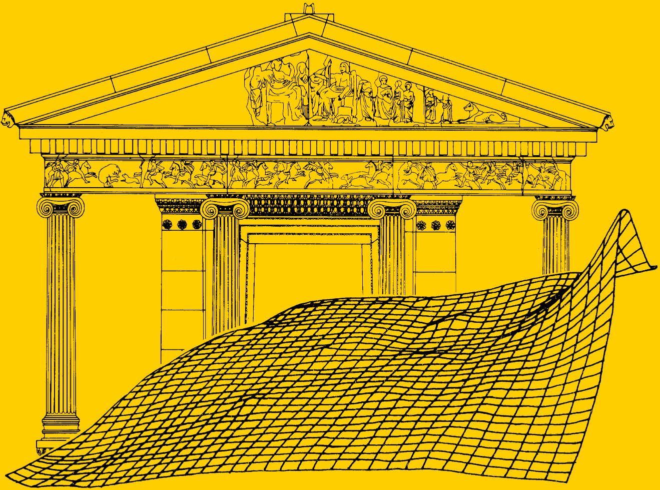

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INNOVAZIONI E TRADIZIONI TECNOLOGICHE PER LO STUDIO DEL PASSATO

Atti delle Giornate di Studio
“Archeologia e Nuove Tecnologie:
dalla teoria ai protocolli esecutivi”
(Siena, 25-27 ottobre 2023)

a cura di
Stefano Bertoldi e Luca Luppino

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Supplemento 13, 2025

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LEVERAGING LINKED DATA FOR ENHANCED KNOWLEDGE REPRESENTATION IN HISTORICAL CENTERS SAFETY ASSESSMENT: INSIGHTS FROM CASTELNUOVO DI PORTO, ROME

1. Introduction

The scientific community focuses several efforts on the conservation of historical centers due to their historical significance and their crucial role in society and the economy. In particular, residential architecture within historical centers, either listed or not, is a resource that defines the morphology and character of a historical center and contributes to its cultural and social identities. However, the structural conditions of these constructions often do not meet modern lifestyle standards, especially from the point of view of their structural safety. In this context, a major concern regards the so called 'masonry aggregates', namely groups of adjacent buildings structurally behaving as a whole, which demonstrated to be particularly vulnerable to seismic events (Carocci 2012; Battaglia *et al.* 2021).

The structural safety evaluation of masonry aggregates, and the consequent definition of an action plan for their conservation, requires a cognitive phase through an in-depth analysis of their features and preservation state (Carocci, Circo 2014). A large part of current guidelines focuses on the historical analysis, preliminary to numerical evaluation (Dipartimento di Protezione Civile, 2010). During analysis evaluation, the stakeholders involved make decisions that impact the numerical modeling (e.g. mechanical properties, types of structural discretization), which can significantly influence the results of the numerical simulation.

A critical point is the possibility of reaching an adequate understanding of the assessed building aggregate. This concerns especially the characterization of mechanical properties, since it is not often possible to perform very invasive tests on the constructions. For this reason, it is possible to refer to similar constructions for which data is accessible, to be compared to the data acquired in the field. In addition, it is possible to use reference values incorporated in National and International standards; as an example, in the Italian case, they are referred to from a typological analysis of the masonry, which can also be done with the help of a visual survey (Borri *et al.* 2015). Consequently, the knowledge analysis of masonry aggregates results in the generation of heterogeneous data that needs to be compared and interpreted.

In the Architecture, Engineering, and Construction Operation (AECO) sector, the past two decades have brought significant changes in the management of building-related data. More and more countries are gradually incorporating Building Information Modeling (BIM) into their regulations. While the emergence of this new methodology has shown positive effects in the sector, it has also introduced new challenges. In particular, the necessity of standardization of processes and training of experts to use this new tool is one of the main interests of the scientific community.

In the realm of built heritage, BIM has proven successful for different purposes (Gigliarelli *et al.* 2017; Piselli *et al.* 2020; Martinelli *et al.* 2022), including structural analysis (Crespi *et al.* 2016; Ursini *et al.* 2022a; Leonardi *et al.* 2024). However, a significant hurdle has been adapting a methodology originally tailored for new constructions to accommodate heritage buildings. A current trend involves the utilization of Linked Data and Semantic Web languages to enhance the capabilities of BIM, facilitating better representation of diagnostic data from surveyed buildings while also improving data interoperability (Berners-Lee *et al.* 2001). This is particularly relevant because existing BIM formats have shown limitations in describing historical building elements and interoperating with analysis/simulation apps. Hence, there is a growing adoption of ontologies in heritage (and non-heritage) applications (Cursi *et al.* 2022).

In the context of computer and information sciences, an ontology is a «formal and explicit specification of a shared conceptualization» (Gruber 2016). That is, an ontology defines a set of representation primitives with which to model a domain of knowledge or discourse. Representation primitives are typically classes (or sets), attributes (or properties) and relations (or relationships between class members). Definitions of representation primitives include information about their meaning and constraints on their logically consistent application. Because of their independence from lower-level data models, ontologies are used to integrate heterogeneous databases, enable interoperability between different systems, and specify interfaces for independent knowledge-based services.

Despite the ongoing efforts within the scientific community to propose various ontologies for buildings and heritage, there still needs to be a specific ontology tailored to handle both direct and indirect analysis of masonry buildings and aggregates in historical centers, particularly for structural analysis purposes. In a past contribution, the authors have proposed two ontologies with the aim of: (a) characterising the masonry at a morphological level (the Historic Masonry Ontology); (b) identifying the most probable collapse mechanisms (the Failure Mechanisms Ontology) (Leonardi *et al.* 2023). A new step is added in this contribution, by introducing the Historic Survey Ontology (HSV). The purpose of the HSV ontology is to represent the documentation associated with the construction under consideration, and it is used in conjunction with existing ontologies, to implement a comprehensive linked data model.

In this article, the methodology is tested on a masonry aggregate in the historical center of Castelnuovo di Porto, Rome. The case study demonstrates how the linked data approach enables a more coherent representation of the construction while maintaining connections between various data types, including books, site drawings, point clouds, photos and, more specifically, BIM models. Furthermore, the proposed methodology is designed to be scalable and can be applied to other case studies.

2. Critical analysis of the state of the art

The digitalization of the AECO sector marks a significant advancement in managing the design of new constructions and in preserving existing ones. One of the earliest approaches to digitising built heritage through modelling involves 3D surveying and modelling techniques, as well as the integration of 2D imagery to create realistic digital models, referred to as reality-based models (Jiménez Fernández-Palacios *et al.* 2017; Remondino *et al.* 2018; Cipriani *et al.* 2019). As a result, digital photogrammetry (Apollonio *et al.* 2021; Ulvi 2021) and acquisition with 3D laser scanners (Buscemi *et al.* 2020; Hamal *et al.* 2020) techniques gained prominence. At the same time, it was also realised the necessity of associating such comprehensive geometry with alphanumeric data. Hence, several efforts have been done to extend the BIM methodology to the built heritage, and it appears the acronym HBIM, with the meaning of Historic or Heritage BIM (Maurice Murphy *et al.* 2009; Logothetis *et al.* 2015; Pocobelli *et al.* 2018; Barontini *et al.* 2021).

Because BIM applications were originally developed for the design of new buildings, they often lack effective modeling tools to create geometries adherent to the needs of specialists involved in a process regarding the historical built environment. A current trend is the use of advanced acquisition methods, as a reference for implementing the model (Oreni *et al.* 2014; Rocha *et al.* 2020), even for structural analysis purposes (Castellazzi *et al.* 2015; Argiolas *et al.* 2019; Ursini *et al.* 2022). However, challenges are encountered in process automation and integration of the point cloud in the BIM logic (Werbrouck *et al.* 2020).

The issues are not only related to the software authoring tool, but also to the limitations of the most popular neutral exchange format, namely the Industry Foundation Classes (IFC), which does not allow a comprehensive representation of heritage objects, and the association of complex metadata with the model. Consequently, with the scope of overcoming the limitation of the semantic structure of IFC (Gómez-Romero *et al.* 2015), while improving interoperability with other tools (Turk 2020), several studies focus on the use of semantic web languages associated with BIM models (Cursi *et al.* 2022).

Specific extensive ontologies were proposed to represent museum collections (Crofts *et al.* 2003), architectural orders (Simeone *et al.* 2014), parts of religious buildings (Quattrini *et al.* 2015; Garozzo *et al.* 2017), non-destructive techniques for testing (Kouis, Giannakopoulos 2014).

Recent contributions, instead, preferred the use of more concise ontologies linked together, as a network of different domain modules (Bonduel 2021; Leonardi *et al.* 2023).

3. The Historic Survey Ontology

It is here proposed the Historic Survey Ontology (HSV), with the scope of connecting heterogeneous data (geometry in different formats, damage scenarios, materials), from different sources and types (images, point clouds, historical documentation, scientific articles, up to BIM models), encapsulating the knowledge gathered on a masonry construction (also during direct and indirect surveys performed to define structural modeling assumptions) in a single graphical database, taking into account the current guidelines and state of the art associated with the knowledge process of a masonry aggregate (Fig. 1). Moreover, it follows the idea of modularity, and was created to be used in conjunction with existing relevant ontologies.

The sources involved in the assessment of the construction are modeled in the *hvs:Document* class, and its subclasses: *hsv:Publication*, *hsv:Photo*, *hsv:Drawing*, *hsv:BuildingInformationModel*, *hsv:PointCloudData*. Each of these sources can be associated with a stakeholder, modeled using the class *hsv:Author* (for *hsv:Publication*, *hsv:Photo*, *hsv:Drawing*, *hsv:BuildingInformationModel*), *hsv:inspector* and *hsv:PostProcesser* (for *hsv:PointCloudData*) proposed as a subclass of the existing *foaf:Person* (Brickley, Miller 2000). In the domain of *hvs:Document* it is defined the property *hvs:filePath* (subclass of *owl:DataTypeProperty*) to link external files to the ontology, in the range *xsd:anyURI*.

The ontology extends beyond the scale of individual aggregates, enabling the modeling of knowledge indirectly associated with the aggregate under examination. For example, documentation about the historical center where the aggregate is situated can provide insights into the construction period. Similarly, information about a construction technique prevalent in the region during the aggregate's construction period may be available. In such instances, the ontology facilitates distinguishing whether the information pertains directly to the aggregate or to a broader area in which the aggregate is situated.

In particular, the *hsv:Region*, denotes a relatively large portion of the territory characterized by homogeneous constructions techniques in a specific period of time. Indeed, the concept of *hsv:TraditionalConstructionTechnique*

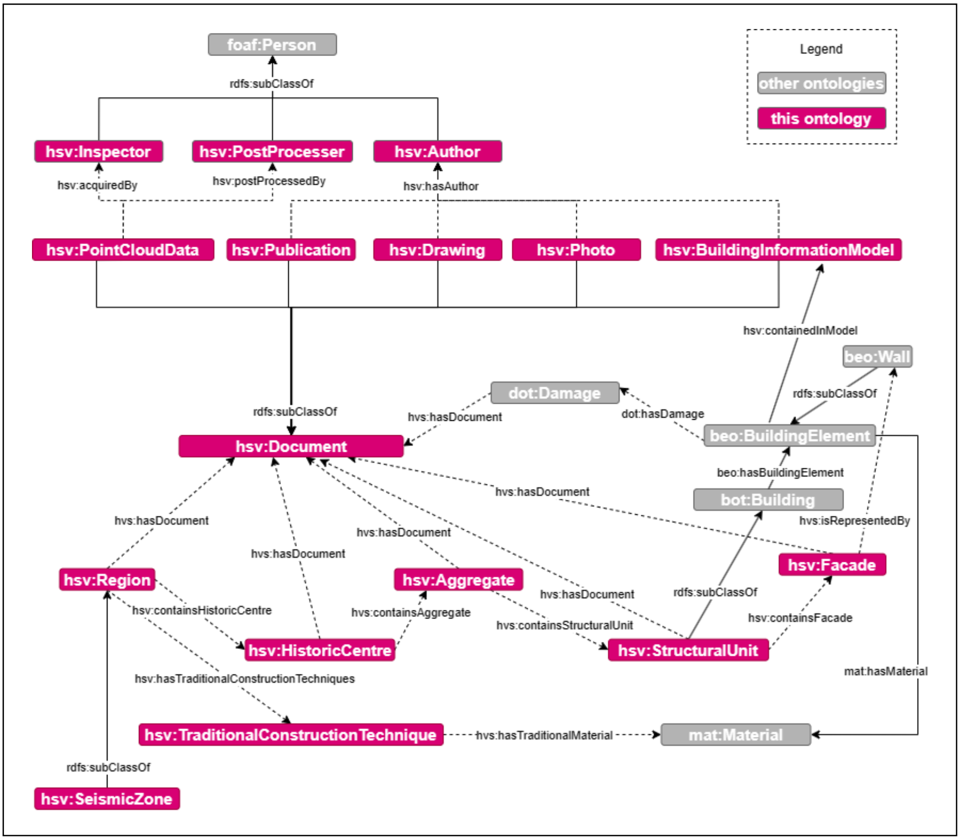


Fig. 1 – Overview of the HSV ontology.

is modeled as a class relating to a *hsv:Region*, by the object property *hsv:hasTraditionalConstructionTechnique*. Moreover, a *hsv:Region* can also be a *hsv:SeismicZone*, for delineating the territory's susceptibility to seismic hazards. Finally, the *hsv:HistoricCentre*, refers to a more delimited area representing the town where the building is situated.

On the building scale, the ontology distinguishes between *single buildings* and *aggregate buildings*. While existing BIM models and ontologies primarily focus on single buildings, the proposed ontology introduces the *hsv:Aggregate* defined as a 'collection of buildings exhibiting overall structural behavior'. In the aggregate, individual buildings are represented by the class *hsv:StructuralUnit*, considered equivalent to the class *bot:Building*. Structural units can be characterised by a specific 'position in the aggregate', modeled in the ontology as a ‘Data Property’. Moreover, the Building Element Ontology (BEO) (Pauwels 2018) and Material Property Ontology (MAT) (Poveda-Villalón, Chávez-Feria 2020) are used to model the building elements associated with the *hsv:StructuralUnit*. Using this, it is possible to map the information of the elements from the semantic model to a corresponding BIM model, by means of a common GUID between objects. Another concept included in the model is *hsv:Façade*, designed to represent the perimeter walls of a structural unit. This feature can be utilized to describe various aspects of façade walls, such as the arrangement of openings, and to link on-site data collection, such as photographs or drawings, to the model. Finally, the Damage Topology Ontology (Hamdan *et al.* 2019) is connected to the proposed ontology to describe the possible presence of damage.

4. Practical application of the linked data methodology

The ontology was tested on a case study, that is among the oldest of the historical center of Castelnuovo di Porto, Rome, dating back to the 13th and 14th centuries CE. The knowledge process of the aggregate involved several stages, both on-site and in-office. Visual and photographic surveys were done during the first visits. Drawings and annotations highlighting the key features of the construction were also made at this stage. Once that preliminary data was gathered, an advanced survey was conducted, during which point cloud data was collected using a movable scanner equipped with SLAM (Simultaneous Localisation and Mapping) technology.

In the office, the analysis primarily consisted of examining existing documentation about the historical center and a wider area. This stage allowed for a deeper understanding of plausible building types. Additionally, after each on-site phase, information was integrated into BIM and semantic models. A linked data approach was used to interconnect the information gathered.

4.1 *The historical center of Castelnuovo di Porto*

Castelnuovo di Porto is an Italian historical center located in the Roman Campagna, in the northern part of the metropolitan area of Rome (Fig. 2). The urban fabric is radial, developing around a focal point, the Colonna Castle. The history of this historical center began around the first half of the 10th century CE when the first medieval castle was constructed atop the ancient site of Pentapolis. Over the centuries, it was attacked by Saracens and Hungarians and suffered from a devastating fire. Survey findings indicate significant architectural resemblance among urban structures near the castle, characterized by shared typologies of construction techniques (Centroni, Castanoli 2007).

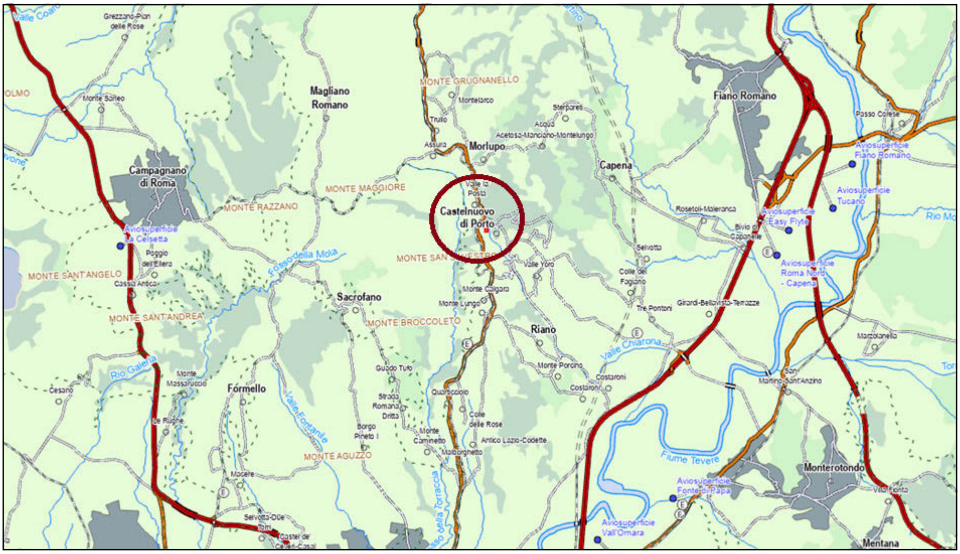


Fig. 2 – Location of the municipality of Castelnuovo di Porto in the Lazio region, along the via Flaminia (image from Google Maps)

The configuration of the built heritage residential buildings in Castelnuovo di Porto follows the inclined morphology of the site (Fig. 3). The residential units consist of basement rooms with access to the valley in the above-ground front and dwellings on the upper floors with upstream access. External accesses consisting of stone stairs (*profferli*) are particularly frequent.

The main load-bearing system consists of an unreinforced masonry wall, specifically built with the technique of '*muratura a tufelli*' (tuff-block masonry). This technique typical of Late antiquity appeared in the Roman Campagna in the second half of the 3rd century CE and was present in the north of Italy in the 1st century. At its origin, the technique consisted of parallelepiped tuff blocks distributed according to a regular running bond. In some cases, brick elements are present and placed in a quite regular manner. Over time, and especially during the Middle Ages, employing more irregular blocks of tuff became common due to the practice of reusing materials from existing fabrics (Esposito 1997). Several variants of this type of construction technique have been found in the historical center of Castelnuovo di Porto, differing in size and arrangement of the tuff blocks and the presence of brickworks. Especially when tuff blocks are irregular, the presence of more regular brick elements between tuff blocks is crucial since it increases the structural capacity of the masonry, improving the distribution of loads.

150/Planimetria generale di Castelnuovo di Porto
(dis. C. Panepuccia, G. Salvi).

Legenda

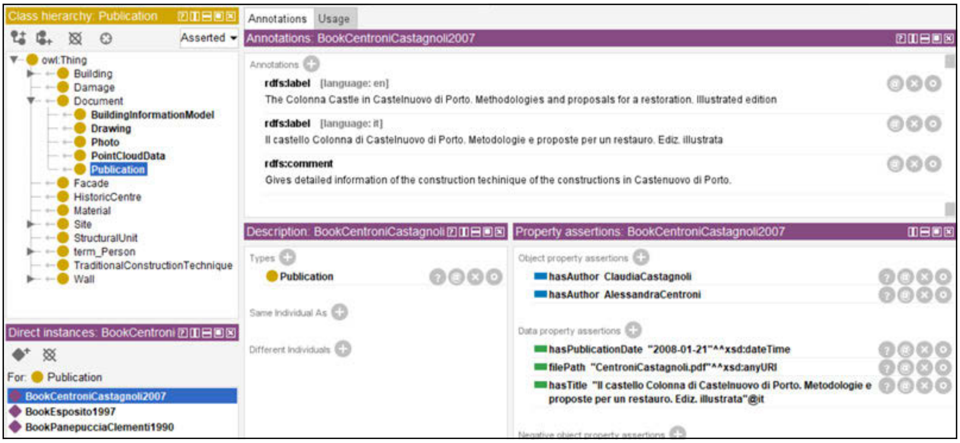
A — Rocca Colonna
B — Cattedrale di S. Maria Assunta
C — Palazzetto cardinalizio
D — Ex Oratorio della Confraternita del nome di Gesù e Compagnia del SS. Sacramento
E — Palazzo Paradisi
F — Palazzo già Miselli, ove soggiornò Carlo III di Borbone
G — Casa medievale già Colonna
H — Casa medievale con *profferta*
I — Palazzi ragguardevoli del sec. XVI
L — Palazzo ragguardevole con decorazioni a "punte di diamante" graffite
M — Porta *Maiori*
N — Porta *Vecchia*
O — *Particella*
P — per: chiesa Madonna delle Virtù; Osteria della Posta; chiesa SS. Agostino e Antonio Abate
Q — per la chiesa di S. Sebastiano
R — Corpo edilizio di difesa del sec. XV, demolito
S — già quartiere degli ebrei
T — Tom difensive del sec. XV

Fig. 3 – General plan of the historic center of Castelnuovo di Porto (Clementi, Panepuccia 1991). Note the central position and dominant profile of the castle in relation to the surrounding buildings of the old town, which develop in a ring-like layout.

In the urban fabric and in the castle, roofs and floors were originally wooden, but the on-site visit revealed the presence of concrete slabs in some portions of the assessed aggregate. Regarding openings (doors and windows), common types can be found in the castle and the smaller building aggregates. In particular, the oldest windows date back to the Middle Ages and are made of tuff lintels or arches. On the other hand, bigger windows of plastered bricks were opened during the Renaissance. Entrances typically consist of wide portals with stone arches, often featuring a double arch in cases of larger openings. Linteled doors, made of plastered bricks, are common as well. Finally, corner elements (*cantonali*) are often present to improve the bonding between orthogonal walls. In this case, larger and more regular tuff blocks are present.

4.2 *The linked data model*

The linked data model was done using the software Protégé (version 5.6.1). The first part of the modelling consisted of introducing the namespaces of all the ontologies required for the model and importing the classes and properties required. Afterwards, the individuals (specific instances of the classes) were added. External references in the documentation are linked to the model using a xsd:anyURL value. Using annotations, through the classes *rdfs:label* and *rdfs:comment*, it was possible to add detailed information in multiple languages. This aspect is relevant, for example, in the instances of the class *hsv:Publication*, as the books consulted were in Italian. Fig. 4 shows the model in Protégé, focusing on one of the instances of *hsv:Publication*,



BookCentroniCastagnoli2007
BookEsposito1997
BookPanepucciaClementi1990

rdfs:label [language: en]
The Colonna Castle in Castelnuovo di Porto. Methodologies and proposals for a restoration. Illustrated edition

rdfs:label [language: it]
Il castello Colonna di Castelnuovo di Porto. Metodologie e proposte per un restauro. Ediz. illustrata

rdfs:comment
Gives detailed information of the construction techinique of the constructions in Castenuovo di Porto.

Types: **Publication**

hasAuthor ClaudiaCastagnoli
hasAuthor AlessandraCentroni

hasPublicationDate "2008-01-21"^^xsd:dateTime
filePath "CentroniCastagnoli.pdf"^^xsd:anyURI
hasTitle "Il castello Colonna di Castelnuovo di Porto. Metodologie e proposte per un restauro. Ediz. illustrata"@it

Fig. 4 – Example of individual in the HSV ontology in Protégé.

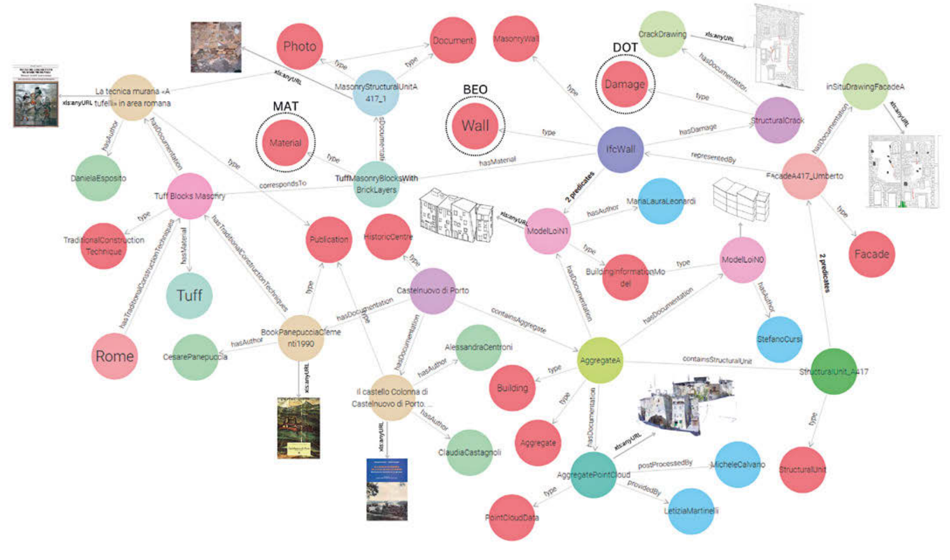


Fig. 5 – Overview of the linked data model.

showing the use of English and Italian annotations, Object Properties and Data Properties.

The integration with the BIM model relied on common GUIDs shared between the objects within the IFC file and corresponding classes in the associated ontologies. Specifically, these ontologies included the Building Element Ontology (BEO) and the Material Property Ontology (MAT). For this application, the IFC model was developed using the open-source software Blender (version 4.0) using the plugins 'Point Cloud Visualiser' and 'Blender BIM'. The Level Of Information Need used for this model is the one suggested in Leonardi *et al.* 2024, since the scope is the structural simulation. Regarding the material, the class of the MAT ontology and the IFC were used together with the class of *hsv:TraditionalConstructionTechnique*, assessed through 1) existing documentation such as the book of Esposito (Esposito 1997) together with 2) data gathered *in situ*. Finally, the presence of the damaged area was represented using the Damage Topology Ontology (DOT), linked with documentation gathered on site, such as drawings or pictures. The complete model was exported in the standard turtle format. Fig. 5 shows an overview of the application, highlighting how three textbooks were consulted: two specifically relative to the historical center of Castelnuovo di Porto, while the third about a wider area in the province of Rome. The latter shows how a document about a broader area provides insights regarding a specific construction technique (Tuff brick masonry), one of whose variants is present *in situ* (Tuff masonry block with brick layers) and to which photographic documentation also corresponds.

The figure also shows the integration of BIM, point cloud data, and hand drawings. The point cloud data and the BIM model are associated with the 'Aggregate' class. BIM is modelled as an external document to be associated with a Uniform Resource Identifier (URI), but more specific relationships are allowed using the BEO ontology. For instance, walls are not only modelled in the BIM model but also explicitly represented in the ontology to enrich the information.

In this application, drawings are associated with the facade class and allow the damaged scenario, which is also represented in the DOT ontology. Finally, it was possible to associate the documentation with different actors, whether authors of existing documents, models, or data collected *in situ*.

5. Discussion and conclusion

This article presented a new approach for connecting and managing data acquired during the knowledge phase for the structural assessment of masonry constructions in historical centers, to overcome the limits of traditional technologies.

The proposed methodology is based on the use of linked data technology. In particular, a new ontology was defined, the Historic Survey Ontology, to manage the documentation associated with different parts of the assessed construction. This ontology, combined with relevant existing ontologies, was used to assess an existing aggregate in the historical center of Castelnuovo di Porto, Rome. The practical application demonstrates how a linked data approach allowed a comprehensive representation and organisation of the knowledge acquired about the construction, by integrating various types of information into a single model, providing a detailed mapping of both the direct and indirect analyses performed, while maintaining links between diverse sources and tracking the involved actors. The linked data model is continuously updated while the historical assessment is performed. In this way, it is possible to collate the knowledge in the same system, avoiding incongruences and repetitions, and improving data interpretation. In this context, the BIM model is created specifically for structural simulation purposes. It's designed to contain only the necessary information for this task while remaining connected to the preliminary data that informed the final modeling assumptions. In this way, the semantics of the BIM model are incorporated into a larger integrated formal model, in which BIM entities, relationships and rules are combined with other concepts and relationships, extending the domain(s) represented and increasing the semantic level of the representation.

Drawing upon contemporary standards and guidelines, this approach will facilitate the deduction of additional data from the initial dataset. For instance, it will establish guidelines for modeling beam elements based on connection quality. Additionally, applying the method to a different case study, encompassing various aspects of requalification such as energy analysis, will enable to fully leverage the method's interoperability.

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ABSTRACT

The structural safety of built heritage (listed or not) is fundamental to the preservation of historical centers. In many cases, especially in Southern Europe, the different buildings of the urban fabric form a single yet complex structural compound. One of the most difficult phases of the assessment of these structures is the cognitive phase, necessary to develop a shared understanding of the building across various disciplines and areas of expertise, and, which involves the synergy of stakeholders with different backgrounds and the production of heterogeneous data. This article proposes a Linked Data methodology for managing this complex part of the assessment. This methodology is based on using the Historic Survey Ontology (HSV), which the authors developed to manage the documentation associated with various parts of the construction under consideration. HSV, used together with relevant existing ontologies, enables the management of heterogeneous data within a unified, comprehensive model, as demonstrated in the application to a study case.

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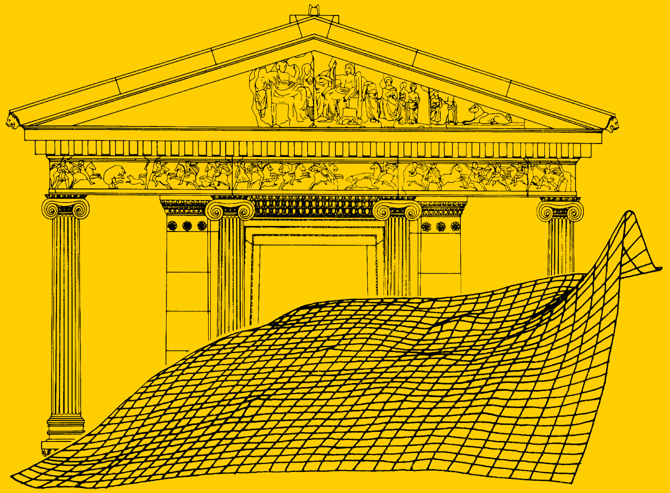

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