., 2016).

Nevertheless, despite the relevance of such approaches, the unstructured nature of the semantic descriptions associated with the data often hinders their effective processing. To address this issue, various methodologies and technologies have been developed to enhance the management of linked digital content. These efforts primarily rely on formal structures that describe both implicit and explicit conceptual elements and their relationships (Acierno et al., 2017).

Beyond theoretical and methodological aspects, some studies have focused on linking semantic labels or attributes (such as vocabulary terms and structured concepts) to ortho-images or digital 3D models (Poux et al., 2020). Other research has explored the integration of 3D digitalization results within the Building Information Modelling (BIM) paradigm (Bruno et al., 2018; Tommasi and Achille, 2017).

However, reality-based 3D reconstruction and 3D information systems are still generally considered separate domains, with only a few projects treating them as complementary components of a single framework. Despite the adoption of diverse approaches, some studies have attempted to combine semantics and geometry through extensions of the CIDOC CRMdig model and other ontologies (Catalano et al., 2020; Messaoudi et al., 2017). Nonetheless, most 3D annotation methods remain limited to static and non-scalable representations, restricting the ability to handle the continuous flow of information required for cultural heritage studies. A line of research that has attempted to integrate all these aspects is the one conducted at the CNRS in Marseille, which led to the creation of the Aïoli platform (Abergel et al., 2023).

3. Case-study and Methodology

The adoption of an ontological model for the multidisciplinary observation of an architecture's conservation state appears to be a promising solution for structuring semantically enriched 3D representations of historical buildings. The ongoing research

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proposes the use of domain-specific ontological models for reality-based 3D and annotations of conservation conditions. By integrating both qualitative and quantitative descriptors into interconnected 3D annotations, this approach—developed using dedicated ontologies—aims to consolidate data, information and knowledge related to different focuses, such as construction techniques and the monitoring of deterioration phenomena. A concrete case study applies this methodology to the medieval church of San Giovanni a Porta Latina in Rome, palaeochristian church founded in the 5th century and restored several times.

During the analysis of segmentation and semantic annotation processes for point clouds, it became evident that there is a notable lack of tailored open tools specifically designed to address the needs of 3D documentation in the context of cultural heritage. Most of the currently available solutions—whether software, optimized formats, plug-ins, or cloud platforms—are primarily developed for two well-established domains: GIS, which focuses on large-scale spatial data management and visualization, and BIM, which deals with semantically enriched 3D models, yet is inherently structured around contemporary building logic.

In the GIS domain, formats such as Entwine Point Tiles (EPT), COPC, COG, and 3D Tiles are designed for the efficient storage and visualization of large-scale point cloud datasets, often integrated with GIS software like QGIS or platforms such as Cesium. While these solutions support interoperability and efficient compression, they do not offer advanced semantic segmentation capabilities or allow flexible management of architectural-historical classifications.

In the BIM environment, some tools support the integration of point clouds within HBIM workflows, but they generally show significant limitations in terms of segmentation granularity and are still poorly suited to the stratigraphic and material complexity typical of historic buildings.

Even the most innovative solutions for handling large datasets—such as TileDB, Zarr, or Parquet—focus on computational performance and data scalability but often overlook the need for complex semantic classification directly within the point cloud environment. In many cases, semantic classification is limited to numerical or generic labels, without providing a user-friendly interface for thematic, manual, and layered annotation.

This scenario led the present research to adopt CloudCompare and its Cloud Layers plug-in, which—although not originally developed for ontological or GIS-based applications—allows for precise, multi-layered, and open manual segmentation. While less automated, this approach proved to be more suitable for representing the cultural, material, and chronological complexity of the case study building.

3.1 Integrated Architectural Survey

To proceed with the subsequent analyses, a survey of the ecclesiastical building was carried out using an integrated methodology that combined the Leica BLK 360 laser scanner with drone and ground-based photogrammetry. This approach enabled the acquisition of the morphometric characteristics of the surfaces which were reproduced within a virtual environment.

The result is a three-dimensional numerical model that describes the surfaces and allows scholars and professionals, involved in the documentation and conservation of the architecture, to explore and study them. This digital model served as the foundational dataset upon which further acquisition operations were planned, acting as a system for the collection, management and archiving of heterogeneous data derived from other survey and documentation methodologies applied to the same building.
During the acquisition phase, 84 scans were carried out inside the site, strategically designed to optimally cover all internal spaces and external façades, while minimizing non-detectable areas. The scans were then aligned and registered into a single model—or point cloud—using Leica Cyclone Register software and subsequently exported in LAS format. This unified point cloud enabled the study of relationships between internal spaces, access points, service areas, and their connections with the external surroundings. These elements are clearly distinguishable, yet they maintain a strong stylistic and formal consistency, even in relation to the surrounding architectural structures.

At the same time, to document not only the metric and geometric aspects but also the material and chromatic characteristics, a photographic campaign was conducted with the aim of producing a textured model of the building. The photographs were taken using a Sony Alpha 7 MK II digital camera, with ISO fixed at 100, aperture set to f/7.5, and variable shutter speed depending on the lighting conditions.

Photographs were captured while maintaining a consistent distance from the surfaces, a task facilitated using a DJI Air 2 UAV (SAPR) system for acquiring the higher parts of the church and bell tower. A total of 387 aerial images and 499 ground-level images were acquired using the drone and a Sony Alpha 7 MK II digital camera, with ISO fixed at 100, aperture set to f/7.5, and variable shutter speed based on lighting conditions. All images were subsequently processed in Agisoft Metashape to generate a continuous and textured 3D model of the church.

Figure 1. Point cloud of San Giovanni a Porta Latina, Rome.

This approach, which integrated various acquisition techniques, made it possible to construct a unified and interactive three-dimensional digital model (Fig. 1), offering new analytical opportunities. The model—and its parts extracted for specific studies—served as the basis for the multi-layer semantic analysis described below.

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3.2 The Ontological Model

The results presented are part of a larger research project in which all the 3D acquisition and data processing for the realization of the point cloud have been modelled. Such mappings have been possible using different ontological models: CIDOC CRM base, its extensions CRMsci, CRMinf and CPM.

Due to the focus of the present contribution, for clarity and relevance purposes, only the formalization of the multidimensional annotation levels described are shown to explicitly represent the entities and the relationships existing among them.

In particular, the levels of definition chosen for annotations are:

1. Constructive element;
2. Construction technique;
3. Materials;
4. Chronological reference;
5. Decay;
6. Diagnostic technique.

Fig. 2 shows how those levels of annotation, related to a segmented point cloud, are modelled.

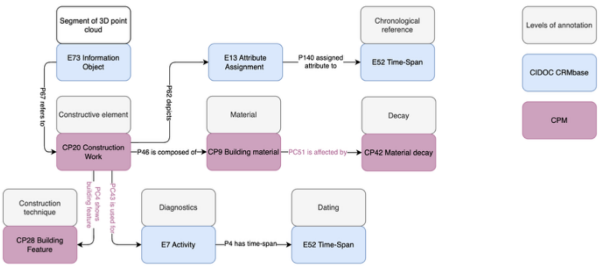

Figure 2. Schema of relations and modelling of the description levels annotated.

Each portion obtained by the segmentation of a 3D point cloud is a E73 Information Object and it refers to an architecture constructive apparatus which is a CP20 Construction Work (subclass of CP2 Architecture Work which is subclass of E24 Physical Human-Man Thing). The built piece of architecture is composed of materials which are modelled as CP9 Building Material (subclass of E24 Physical Human-Man Thing). The composing material might be affected by degradation phenomena, which are considered as a non-pathological state of the material (Acierno and Fiorani, 2025). The superficial degradations are CP42 Material Decay (subclass of E5 Event).

Furthermore, the segmented constructive element is characterized by a specific construction technique which is CP28 Building Feature (subclass of CP27 Architecture Analysis Output, subclass of E13 Attribute Assignment) and can be traced back, thanks to experts' assertions instances of E13 Attribute Assignment, to a specific time which is E52 Time Span. The built element, finally, can be used for diagnostic activity (E7 Activity) that was performed in a particular time which is E52 Time Span.

Once outlined the formalization and relations of the information annotated, it appears of interest to highlight that the terms used for labelling were curated in order to make their usage and interrogation more agile. In particular, the terms used for labelling the segmented elements of 3D point clouds are the result of a joined collaboration with the teamwork responsible for the Project CHANGES, Spoke 5, WP6 Uniroma1, DSDRA, AstRe-LabMat, founded by PNRR resources.

Moreover, the terms related to decay were borrowed by the vocabulary created by CNR-ICR in 1990 (Raccomandazioni NORMAL 1/88, 1990), those related to diagnostics from the thesaurus developed by the project E-RIHS. The exploitation and exportation of thesaurus was made possible by the use of Opentheso, an open-source multilingual thesaurus management software developed by the Technological platform WST (Semantic Web & Thesauri) located at the MOM in partnership with the GDS-FRANTIQ.

On the other hand, those referring to the attribution of constructive elements, construction techniques and materials were inserted freely in order not to limit the granularity of the documentation.

Nonetheless, once completed the labelling process and extracted the terms used, data curation procedures were followed to ensure the integration of information from different sources as well as alignments with external thesauri such as AAT, Perouse, Wikidata and Pactols thanks to vocabulary management tool Opentheso (Rousset 2024). The pipeline related to the management and enrichment of the final thesaurus will be developed in a future contribution.

3.3 Multi-layer Semantic Segmentation

The point cloud of the ecclesiastical building of San Giovanni a Porta Latina was manually segmented using the open-source software CloudCompare. This methodological choice was based on the specific goal of the research, which does not aim to explore or optimize automatic segmentation techniques—an area that is already extensively investigated and rapidly evolving in both 2D and 3D heritage documentation, as discussed in Section 2.2—but rather to develop and validate an ontologically grounded 3D annotation workflow.

Segmentation was carried out according to five thematic layers (Constructive element; Construction technique; Materials; Chronological reference; Decay) previously formalized through the abovementioned reference ontologies (Fig. 3).

The Cloud Layers plug-in within CloudCompare enables the classification of the point cloud by assigning each segmented portion a category attributed semantically, which is visually represented by a predefined color. These class labels are immediately displayed within the 3D environment of the software, facilitating visual validation and consistency checks. A key feature of this workflow is that these labels are also exported in ASCII format, written into the seventh column of the textual file, after the X, Y, Z coordinates and RGB values of each point.

Each annotation is represented by a numerical identifier (e.g., "13" for *Opus mixtum*), which requires a mapping step between the assigned number and the label defined by the annotator. This classified point cloud serves as the basis for its conversion into RDF (Resource Description Framework) format, in accordance with the chosen ontologies. The conversion process involves the following steps:

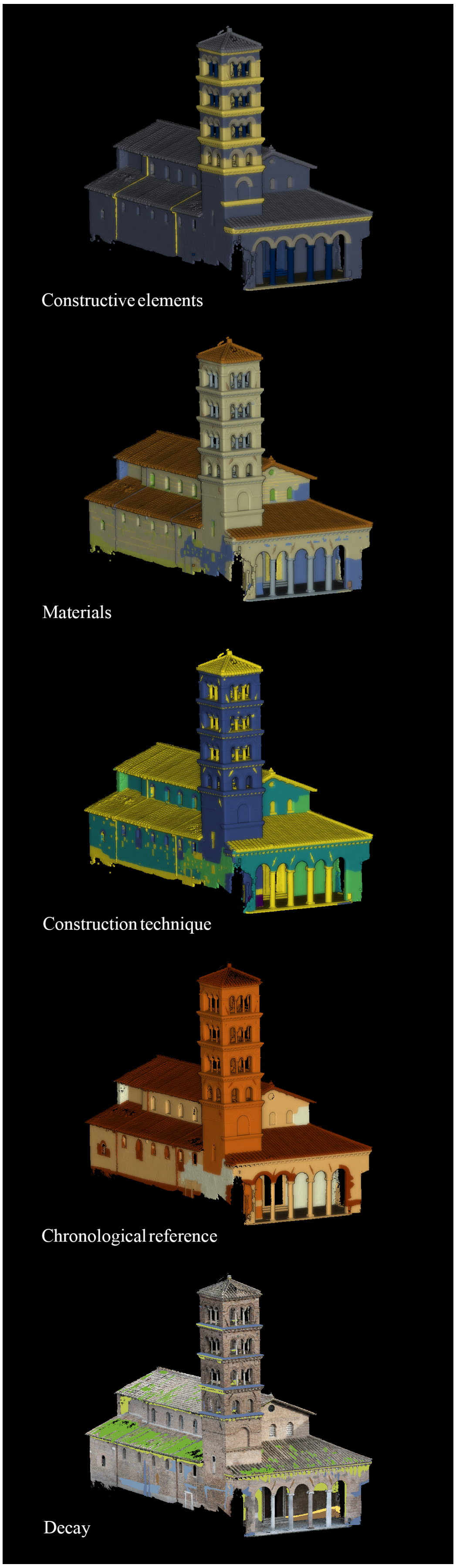

Figure 3. Semantic segmentation of the point cloud of San Giovanni a Porta Latina

-Parsing the ASCII file: each line is interpreted as an instance of a 3D point, whose attributes (coordinates, color, class label) are extracted.
-Semantic mapping: the numerical identifier attributed is matched with the corresponding ontological classes (e.g. OpusMixtum is an instance of 'construction technique', which is CP28 Building feature).
-RDF serialization: for each point or segmented portion, RDF triples are generated, such as:

```
:Point1234 a :SegmentedPoint;
:hasCoordinates "X,Y,Z" ;
:hasMaterial :Tufo;
:hasConstructionTechnique :OpusMixtum.
```

The result is an RDF file (in RDF/XML, Turtle, or JSON-LD syntax) that, after being processed and imported into a triplestore (eg. Fuseki, GraphDB, Blazegraph, etc.), can be queried using SPARQL.

To make the experimental phase more manageable from a computational perspective and simplify the evaluation of the queries, a representative portion of the external wall of the left nave was selected instead of applying a general sub-sampling of the entire point cloud. This subset includes multiple thematic classes and interrelationships, allowing for a full test of the workflow and the effectiveness of multilayer semantic querying. However, the entire point cloud was segmented using the same thematic criteria, meaning that the proposed workflow is scalable and can be extended to the full dataset.

3.4 Semantic Queries and Implications for Architectural Conservation

The multilayer segmentation and semantic annotation of the 3D model allows the dataset to be queried through formal SPARQL language, leveraging the semantic relationships defined in the underlying ontologies. This represents a significant shift in the field of architectural conservation documentation, as it enables direct and structured inferencing to geometric, material, chronological, and decay-related information. Instead of relying solely on two-dimensional drawings—which often fail to fully capture the stratified complexity of historic architecture—restoration practices can work on a structured, queryable digital representation: a 'digital twin' of the building.

Thanks to the RDF encoding of information, it becomes possible to formulate descriptive, quantitative, and comparative queries, which are essential to support informed conservation decisions. Some examples of the kinds of queries that can be executed include:

"What percentage of brick masonry is affected by biological patina?" (Fig. 4). This query requires calculating the incidence of a specific decay (biological patina) on a given material (brick). In SPARQL, it may be expressed as:

```
SELECT (COUNT(?x) AS ?numBrick)
WHERE {
  ?x rdf:type ex:Material .
  ?x ex:hasType ex:Brick .
  ?x ex:affectedBy ex:BiologicalPatina .
}
```

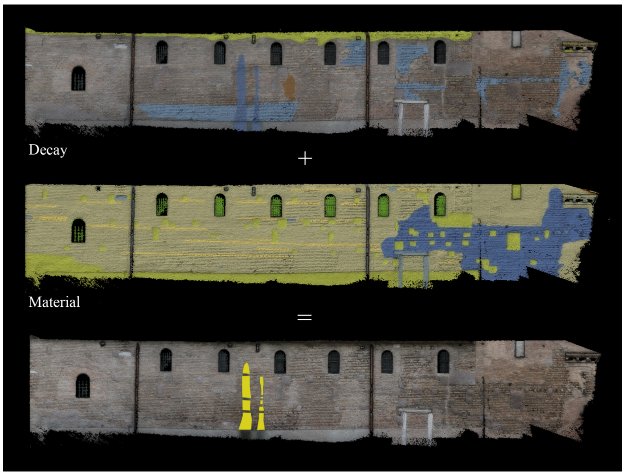

Figure 4. Example of the visualization of the third proposed query about the percentage of brick masonry affected by biological patina.

"Masonry from which historical period is affected the most by joint scour?". This query aims to correlate building chronology with a specific decay phenomenon. In SPARQL:

```
SELECT ?period (COUNT(?masonry) AS ?affectedWalls)
WHERE {
  ?masonry rdf:type ex:MasonryWall .
  ?masonry ex:hasChronology ?period .
  ?masonry ex:affectedBy ex:JointScour .
}
GROUP BY ?period
```

"What is the predominant construction technique in the 12th century?" (Fig. 5). This query involves counting and comparing instances of construction techniques associated with a specific chronological phase. In SPARQL:

```
SELECT ?technique (COUNT(?x) AS ?count)
WHERE {
  ?x ex:hasChronology ex:12thCentury .
  ?x ex:hasConstructionTechnique ?technique .
}
GROUP BY ?technique
ORDER BY DESC(?count)
LIMIT 1
```

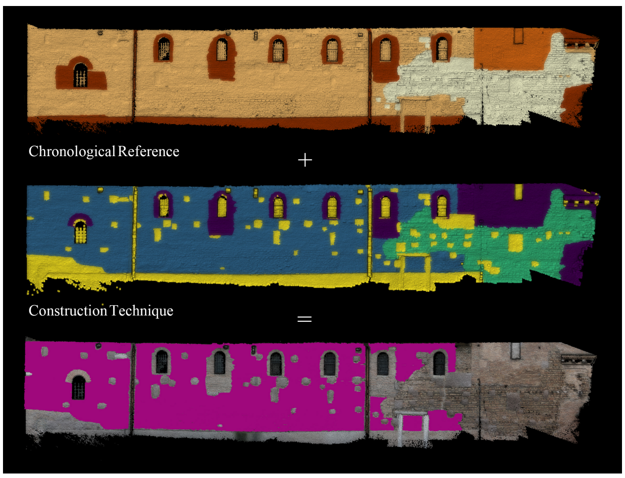

Figure 5. Example of the visualization of the third proposed query about the predominant construction technique in the 12th century.

These examples demonstrate how the semantically enriched 3D model—through the integration of ontologies and RDF data structures—enables in-depth queries into the material, constructive, and conservation-related characteristics of the building. The most innovative aspect lies in the possibility of conducting cross-analyses on features that are traditionally managed separately and statically in conventional 2D documentation workflows.

Operationally, this methodology functions as a decision-support tool for restoration, allowing professionals to highlight critical issues, identify recurring decay patterns, and correlate construction techniques with material vulnerabilities. It also ensures traceability and transparency in the rationale behind conservation choices.

The shift from static graphic drawings to queryable semantic models thus marks a substantial innovation in the field of architectural conservation. Working directly on the point cloud—i.e., on the three-dimensional, faithful survey of the building—makes it possible to preserve the inherent complexity of the built heritage. It offers a non-reductive, relational, and stratified reading of the architectural object. This approach opens up new possibilities not only for documentation and analysis but also for long-term conservation planning and preventive maintenance.

4. Conclusion and Future Perspectives

This paper presents the application of domain-specific ontologies to reality-based 3D model in association with its semantic annotation aimed at managing data resulting from annotations which document the consistency and conservation state of architectural heritage. By integrating three key dimensions—semantic, spatial and qualitative—the proposed model allows for both qualitative and quantitative information to be encoded within a shared knowledge base. The semantic correlation engine used supports a collaborative framework in which spatially referenced annotations can be created and semantically classified within a reality-based 3D representation. Through segmentation and annotation processes, architectural components are associated with their specific features, allowing for the generation of a multi-layered descriptive system.

Through a geometric analysis process and a dedicated segmentation and annotation phase, architectural elements are associated with their specific conceptual classes and attributes. Furthermore, the spatial overlapping of annotations across thematic layers generates a system of interconnections that allows users to extract data and relationships between descriptive classes via SPARQL queries. These aspects open up important perspectives for studying co-occurrences—such as the relationships between degradation phenomena, materials and diagnostic technique—and inferenced relations through the formalization via domain ontology concepts.

In this application, segmentation and annotation were performed directly on a discrete point cloud, rather than on a photogrammetric mesh. Each point was annotated semantically, demonstrating an approach to classification that does not rely on surface reconstruction or image masks. While the tools used were not initially designed for this specific purpose, they were adapted to meet the needs of the research, successfully validating the proposed methodology—albeit on a limited dataset.

It is important to note that this approach is not currently user-friendly and requires personnel with specific technical expertise. Nonetheless, the workflow has shown to be effective and replicable. Future developments aim to refine this methodology using more advanced and widely adopted tools for photogrammetric point cloud segmentation and annotation. These tools also offer the possibility to enrich the point cloud with additional metadata, external links and dynamic interactions, thus increasing both the interoperability and usability of the resulting semantic model.

The approach proposed in this study contributes to the ongoing development of scalable and interoperable 3D annotation workflows, integrating semantic and spatial dimensions to enhance current methodologies for the digital documentation and investigation of cultural heritage.

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