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Merging and Expanding existing Ontologies to cover the Built Cultural Heritage domain; case study Cuenca-Ecuador

Olga Zalamea

Supervisor(s):
Prof. dr. Thérèse Steenberghen
Prof. dr. Maarten Vergauwen

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MERGING AND EXPANDING EXISTING ONTOLOGIES TO COVER THE BUILT CULTURAL HERITAGE DOMAIN; CASE STUDY CUENCA, ECUADOR

Olga ZALAMEA PATIÑO

Supervisor:
Prof. dr. Thérèse Steenberghen

Co-supervisor:
Prof. dr. Maarten Vergauwen

Members of the Examination Committee:
Prof. dr. Anton Van Rompaey
Prof. dr. Koenraad Van Balen
Prof. dr. Sisi Zlatanova
Prof. dr. Verónica Heras

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Dedicatory

For you,
because of you Piedad Alejandra.

Para ti y
gracias a ti Piedad Alejandra.

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Abstract

Proper management of heritage cities requires data integration and coordination of multidisciplinary stakeholders. The integration of data involves a large amount of information, not only thematic but also spatial. With GIS and BIM being the most popular technologies used, there is a plethora of multi-scale information that is currently managed individually and has the potential to be integrated.

Traditional knowledge representation systems are typically centralized, requiring everyone to share exactly the same definition of a common concept. In addition, when a system is queried, an explicit understanding of the structure of the system is required. However, in a multidisciplinary domain as cultural heritage, it is difficult to share the same terminology and structure. Thus, it is necessary to build a flexible model that allows the harmonization of heterogeneous heritage information and the efficient querying of information. Flexibility allows the model to be easily adapted and to include the views of different stakeholders. This thesis proposes the reuse and extension of existing ontologies to fulfill these multi-scale information requirements of built cultural heritage management.

Ontologies are conceptual models with a flexible structure that, accompanied by linked open data principles, have demonstrated to be a suitable solution in domains such as Cultural Heritage. In these domains data come from several sources and in different formats, thus impeding the integration of the information. Most of the ontological work applied to Cultural Heritage so far has focused on intangible cultural heritage, movable heritage and archeological sites. For the immovable heritage such as historical buildings and monuments, there is still a need for deeper research to elaborate solutions that allow full integration of Built

Heritage data with data from other domains. In particular, it is necessary to integrate historical information with 2d and 3d spatial information, which is often handled in an isolated manner. The BCH-ontology is developed, verified and applied in Cuenca.

The Historic Centre of Santa Ana de los Ríos de Cuenca located in Ecuador, was registered in the World Heritage List in 1999. Cuenca, like other heritage cities, is facing harmonization challenges because of the way information has usually been stored and managed. In Cuenca a preventive conservation approach is used which considers periodic assessments of risks and threats and not only the assessment of state. It allows detection of damages in an early stage. Deterioration causes can be addressed first and intervention is kept to a minimum. The ontology created in this research is capable of representing preventive conservation information but also allows other approaches to be used.

The On-To-Knowledge methodology is applied in the ontology development process. This methodology comprises the Knowledge Meta process and the Knowledge process. In the Knowledge Meta process, terms related to preventive conservation are identified by means of a taxonomy which is later used to identify related existing ontologies. Three ontologies are identified and merged, i.e. Geneva City Geographic Markup Language (Geneva-CityGML), Monument Damage ontology (MONDIS) and CIDOC Conceptual Reference Model (CIDOC-CRM). Additional classes and properties are defined to provide a complete semantic framework for management of built cultural heritage called BCH-ontology which is later technically verified and improved. In this thesis we particularly take into account the built cultural heritage of historic buildings as well as their components, but we also study the context, such as sectors, building blogs, take and sections. In the Knowledge process, the BCH-ontology is validated through use cases where data provided by the stakeholders are translated into semantic means and are linked so that some basic queries can be executed. Further applications are then explored through workshops with the stakeholders, including governmental departments at local and regional level and research groups. Finally, specific examples show the general advantages of ontologies over traditional systems.

As a result, the BCH-ontology has been created as a contribution to the management of heritage cities specifically to reduce the problems of information heterogeneity. The local applications in which BCH-ontology can be used have been identified with the stakeholders, showing intra- and inter-institutional integrations. In the case of Ecuador, BCH-ontology also shows a practical case of implementation of the linked open data principles which have been included in the country's Open Data Law published in July 2022, which despite being in force, is not correctly applied yet due to lack of clear examples of its use. The BCH-ontology will help address this problem.

Resumen

La correcta gestión de las ciudades patrimoniales requiere la integración de datos y la coordinación de agentes multidisciplinares. La integración de datos implica trabajar con una gran cantidad de información, no sólo temática sino también espacial. Siendo el SIG y el BIM las tecnologías más utilizadas, existe una gran cantidad de información que actualmente se gestiona de forma individual y que tiene el potencial de ser integrada.

Los sistemas tradicionales de representación del conocimiento suelen estar centralizados y exigen que quienes lo usan compartan exactamente la misma definición de un concepto común. Además, cuando se consulta un sistema, se requiere una comprensión explícita de su estructura. Sin embargo, en un ámbito multidisciplinar como el patrimonio cultural, es difícil compartir la misma terminología y estructura. Por ello, es necesario construir un modelo flexible que permita la armonización de información patrimonial heterogénea y la consulta eficiente de la información. Esta tesis propone la reutilización y ampliación de las ontologías existentes para cumplir todos los requisitos de este contexto de patrimonio cultural multiescala.

Las ontologías son modelos conceptuales con una estructura flexible que, acompañados de principios de datos abiertos enlazados, han demostrado ser una solución adecuada en dominios como el Patrimonio Cultural. En estos dominios los datos proceden de varias fuentes y en diferentes formatos, lo que dificulta la integración de la información. Hasta ahora, la mayor parte de los trabajos ontológicos aplicados al patrimonio cultural se han centrado en el patrimonio cultural inmaterial, el patrimonio mueble y sitios arqueológicos. En el caso del patrimonio inmueble, como los edificios y monumentos históricos, sigue siendo

necesaria una investigación más profunda para elaborar soluciones que permitan la plena integración del patrimonio construido con datos de otros dominios. La ontología BCH se desarrolla, verifica y aplica con la colaboración de actores de interés de Cuenca.

El Centro Histórico de Santa Ana de los Ríos de Cuenca, situado en Ecuador, fue inscrito en la lista del patrimonio mundial en 1999. Cuenca, al igual que otras ciudades patrimoniales, se enfrenta a retos de armonización debido a la forma en que habitualmente se ha almacenado y gestionado la información. En Cuenca se utiliza un enfoque de conservación preventiva que considera evaluaciones periódicas de riesgos y amenazas y no sólo la evaluación de la condición de las edificaciones, permitiendo así detectar los daños en una fase temprana. Las causas del deterioro pueden abordarse en primer lugar y la intervención se reduce al mínimo. La ontología creada en esta investigación es capaz de representar información sobre conservación preventiva, pero también permite utilizar otros enfoques.

La metodología On-To-Knowledge se aplica en el proceso de desarrollo de ontologías. Esta metodología comprende el metaproceso de conocimiento y el proceso de conocimiento. En el metaproceso del conocimiento, los términos relacionados con la conservación preventiva se identifican mediante una taxonomía que posteriormente se utiliza para identificar las ontologías existentes. Se identifican y fusionan tres ontologías: Geneva City Geographic Markup Language (Geneva-CityGML), Monument damage ontology (MONDIS) y CIDOC Conceptual Reference Model (CIDOC-CRM). Se definen clases y propiedades adicionales para proporcionar un marco semántico completo para la gestión del patrimonio cultural denominado ontología BCH que posteriormente se verifica y mejora técnicamente. En el proceso de conocimiento, la ontología BCH se valida mediante casos de uso en los que los datos proporcionados por las partes interesadas se traducen a medios semánticos y se vinculan de modo que puedan ejecutarse algunas consultas básicas. A continuación, se exploran otras aplicaciones mediante talleres desarrollados con los actores de interés. Por último, ejemplos concretos muestran las ventajas generales de las ontologías sobre los sistemas tradicionales.

Como resultado, se ha creado la ontología BCH como contribución a la gestión de las ciudades patrimoniales, concretamente para reducir los problemas de integración de la información. Las aplicaciones locales en las que se puede utilizar la ontología BCH se han identificado con los actores de interés, mostrando integraciones intra e interinstitucionales. En el caso de Ecuador, ontología BCH también muestra un caso práctico de aplicación de los principios de datos abiertos enlazados que se han incluido en la Ley de Datos Abiertos del país publicada en julio de 2022, que a pesar de estar en vigencia aún no se aplica correctamente debido a la falta de ejemplos claros de su uso. La ontología del BCH contribuye a solucionar este problema.

Beknopte samenvatting

Aangepast beheer van erfgoedsteden vereist gegevens integratie en coördinatie van multidisciplinaire stakeholders. De integratie van data behelst een grote hoeveelheid van zowel thematische als ruimtelijke informatie. GIS en BIM zijn de meest gebruikte technologieën waardoor er momenteel een overvloed aan meerschalige, potentieel integreerbare informatie aanwezig is, die nog afzonderlijk wordt beheerd.

Traditionele kennis-representatie systemen zijn meestal gecentraliseerd, en vereisen exact dezelfde definities van gemeenschappelijke concepten. Bovendien is een expliciet begrip van de structuur van het systeem nodig om een bevraging te formuleren. In een multidisciplinair domein als cultureel erfgoed is het echter moeilijk om dezelfde terminologie en structuur te delen. Daarvoor is een flexibel model nodig dat de harmonisatie van heterogene erfgoed-informatie en efficiënte bevraging toelaat. Dit proefschrift stelt het hergebruik en de uitbreiding van bestaande ontologieën voor om te voldoen aan deze meer-schalige informatie-noden voor het beheer van gebouwd cultureel erfgoed.

Ontologieën zijn conceptuele modellen met een flexibele structuur die, samen met open data principes, een geschikte oplossing zijn in domeinen als Cultureel Erfgoed. In deze domeinen komen gegevens samen uit verschillende bronnen en in verschillende formaten, waardoor de integratie van informatie wordt belemmerd. In cultureel erfgoed staat ontologie het verst wat betreft immaterieel cultureel erfgoed, roerend erfgoed en archeologie. Voor het onroerend erfgoed zoals historische gebouwen en monumenten was er behoefte aan onderzoek naar oplossingen voor de integratie van gegevens van Gebouwd Erfgoed met

gegevens uit andere domeinen. Daarvoor werd de BCH-ontologie ontwikkeld, geverifieerd en toegepast in Cuenca.

Het historische centrum van Santa Ana de los Ríos de Cuenca, gelegen in Ecuador, werd in 1999 geregistreerd op de Werelderfgoedlijst. Cuenca wordt, net als andere erfgoedsteden, geconfronteerd met informatie harmonisatie-uitdagingen vanwege de manier waarop data gewoonlijk wordt opgeslagen en beheerd. In Cuenca wordt preventieve conservatie toegepast, niet alleen op basis van onderzoek van de toestand van het erfgoed, maar tevens rekening houdend met periodieke evaluaties van risico's en bedreigingen. Hiermee kan schade in een vroeg stadium worden opgespoord. Oorzaken van verval kunnen als eerste worden aangepakt waardoor ingrijpen tot een minimum wordt beperkt. De ontologie die in dit onderzoek is gecreëerd, laat toe om informatie over preventieve conservatie weer te geven, en laat ook andere toepassingen toe.

.De 'On-To-Knowledge' methodiek wordt toegepast voor het ontologie ontwikkelingsproces. Deze methodiek omvat het 'Knowledge Meta-proces' en het 'Knowledge-proces'. In het 'Knowledge Meta-proces' worden termen die verband houden met preventieve conservatie geïdentificeerd door middel van een taxonomie die later wordt gebruikt om verwante bestaande ontologieën te identificeren. Drie ontologieën worden geïdentificeerd en samengevoegd, namelijk Geneva City Geographic Markup Language (Geneva-CityGML), Monument Damage ontology (MONDIS) en CIDOC Conceptual Reference Model (CIDOC-CRM). Aanvullende klassen en eigenschappen worden gedefinieerd om een compleet semantisch kader -met name de BCH-ontologie- te bieden voor het beheer van gebouwd cultureel erfgoed. Deze BCH-ontologie wordt vervolgens technisch geverifieerd en verbeterd. In het kennisproces wordt de BCH-ontologie gevalideerd door middel van use cases waarbij gegevens die door de belanghebbenden worden verstrekt, worden vertaald naar semantische concepten en gekoppeld zodat basisquery's kunnen worden uitgevoerd. Verdere toepassingen worden vervolgens onderzocht in workshops die zijn ontwikkeld met de belanghebbenden. Tot slot tonen specifieke voorbeelden de algemene voordelen van ontologieën ten opzichte van traditionele systemen.

De BCH-ontologie is gecreëerd als een bijdrage aan de preventieve conservatie van erfgoedsteden, met name om de problemen van informatie-integratie te verminderen. De lokale toepassingen waarin BCH-ontologie kan worden gebruikt, zijn geïdentificeerd met de stakeholders, wat mogelijkheden voor intra- en inter-institutionele integratie aantoont. In het geval van Ecuador illustreert de BCH-ontologie ook een praktisch voorbeeld van de implementatie van de linked open data principes opgenomen in de open data wet van juli 2022. Hoewel van kracht, wordt deze wet nog niet correct toegepast bij gebrek aan duidelijke voorbeelden van de toepassing ervan. De BCH-ontologie draagt bij aan de oplossing dit probleem.

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Chapter 1: Introduction

In the current chapter, the features of Build Cultural Heritage (BCH) management in historical centres [Section 1.1], followed by the description of the preventive conservation approach [Section 1.2], and the tools for specific data management [Section 1.3] allow us to identify issues concerning cultural data integration in the heritage domain [Section 1.4]. The hypothesis pointing out to the applicability of ontologies for the BCH-domain [Section 1.5] lead to the selection of the research objectives: To build, evaluate and apply an ontology for the integration of BCH data [Section 1.6]. An overview of the whole document is presented at the end of the chapter.

1.1 World heritage definitions

The United Nations Educational, Scientific and Cultural Organization (UNESCO), established in 1945, is a great influence in the conservation of world heritage. Multiple guidelines and international treaties support conservation activities. The convention concerning the protection of the world's cultural and natural heritage adopted in 1972 classified cultural heritage (CH) as: Monuments, group of buildings and sites. According to the Valletta convention (ICOMOS, 2011), adopted by International Council on Monuments and Sites (ICOMOS) in 2011, a group of buildings refers specifically to urban areas and historic towns: "Historic towns and urban areas are made up of tangible and intangible elements. The tangible elements include, in addition to the urban structure, architectural elements, the landscapes within and around the town, archaeological remains, panoramas, skylines, view-lines and landmark sites. Tangible elements of historic towns are also referred to as BCH. Intangible elements include activities, symbolic and historic functions, cultural practices, traditions, memories, and cultural references that constitute the substance of their historic value."

International heritage soft-laws, "International Charters" and guidelines underline the necessity to integrate Cultural Heritage management with information from several sources such as legislative regulations, administrative measures and multidisciplinary studies about historic centres and urban areas (Australia ICOMOS, 2000; ICOMOS, 1987; World heritage centre, 2017). This multidisciplinary undertaking can benefit from other disciplines such as management of the natural environment, businesses, tourism, and finances (Chung, 2007). For example, indicators such as the level of pollution, vehicle vibration and rainfall can ensure a better estimation of the building vulnerability. However, this information is collected by different governmental or particular organizations. Additionally, residents' participation is also recommended because this allows for more accurate, up to date and detailed inventories since they interact with the heritage building daily. Traditional knowledge representation systems typically fail to manage multidisciplinary data.

According to Wu and Li (2006), a phenomenon's spatial or temporal dimension is known as scale, and information transfer between scales is scaling. BCH management implies multiscale operations at several geographic scales: city, zones or sectors, sites, buildings, among others. Inventories for example are typically performed at the level of the building but management decisions are taken at the level of the city or a sector. The demolition of a building has direct implications on the general appearance and composition of the sector. Conversely, conservation plans set at the level of the sector have effects on actions on individual buildings. Thus, scaling is crucial since a change on one geographic scale can impact another and has to be included in BCH analyses.

Geographic scales are represented by models where resolution is the smallest distinguishable part of an object (Tobler, 1988). For example, depending on the requirements for future analyses, a building could have a multiresolution representation such as a footprint, a cuboid, a solid shape or a very detailed 3D model with interior specifications and topological relations (Löwner et al., 2013). 3D feature models are popular among BCH-managers since they provide interesting possibilities for visualization and analysis(Deng et al., 2016). Recently 4D has also been included (Matthys et al., 2021). Due to the need to integrate multidisciplinary studies, the inclusion of multiresolution data should also be allowed.

1.2 Preventive Conservation

In order to control the properties listed in the World Heritage List (WHL) established two processes(World heritage centre, 2017): periodic reporting and reactive monitoring. The state parties report on the legislative and administrative provisions they adopted and on the state of conservation of the properties. Periodic Reporting is a long-term conservation tool that warrants the conservation of the properties and their outstanding universal values. Reactive monitoring is necessary when exceptional circumstances affect the outstanding universal value or the state of conservation of a property.

UNESCO does not suggest a specific method to be employed for the protection and conservation of the state parties' heritage. Instead, general guidelines specify that the state party should develop scientific and technical studies and research. In this regard, several UNESCO chairs are established to research specific methodologies such as Preventive Conservation Approach (PCA) (UNESCO, 2017).

For several decades the preventive conservation topic was discussed mainly for the management of collections of artifacts in museums. According to the Getty Conservation Institute (GCI) conservator activities should be focused on prevention and slowing the objects deterioration by controlling the environment where collections are located. This is not a feasible idea for BCH since most of the time the environmental conditions cannot be changed or optimized (Cardoso et al., 2018).

Preventive conservation of BCH considers periodic assessments of risks and threats and not only the assessment of state. It allows detection of damages in an early stage, deterioration causes can be addressed first and intervention is kept to a minimum (Forster & Kayan, 2009).

Della Torre (2010) proposed a PCA for BCH in three levels which later in 2015 are defined by Van Balen (2015): primary prevention aims to avoid the causes that produce the loss of heritage values; secondary prevention recommends monitoring the assets to achieve an early detection of symptoms; tertiary prevention aims to avoid spreading existing or new unwanted effects. Van Balen also pointed out that the aim is to maintain heritage values as much as possible within their social context. Analogously, as an example, in preventive medicine, these three types of prevention are also applied. Primary prevention is practiced prior to the origin of disease. It refers to means to avoid the causes of a disease. Secondary prevention is practiced after the disease can be recognized, but before it has caused suffering and disability. It refers to means to control a population on a regular basis in order to get an early detection of the symptoms of a disease. Tertiary prevention is practiced after suffering or disability has been experienced, in order to prevent further deterioration. It refers to means to avoid that a disease extends once it is present (Van Balen, 2015). Preventive conservation is essential for BCH management as it allows early detection of damages.

In 2009, the Raymond Lemaire International Centre for Conservation (RLICC) at the KU Leuven - Belgium, the Monumentenwacht Vlaanderen

(MWVl) and the University of Cuenca – Ecuador established the UNESCO chair on Preventive Conservation, Monitoring and Maintenance of Monuments and Sites (PRECOM^{3}OS). Its research and educational activities focus on the preventive conservation of monuments and sites. These activities are the development of tools and techniques, legal frameworks and policies to improve preventive conservation strategies in several social and cultural contexts (PRECOM3OS, 2009).

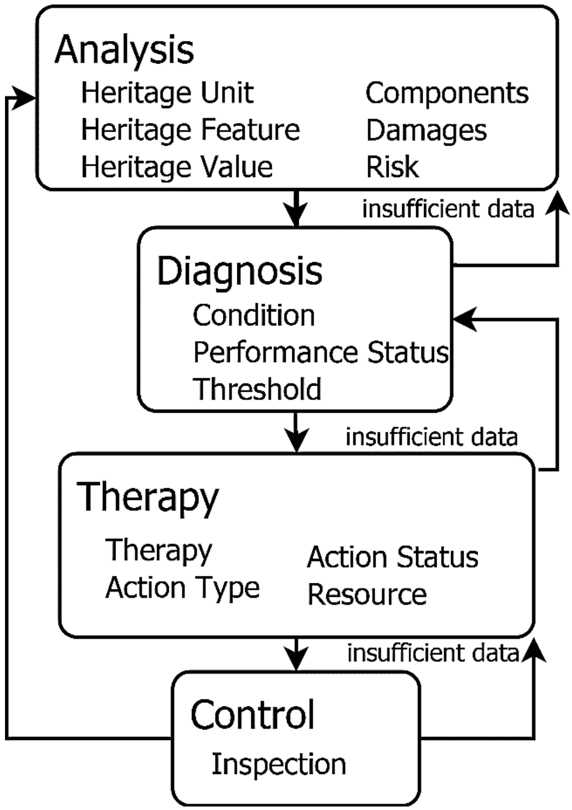


Figure 1.1 Conceptual diagram defining the data required in each phase of the Preventive conservation cycle (Heras, 2014).

The preventive conservation cycle (PCC) is a methodological model shared by the PRECOM^{3}OS associates. The model focuses on the ICOMOS Charter -Principles for the Analysis, Conservation and Structural

Restoration of Architectural Heritage (ICOMOS, 2013). It comprises four phases (Figure 1.1): the analysis searches for substantial information and data; during the diagnosis, the individual damage causes are identified; remedial measures are chosen during the therapy; and the control phase checks the efficiency of the interventions (ICOMOS, 2013).

Heras (2014) defined the specific information needed on each phase of the PCC through a data model based on a city geographic markup language Application Domain Extension(CityGML-ADE)(Figure 1.1). This model is a good guide for the design of heritage management systems.

1.3 Cultural heritage data management

Information about historical buildings needs to be represented, processed and shared by stakeholders. To this end, different technologies are developed with different purposes: data management, data exchange and data integration.

1.3.1 Data management tools

Data management tools aim to represent and process heritage data. The most popular technologies are: Geographic information systems (GIS) and Building information modeling (BIM).

Geographic information links location to other thematic information (Du et al., 2013; Longley et al., 1999). A GIS is a computer application capable of performing operations such as: acquisition, compilation, visualization, query, and analysis on geographic information. Some general purpose commercial software includes: Quantum GIS (QGIS) (QGIS project, 2018), ArcGIS (ESRI, 2001), SAGA (Conrad et al., 2015) and others.

GIS has been widely used in the heritage domain due to the powerful capabilities of this tool. One important feature is the focus on a territorial scale which allows users to manage large regions where heritage buildings are located. In the heritage domain there are several applications of GIS such as heritage inventories (Crlisle et al., 2014) and 3D analyses (Centofanti et al., 2012; Filip Biljecki et al., 2015; Karsli, 2003).

BIM are digital representations of facilities with physical and functional characteristics. They share the facility information to support decisions making during the building's life-cycle (National BIM Standard, 2018). Most of the work on BIM focuses on representing the condition of a facility as it was designed. This tool was designed to support the Architecture, Engineering, and Construction / Facility Management (AEC/FM) domain. Some examples of this tool are: ArchiCAD (Simmons, 1998), and Autodesk Revit (Autodesk, 2010). In the heritage domain we can find examples of heritage building restoration projects built for evaluation (Ciribini et al., 2015) and reconstructions of different periods of time (Barbato & Morena, 2017).

A special case of BIM applied to heritage data is Heritage Building Information Modelling (Heritage BIM, or HBIM). According to Murphy et al. HBIM is a complete mapping of a Cultural Heritage (CH) building (Murphy et al., 2007). HBIM does not only focus on the geometric representation of historical elements, but on the integration of these with non-geometric information. Archives, operational data, maintenance plans, condition surveys, archaeological investigations, material analysis, and other surveys stored in different formats such as tables, graphs, images, texts, links, etc. can provide a holistic view of a historic building (Yulia Gromova, 2019). Liu et. al (2022) present a current state of the art in this topic.

Saygi and Remondino (2013) made a comparison between GIS and BIM systems applied to the management of cultural properties pointing out the areas where one technology is better than others (Figure 1.2). GIS is mainly used to represent extensive terrain areas while BIM focuses on the individual representation of buildings. In the heritage domain, GIS is used to evaluate heritage zones such as neighborhoods or sectors of the city to determine, for example, the location of vulnerable buildings. BIM is used more in restoration projects where a very detailed representation of the building is needed. The same areas of BIM can be applied to heritage BIM.

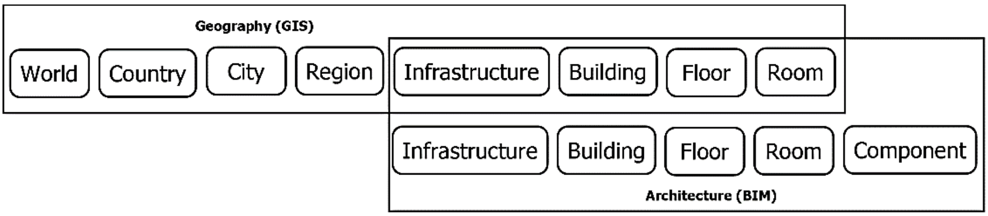


Figure 1.2 Spatial overlap in GIS and BIM. Adapted from (Saygi & Remondino, 2013)

1.3.2 Data exchange formats

In GIS and BIM each software has its proprietary representation. Exchange formats are used to translate information from one software to another. For example, when we want to use in QGIS a 3D model of a building created in ArchiCAD, the original file (ArchiCAD) has to be stored in some open intermediate format that can be interpreted by QGIS. These tasks are common when the information from several stakeholders is shared.

Exchange formats are independent of a particular software program. For 3D representations on GIS and BIM the most widely used formats respectively are: CityGML and the Industry Foundation Classes (IFC). There are several formats for exchanging 2D information such as shapefiles, geoJSON, and KML. Due to their longstanding history and common use, there is more compatibility between these formats than their 3D counterparts, and most applications provide transformations between these formats.

CityGML was created by the Open Geospatial Consortium (OGC) (Gröger et al., 2008). It is a semantic information model which allows the creation of 3D urban objects. It is an open data model based on extensible markup language (XML) capable of storing and exchanging virtual 3D city models. Perhaps the most important characteristics of CityGML are its applicability to different scales, from small areas to large regions, and its capability to characterize 3D objects and terrain in five levels of detail (LoD) (Figure 1.3). For instance, a building can be represented by a very simple model, containing only its footprint up to a very detailed model where the interior is also modeled.

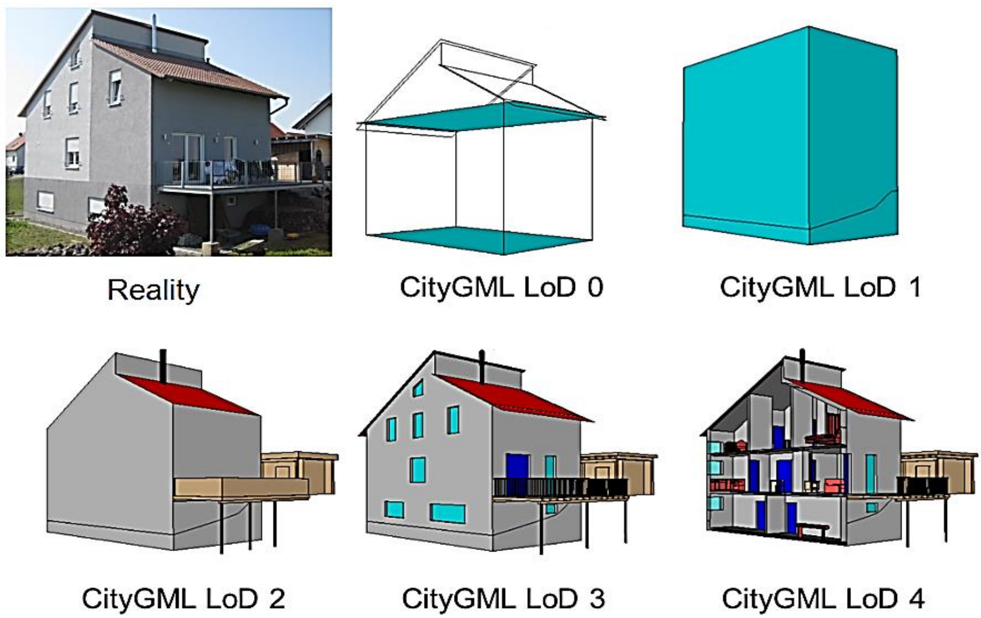


Figure 1.3 LoD at which CityGML standard can represent a real object. (Löwner et al., 2012)

IFC, is a standard created by buildingSMART (Liu et al., 2017). IFC files are platform neutral and can be read and edited by any BIM software enabling interoperability and collaboration within the industry (Dassault Systèmes, Spatial Corp, 2021). It contains more detailed information than CityGML (Liu et al., 2017). BIM integrates architectural, mechanical and structural tasks of a building (Figure 1.4). Arayici (2008)shows a BIM model example of an historical building from East Manchester which is stored using IFC format, so it can be shared among other users. Similarly, most BIM software are capable of storing models using the IFC format as is the case in Huber and Ciribini (2015).

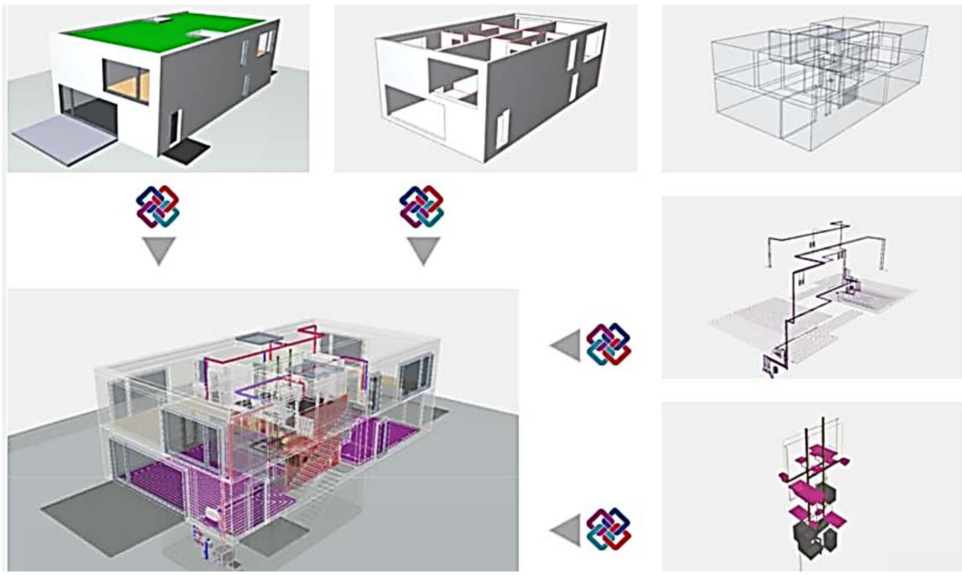


Figure 1.4 Architectural, mechanical and structural engineering tasks coordination during the design phase of IFC. (Liebich, 2014).

1.3.3 Data integration approaches

CityGML and IFC provide an open format for the 3D models generated by GIS and BIM. However, the integration of these two technologies is difficult due to their dissimilarities and mismatches (Liu et al., 2017). As shown in Figure 1.4 the geographic scale represented by them is overlapping to some extent. However, BIM provides more architectural detail than GIS, yet is only suitable for individual buildings. In addition, both formats represent objects differently. For instance, CityGML represents internal and external individual wall surfaces while IFC represents walls as a block.

Several approaches were created in an effort to overcome these matters. These approaches deal with the creation of new intermediate standards (Aien et al., 2015) and extending or transforming IFC or CityGML to support the other additional features (Geiger et al., 2015).

Another approach deals with the creation of reference ontologies. An ontology is a knowledge representation using predefined domain concepts and the relationship between these concepts (Menzel, 2003). A reference ontology carries knowledge from multiple domains and thus facilitates interoperability between them. For example, Deng et al (2016) suggest a semantic city model, an ontology that maps the differences between CityGML and IFC. Additionally, the authors propose an Application Domain Extension (ADE) for CityGML, thus a bidirectional transformation is possible without losing information.

As shown in Figure 1.5, each level is a step toward the heterogeneous data sets integration. In the following section we further explore the state of the art related to Semantic Web and the development of ontologies as integration tools.

In the BCH domain, management decisions are made at larger scales, such as the city or sector. Because of this, our research focuses on the representation of buildings in relation to the context in which they are immersed. In this sense we will focus on the use of GIS, rather than BIM.

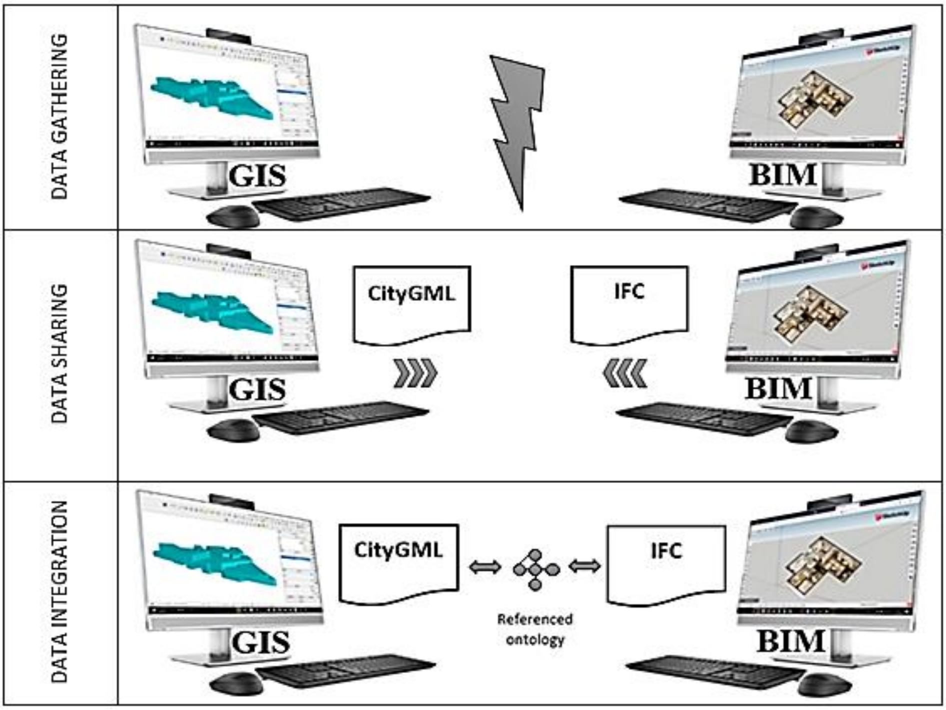


Figure 1.5 Data gathering software, data sharing formats and data integration technology.

1.4 Problem statement

The use of multi-user, multiscale and multiresolution BCH information results in a wide variety of datasets to be processed for different purposes. The BCH stakeholders' aim is to share and integrate the information generated by them in different systems, such as the traditional relational databases and geographic information systems. Several problems are identified when sharing and integrating data from such traditional systems:

● Modification of data models: A proper management of BCH requires data from several domains. For instance, the data about the constitution and condition of heritage buildings is complemented with a risk and threat assessment in the PCA. This assessment can follow any available methodology (Jimenez, 2001; Paolini et al., 2012; Wang, 2015), and it is common practice to try different methodologies. This switching of methodologies results in a complex problem of reengineering since applications, web services and any method employed to share the information have to be modified. To resolve this problem there should be a framework where information can be represented with a more flexible structure, allowing automatic integration of information.

● Harmonization of heterogeneous heritage information: Overlapping non-harmonized heterogeneous heritage information is gathered by several systems and the adoption of a common data model for all those systems is hardly possible (Heras, 2014). Agreements among the stakeholders are needed in advance to define the way the information is integrated but it is also critical to find a representation that is easily adaptable when an agreement has to change.

● Data querying: Relational databases or geographic information systems store information in tables for further querying and there has to be a prior understanding of this structure for querying to be possible. The information that can be queried has to be explicitly stored. Sometimes for a human user it is easy to identify other derived information. For example: the risk level based on the building condition and the damages reported, the heritage value based on the ornamental components, immaterial features and the employment of traditional building techniques. A traditional system that is queried regarding the risk level or the heritage value will only return what is stored in the tables without using inferences based on other attributes.

The following research questions arise from the problem statement:

RQ1: What are the BCH data issues of preventive conservation that cannot be resolved with traditional systems?

RQ2: What are the advantages and shortcomings of currently existing tools and methodologies for the construction, evaluation and use of ontologies for the integration of heterogeneous BCH information?

RQ3: Which ontology requirements can be derived from a use case for resolving the BCH data issues?

RQ4: Which new components can be developed and verified in a multidisciplinary, multiscale and multiresolution ontology for the BCH preventive conservation?

RQ5: How can the BCH preventive conservation ontology be validated through use cases?

1.5 Research hypothesis

The hypothesis of this research is that ontologies are applicable for data sharing and integration in the BCH -domain. However, current ontologies do not fulfill all requirements of this multi-scale Cultural Heritage context.

Ontologies promote discovery of new information by means of the use of logical inferences. Another hypothesis of this research is that these inferences can be applied for the specific BCH-domain.

1.6 Aim and general objectives

The general aim of this research is to create a formal ontology that merges existing ontologies and extends them in order to improve the data integration among stakeholders in the BCH domain, more specifically for Monuments and Sites.

The first specific objective is to **build** a BCH-ontology. This starts with the identification of available ontologies to represent BCH management characteristics. Once the ontologies are identified, we investigate to what extent the identified ontologies fulfil the BCH domain requirements. The identified ontologies are then expanded through the creation of new classes to fulfil the domain requirements, leading to the creation of the BCH-ontology.

The second specific objective is to **verify** the technical aspects of the proposed ontology. Technical and user evaluations are performed to ensure that the proposed ontology is well constructed and fulfils the user requirements.

The third specific objective is to **apply** the BCH-ontology in use cases illustrating its functionality and added value. In this regard, the use case will integrate different data from different stakeholders.

In addition this research investigates the added value of ontologies when compared with traditional approaches such as relational databases in a general context.

1.7 Thesis overview

The overview of this research is presented in Figure 1.6.

Chapter 2 provides a bibliographic overview of semantic web concepts, methodologies and tools for ontology construction, evaluation and population. As a result, the methodology and tools selected for this research are presented.

Chapter 3 presents the characteristics of BCH of Cuenca - Ecuador that makes it a suitable use case for this study. The tools developed by the stakeholders are presented; including a CityGML ADE model based on a PCA which is a first step into data integration. However there are still some semantic gaps impeding stakeholder collaboration in Cuenca which are presented at the end of the chapter.

The main new contribution of this research is presented in Chapter 4: the construction of the BCH-ontology for the documentation and management of BCH, which is then technically verified and its classes and properties are presented. A proof of concept shows how the PCC can be applied to a heritage building using this ontology.

In Chapter 5, the use of the ontology is validated through use cases where data provided by the stakeholders are translated into semantic means, linked and thus some basic queries can be executed. Further applications are explored with the main stakeholders in Cuenca. Then, general advantages of ontologies and considerations for the implementation of the BCH-ontology are discussed.

A general discussion and conclusions are presented in Chapter 6. First, the deliverables or this research are discussed. Then contribution to the BCH domain, the Spatial domain and the local situation of Ecuador are stated. Finally, perspectives for future work are provided.

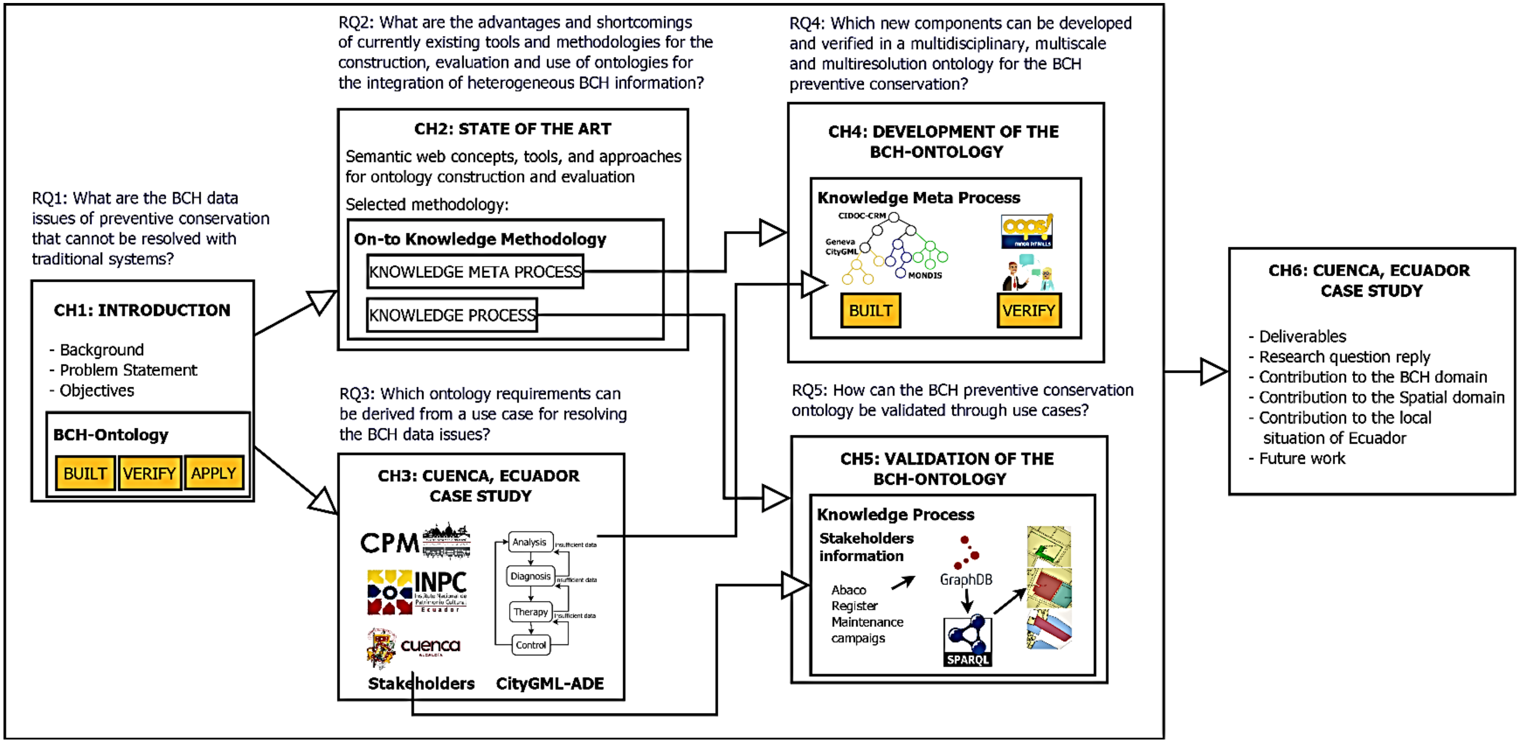


Figure 1.6 Diagram depicting the thesis overview.

Chapter 2: State of the Art

In this chapter, the state of the art of ontologies and semantic web concepts are presented [Section 2.1], followed by an assessment of semantic web methodologies and tools for building ontologies [Section 2.2], the ontology evaluation principles and tools [Section 2.3], and the approaches and tools for data population [Section 2.4]. As a result, the methodology and tools selected for this research are presented [Section 2.5]. Figure 2.1 shows the timeline of the tools explored in this chapter.

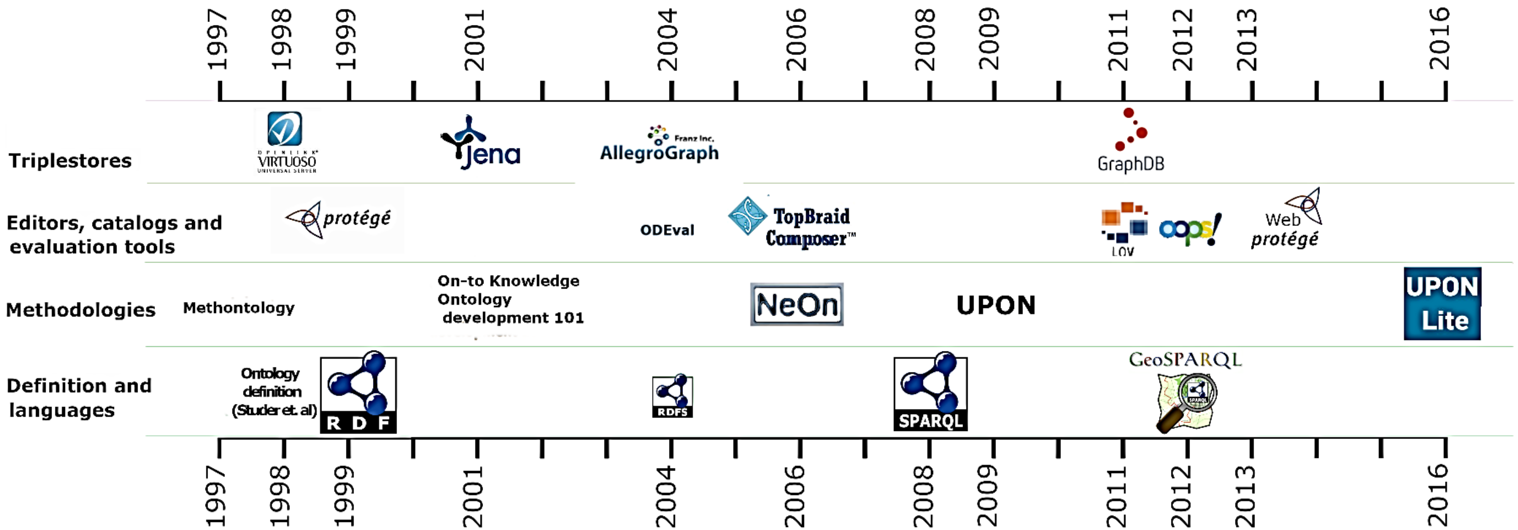


Figure 2.1 Timeline of semantic web tools.

2.1 Semantic Web

Tim Berners Lee (2001), in his introductory article defined the semantic web with a fully integrated example in which personal agents interact between each other in order to extract meaningful information from different systems. Berners Lee as well as other authors (Davies et al., 2006; Studer et al., 2007; W3C, 2011) characterized the semantic web with the following particularities:

- The Semantic Web is intended to be an extension of the World Wide Web (www) and not an independent web. Thus, information that is currently in the web can be reused;
- It should be as decentralized as possible;
- Data on the www will be interpreted by humans as well as by machines;
- Through the semantic web, new intelligent automated information processing will be achieved.

The tools to achieve Berners Lee's conception of the semantic web are Linked Data and ontologies.

2.1.1 Linked Data

Linked Data (Bizer et al., 2009)refer to structured data published and connected on the Web following a set of best practices. When these data is released under an open license, there are known as Linked Open Data (LOD[1]). Table 2.1 denotes the 5-star development schema (Berners-Lee, 2006) where the best practices for publishing data are listed.

[1] LOD Notice the difference between LoD = level of detail and LOD = linked open data

Table 2.1 Best practices for publishing data on the web (Berners-Lee, 2001).

★	Make your information available on the Web under an open license.
★★	Make it available as structured data.
★★★	Use non-proprietary formats.
★★★★	Use Uniform Resource Identifiers (URIs) to denote things, so that people can point at your stuff.
★★★★★	Link your data to other data to provide context.

A data provider gets more stars according to the number of best practices followed. If this provider's data are on the web under an open license, it gets one star; regardless of the format used: texts, images, audios, etc. If additionally these data are structured, e.g. organized in a spreadsheet, 2 stars are granted. Some data formats are proprietary, i.e. a special program (e.g. Microsoft Office) is required to interpret them. On the other hand, non-proprietary formats can be interpreted by a wide range of free or paid programs. The LOD recommendations award 3 stars when the data use non-proprietary formats. To explain recommendations 4 and 5, it is necessary to know that URIs are strings of characters that uniquely identify a resource, for example: a Uniform Resource Locator (URL) that identifies the location of a web page, a Digital Object Identifier (DOI) that identifies a scientific article on the web or an International Standard Book Number (ISBN) that identifies a book (W3C, 2001). So, 4 stars are obtained if URIs are assigned to the data, thus external sources can reference them. The complete schema is achieved when the scattered data are linked to each other to create relationships that provide more knowledge.

This schema is of great importance because when each step is understood, the advantages of integration and information recovery, are understood as well. The fourth star is reached with the use of URIs. This represents one of the major advantages of linked data that promotes information discovery as the data ceases to be textual and becomes an entity from which more information about itself can be discovered. The fifth star is related to the communication between data from different sources. It is, for example, about one actor saying: ‘this is what I understand by ‘historical building’ and another institution replaying: ‘I agree with this part of your understanding and additionally I handle this here’.

With the complete scheme, the automatic exploration of published data and the discovery of new relationships are favored. In this sense, data providers are the decentralized entities that Berners Lee talks about. The application of LOD recommendations only allows syntactic interoperability; additionally semantic interoperability is achieved by using ontologies.

2.1.2 Ontology definition

In any domain when exchanging data it is important to agree on what these data represent. Ontologies are important because they provide this additional context. The definition used by Studer et al. in 1998 (Studer et al., 1998) is the most common definition (Domingue et al., n.d.; Guarino et al., 2009) of an ontology: “Formal, explicit specifications of a shared conceptualization”. Gruber explains the definition of an ontology as follows (Gruber, 1993):

- Formal: The knowledge representation language used to express the ontology provides formal semantics. Thus, the specification of domain knowledge in an ontology is machine-processable and interpreted in a well-defined way.

- Explicit: Knowledge in an ontology is explicit and machine accessible. If the knowledge is not explicit, it is not part of the conceptualization interpreted by a machine.

- Shared: An ontology is the result of reaching consensus among the people of a community which define the domain conceptualization. This task becomes more difficult as the community is larger. Thus, an ontology is limited to a particular community.

- Conceptuality: Knowledge is specified in a conceptual way using terms of symbols representing concepts and their relations. Humans can intuitively assimilate these concepts and relations since they belong to our mental model.

Stakeholders of a domain agree on particular common terminology (concepts) and relationships that will be used to share their data. These agreements are formalized using a knowledge representation language creating an ontology. According to the level of specification of relationships and terminology, ontologies are classified as lightweight or heavyweight ontologies. Lightweight ontologies comprise concepts, concept taxonomies, relationships between concepts and properties that describe concepts; while heavyweight ontologies are lightweight ontologies plus axioms and constraints which clarify the intended meaning of the ontology terms. In the field of BCH, a lightweight ontology is needed, since the main aim of the stakeholders is to characterize BCH assets and their management. This first approximation will provide a good foundation for moving towards a heavyweight ontology. Nevertheless, it is not within the scope of this research to introduce complex reasoning.

2.1.3 Languages used to represent and query ontologies

The language selected to construct an ontology defines the level of expressiveness and reasoning. It is a tool for encoding domain knowledge and sometimes comprises reasoning rules for processing this knowledge. Additionally, the language used to query ontological data allows information retrieval. This section describes Resource Description Framework (RDF), Web Ontology Language (OWL), SPARQL Protocol and RDF Query Language (SPARQL) and Geographic SPARQL (GeoSparql).

Resource Description Framework

RDF is a data model standard for describing resources on the web developed by the World Wide Web Consortium (W3C) (2014a). It was created in 1999 and has been a W3C recommendation since February 2014.

Each RDF statement consists of a triple (Figure 2.2): a subject, a predicate (also called property) and an object. A subject is a resource from the world which can be identified. The predicate defines some characteristic or property about the subject (Figure 2.2a) or a relationship between two resources (Figure 2.2b). The object is the value of the property being described or another resource.

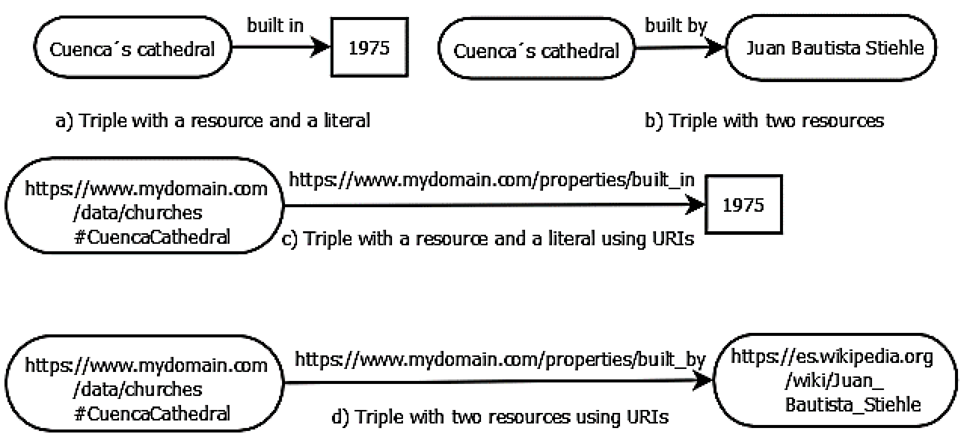


Figure 2.2 Triples examples: a) a triple with a literal as object. b) a triple relating two resources. c, d)triples a and b using their full URIs.

Resources are identified by URIs (W3C, 2001). HTTP URIs refer to identifiers that are available on the www, and from now on we refer to the latter as URIs. Each URI encodes both human-readable information (Hypertext Transfer Protocol-HTTP) and machine readable information (RDF). When an agent such as a web browser accesses a URI, it starts a content negotiation that displays the HTTP version of the resource (a web page). However, the URI can also be accessed by a computer program in which case an RDF document is retrieved, which can be interpreted by the program.

When URIs are used and organized in a hierarchical way, ontologies are created, which are nothing more than conceptual models that represent a domain. However, these models are flexible since they use the subject-property-object pattern that allows connecting new nodes and information networks according to the need for change, without affecting the remaining model.

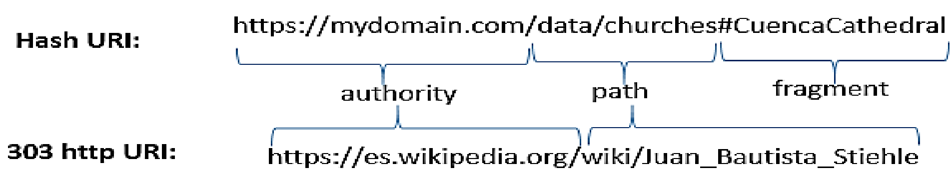


Figure 2.3 URIs components: authority, path, and fragment. Only hash URIs use fragments.

There are two approaches to defining URIs (Figure 2.3): 303 HTTP and hash URIs. 303 HTTP URIs consist of an authority and a path while hash URIs contain an additional fragment. For 303 URIs, an individual URI is assigned to each resource; hash URIs on the other hand combine resources into a single document. The application of one or the other depends on the domain and the way the resources are handled internally. In Cools URIs (W3C Interest Group, 2008) the advantages of the two approaches are compared: hash URIs can retrieve large datasets at once and therefore speed up access to information. On the contrary, if one needs information from specific resources it would be undesirable to retrieve information that is not of interest and hence 303 URIs are more inherent. URIs can become complex strings that are difficult to read and interpret, thus namespaces can be used. They define a prefix that simplifies the URI; in Figure 2.4 the prefixes ‘churches’, ’bchoPro’ and ‘wiki’ are used.

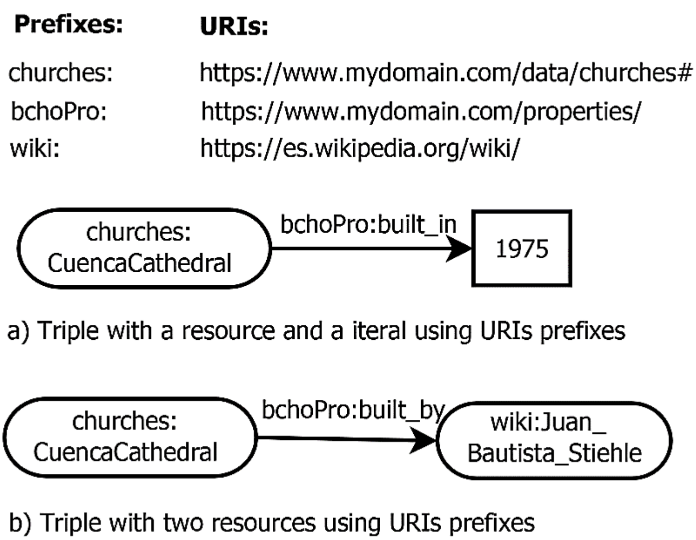


Figure 2.4 Triples examples from Figure 2.2 using prefixes ‘churches’, ’bchoPro’ and ‘wiki’.

In general, triples allow the representation of general facts, but sometimes facts are complex. For example, the address of the cathedral: this information could be stored as a string, also known as literal (Figure 2.5a), but some related meaning is lost. On the other hand, blank nodes can be used to represent that the address itself comprises several parts (Figure 2.5b). Blank nodes are used to represent complex data, they do not employs URIs, instead their names start with “_:”.

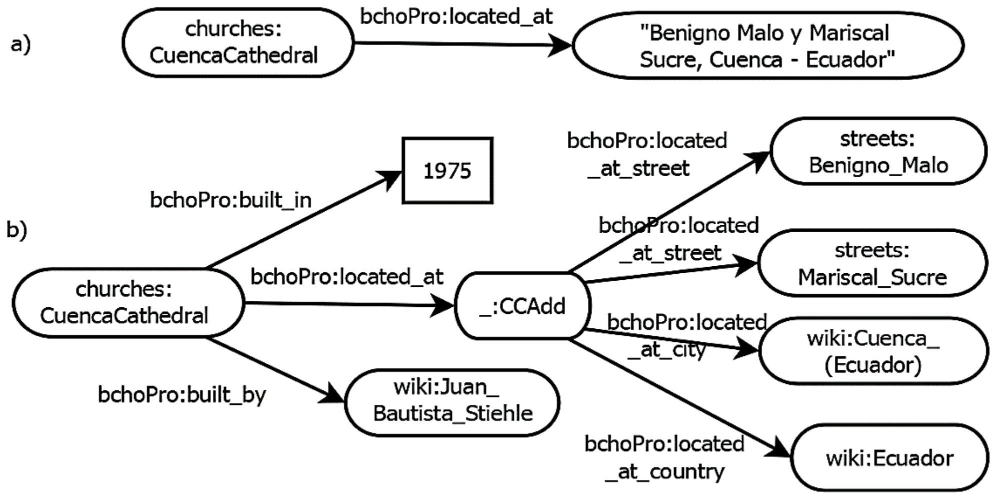


Figure 2.5 This example shows how the blank node '_:CCAdd' (b) can be used to provide more semantics than a literal (a).

A graph is composed of a collection of triples (Figure 2.6). In a graph, the subject and object are represented by nodes and the predicate by an arrow. There is a difference between nodes representing resources and literals, since resources allow obtaining more information. Graphs can be stored using different formats, Table 2.2 shows N-Triple and Turtle formats of the graph created with the triples from Figure 2.6. These formats are the longest and most compressed formats respectively.

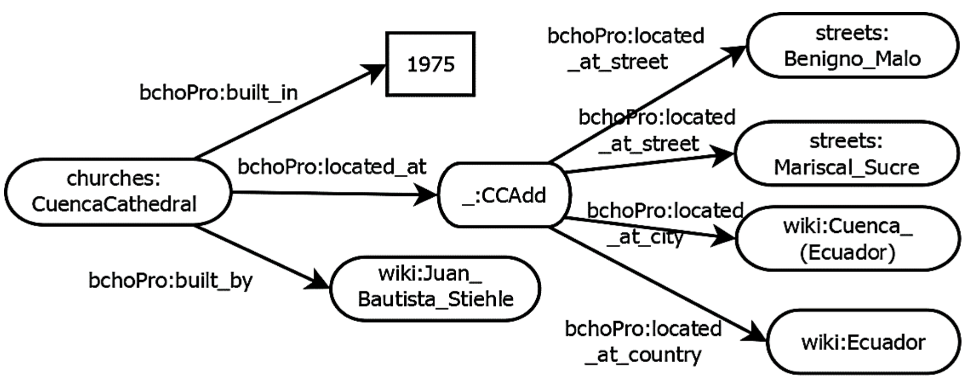


Figure 2.6 Graph created with the triples from figures 2.3 and 2.4b.

Table 2.2 N-Triple and Turtle formats of the graph in Figure 2.6

XML with prefix

```
<https://BCHOntology/data/churches#CuencaCathedral>
<https://BCHOntology/properties/built_on>
“1975”^^ http://www.w3.org/2001/XMLSchema#dateTime.

<https://BCHOntology/data/churches#CuencaCathedral>
<https://BCHOntology/properties/built_by>
<https://es.wikipedia.org/wiki/Juan_Bautista_Stiehle>.

<https://BCHOntology/data/churches#CuencaCathedral>
<https://BCHOntology/properties/located_at> <_:CCAdd>.

<_:CCAdd>  <https://BCHOntology/properties/located_at_street>
<https://BCHOntology/data/streets#Benigno_Malo>.

<_:CCAdd>  <https://BCHOntology/properties/located_at_street>
<https://BCHOntology/data/streets#Mariscal_Sucre>.

<_:CCAdd>  <https://BCHOntology/properties/located_at_city>
<https://es.wikipedia.org/wiki/Cuenca_(Ecuador)>.

<_:CCAdd>  <https://BCHOntology/properties/located_at_country>
<https://es.wikipedia.org/wiki/Ecuador>.
```

Turtle

```
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix wiki: <https://es.wikipedia.org/wiki/> .
@prefix bchoPro: <https://BCHOntology/properties#> .
@prefix churches: <https://BCHOntology/data/churches#> .
@prefix streets: <https://BCHOntology/data/streets#>.

churches:Cuenca  bchoPro:built_on     "1975"^^xsd:dateTime;
                 bchoPro:built_by     wiki: Juan_Bautista_Stiehle;
                 bchoPro:located_at         _:CCAdd.
_:CCAdd          bchoPro:located_at_street  streets:Benigno_Malo,
                                           Mariscal_Sucre;
                 bchoPro:located_at_city    wiki:Cuenca_(Ecuador);
                 bchoPro:located_at_country wiki:Ecuador
```

Resource Description Framework Schema

RDFs is an extension of RDF created in 2004 and provides the elements to describe the RDF data model (W3C, 2014b). A resource can be a class, an instance, a literal or a blank node. Literals and blank nodes have been previously described. A class (rdfs:class) comprises resources with common features, such as the class ‘Buildings’ which may contain the buildings in a city. In addition subclasses (rdfs:subClassOf) are used to shown a specification of class, for example ‘historicalBuildings’ is a specification of the class ‘Buildings’. The property rdfs:subClassOf describes a hierarchical relationship between classes but with this simple property, subclasses are able to use all the properties of the parent class without specifying anything else.

Properties are used to describe resources: the ‘rdf:type’ property specifies the type of resource. ‘rdfs:domain’ and ‘rdfs:range’ describe a resource as a property. The ‘built_in’ and ‘built_by’ properties (Figure 2.7) have ‘CuencaCathedral’ as domain and ‘1972’ and ‘Juan_Bautista_Stiehle’ as range respectively. The triple the ‘HB45 Performance Status - PHB15 has therapy - HB48 Therapy’ implies that a therapy was assigned based on a status performance. In case there is data on the therapy and not on the performance status, anonymous nodes can be created, since the definition of the property says that a therapy is assigned on the basis of a performance status. This design is not possible in traditional systems, which also shows the flexibility of the ontology model.

There are also subproperties(rdfs:subPropertyOf) which show a specification of a more general property. Additionally, RDFs also provides human-readable versions of names (rdfs:label) and comments (rdfs:comment) of resources. Figure 2.8 shows an example of the RDFs elements.

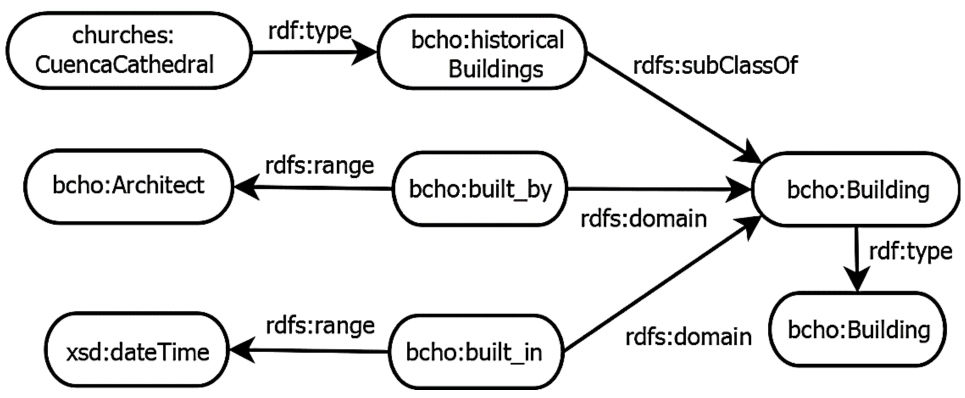


Figure 2.7 Shows example of classes, subclasses and properties.

Web Ontology Language

OWL (W3C, 2013a) was created by the W3C web ontology working group in 2004. The latest version (OWL 2) was created in 2009. OWL 2 is capable of representing more complex information than RDF and does so in two forms: RDF-Based semantics (graphs), also known as OWL 2 Full, and description logics (OWL 2 DL) which are known as Direct semantics. In general OWL 2 extends RDF implementing logical operations such as intersection, union, negation, universal and existential quantifiers, equivalent classes and properties, among others. Some special properties such as: inverse, reflexive, symmetric and transitive (W3C, 2013b) are also defined. A reasoner is a software that can deduce logical consequences, OWL 2 Full implements so many logical operations that a reasoner cannot be executed correctly. On the other hand, OWL DL is a restricted version of OWL 2 Full which allows a reasoner to be able to work with the complete OWL DL language.

Since OWL 2 Full is too complex and extensive for a reasoner, there are three profiles (subsets) of OWL 2 Full, none of which implements negation or conjunction. OWL 2 EL allows basic reasoning and is particularly useful for ontologies containing a large number of properties and classes. OWL 2 QL is used on ontologies with large number of instances where query answering is the main reasoning activity. OWL RL is used for heavy reasoning but expressivity level is very low.

For our cultural heritage ontology the use of OWL is required since basic inferences are needed to find relationships between data from the different stakeholders. The specific profile (EL or QL) is chosen according to the number of classes the ontology has. RL is less suited for our needs because of its low expressivity level.

In our example, in the 'Buildings' class, each building is known as an individual (owl:NamedIndividual). The properties 'built_on' and 'built_by' are known as 'owl:DatatypeProperty' and 'owl:ObjectProperty' respectively (Figure 2.8).

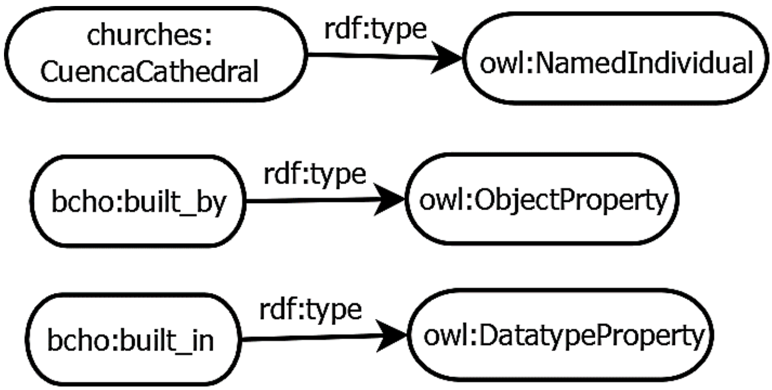


Figure 2.8 Shows examples of individuals, data properties and object properties.

RDF provides a basic representation. According to our criteria, if the goal of an information provider is to make its RDF data available, RDF is sufficient. However when the purpose is to integrate information, OWL is necessary, in particular the use of owl:sameAs property.

SPARQL protocol and RDF Query Language

SPARQL is an official W3C recommendation since January 2008. The current version is SPARQL 1.1 (W3C, 2013a). It is a RDF query language that allows the manipulation and retrieval of RDF data, similar to the Structured Query Language (SQL) for querying databases.
Figure *2.9* shows an example of SQL and SPARQL queries over the same information.

Although apparently, the results are the same there are two fundamental differences: the first is the use of triple patterns for the execution of SPARQL queries and the second is that the results are expressed as URIs so it is always possible to get much more information from this resource. In SQL the results are just text.

SPARQL queries are executed on a set of triples creating a basic graph pattern. Triple patterns have variable subject, predicate, or object. Figure 2.9 (bottom) subject and object are variables. The result is the subgraph of the RDF data that matches the basic graph pattern Figure. 2.10 (W3C, 2013b).

Table Buildings

id	name	construction Date	constructor
1	Cuenca Cathedral	1972	Juan Bautista Stiehle

Table Addresses

building Id	street1	Street2	city	country
1	Benigno Malo	Mariscal Sucre	Cuenca	Ecuador

SQL QUERY

```
Select name, constructiondate, constructor, city
From buildings, addresses
Where buildings.id=addresses.buidingId
```

Result

Cuenca Cathedral	1972	Juan Bautista Stiehle	Cuenca

SPARQL QUERY

```
@prefix bchoPro: https://BCHOntology/properties#.
Select name, constructiondate, constructor, city
{?name bchoPro:built_on ?constructionDate.
 ?name bchoPro:built_by ?constructor.
 ?name bchoPro:located_at ?x.
 ?x bchoPro:located_at_city ?city.
}
```

Result

Churches: Cuenca	“1972”^^ xsd:dateTime	Wiki:Juan_Bautista _Stiehle	Wiki:Cuenca_ (Ecuador)

Figure 2.9 Example of SQL and SPARQL queries over the same information.

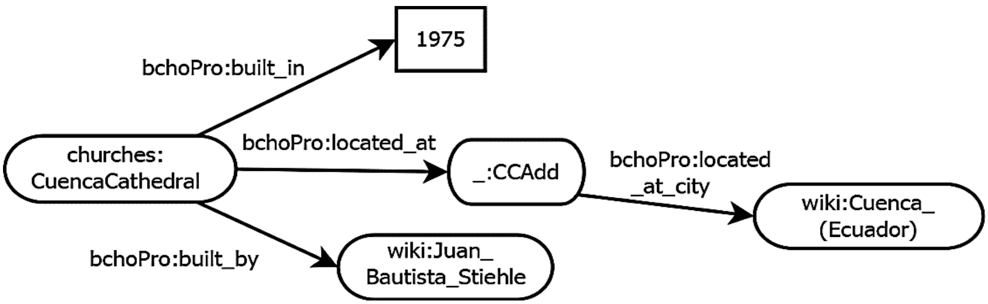


Figure 2.10 Subgraph that matches the basic graph pattern of the SPARQL query in Figure 2.9

Table 2.3 shows an example of a simple SPARQL query. The 'select' clause contains the variables that are part of the result. This example queries for the building identifier and the ownership of the set of triples in the data file. The 'where' clause shows the basic graph pattern that triples must match to be part of the answer. In this case, the query is asking for an instance '?x' that has a buildingID and an ownership. In SPARQL, variables are named with a question mark in front of the variable name. The period at the end of the first triple pattern denotes that both conditions must be true, thus the buildingID "0102030002" is not part of the answer since it does not satisfy the second condition.

Table 2.3 SPARQL query example.

Data	**Query**

_:a buildingID "0102030001"
_:a ownership "private"
_:b buildingID "0102030002"
_:b floorsNumber 2
_:c buildingID "0102030003"
_:c floorsNumber 1
_:c ownership "public"
_:d buildingID "0102030004"
_:d ownership "private"
	SELECT ? Identifier ? Ownership
	WHERE
	{
	?x buildingID ?Identifier.
	?x ownership ? Ownership
	}

Query result:	
Identifier	**Ownership**
"0102030001"	"private"
"0102030003"	"public"
"0102030004"	"private"

Regular expressions (Table 2.4) can also be used on queries. The following example shows a filter in which the buildingID must contain the number "0102030".

Table 2.4 SPARQL regular expressions.

Query	
SELECT ?Identifier WHERE { ?x buildingID ?Identifier. FILTER regex (?Identifier, '0102030') }	**Query result:** **Identifier** "0102030001" "0102030002"

SPARQL queries can also be executed as federated queries, which are queries directed to some specific SPARQL endpoint. A SPARQL endpoint is a web service that allows querying a knowledge base through the SPARQL language. In this sense, a complex query can be fragmented and executed in several endpoints and at the end the answer is combined. More information about SPARQL can be found in SPARQL 1.1 Overview (W3C, 2013a).

Geographic SPARQL

GeoSparql is a spatial extension to the SPARQL query language for geographic information, created in 2012. It provides the following features: An RDF/OWL vocabulary for representing spatial information, a set of SPARQL extension functions for spatial computations, and a set of Rule Interchange Format (RIF) for query transformation. GeoSparql does not define a comprehensive vocabulary for representing spatial information. It instead defines a core set of classes, properties and datatypes that can be used to construct query patterns (Perry & Herring, 2012; W3C, 2013b, 2013c).

The main classes geo:SpatialObject, geo:Feature, geo:Geometry allow the representation of spatial objects. Geo:Feature represents the object itself and geo:Geometry represents the geometry of that object. Some important properties are geo:hasGeometry, geo:dimension, geo:asGML and geo:asWKT. Main datatypes are geo:gmlLiteral and geo:wktLiteral. These properties and datatypes allow the representation and serialization of geometries.

The following example shows the geometry definition of a building. In this case Well-known text (WKT) representation is used to define a 2D polygon. Geometries can also be defined with Geography Markup Language (GML). Figure 2.11 shows the graph of Table 2.5.

Table 2.5 Geometry definition example.

Subject	**Predicate**	**Object**
data:CuencaCathedral	rdf:type	geo:Feature
data:CuencaCathedral	geo:hasGeometry	data:CathedralGeom1
data:CathedralGeom1	rdf:type	geo:Geometry
data:CathedralGeom1	geo:asWKT	"http://www.opengis.net/def/crs/EPSG/0/32717 Polygon ((7211.780 96793.840, ..., 7211.7807 96793.8402))"^^ geo:wktLiteral.

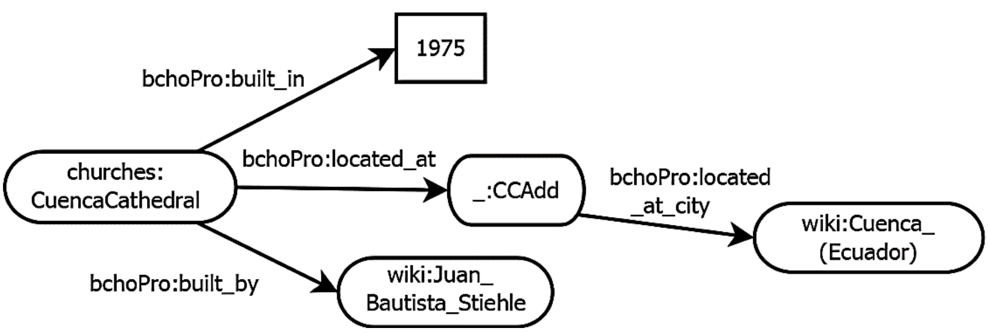


Figure 2.11 Spatial object definition. Cuenca Cathedral has a geometry which is defined as a polygon.

GeoSparql also employs some extensions (Table 2.6) to define geometric functions.

Table 2.6 Spatial functions from Sparql extensions (Perry & Herring, 2012).

Simple Features Topological Relations	**Egenhofer Topological Relations**	**RCC8 Topological Relations**
geo:sfEquals geo:sfDisjoint geo:sfIntersects geo:sfTouches geo:sfWithin geo:sfContains geo:sfOverlaps geo:sfCrosses	geo:ehEquals geo:ehDisjoint geo:ehMeet geo:ehOverlap geo:ehCovers geo:ehCoveredBy geo:ehInside geo:ehContains	geo:rcc8eq geo:rcc8dc geo:rcc8ec geo:rcc8po geo:rcc8tppi geo:rcc8tpp geo:rcc8ntpp geo:rcc8ntppi

The query languages SPARQL and GeoSparql present sufficient, uncomplicated features similar to SQL to facilitate their adoption by proficient SQL users. On the other hand, they also present their own features that make them powerful, such as the use of the subject-predicate-object pattern and the use of logical expressions. GeoSparql allows performing geographic operations which gives it a great advantage over SPARQL, however, its main limitation is that it works in 2D, thus 3D support cannot be implemented unless it is basic information, and then only using tricks, such as those presented in Annex I. In this research the spatial component is of great importance so GeoSparql will be used.

2.2 Ontology engineering

This section describes methodologies for building ontologies, ontology editors, and ontology catalogues.

2.2.1 Ontology development methodologies

Several methodologies have been proposed regarding the development process of ontologies. Gomez-Perez et al. (2004) described and compared different methodologies such as: Cyc (Elkan & Greiner, 1993), Uschold & King (1995), Grüninger & Fox (1995), Kactus (Ath et al., 1995), Methontology (Gómez-Pérez & Fernández, 2007), Sensus (Swartout et al., 1997), and On-To-kowledge (S. Staab et al., 2001). Later, Casellas (2011) complemented the list with the study and comparison of Ontology development 101 (Noy & Mcguinness, 2001), Dogma (Jarrar & Meersman, 2009), Diligent (Pinto et al., 2004), Unified Process for ONtology (UPON) (De Nicola et al., 2009) and NeOn (Suárez-Figueroa et al., 2015). In addition, we include the UPON lite methodology (De Nicola & Missikoff, 2016). Most of these methodologies resemble software development methodologies due to the similar software development cycle which usually comprises phases of requirements gathering, design, implementation and testing. However, it is important to note that the purpose of the two is different as software is developed for a specific purpose whereas an ontology aims to describe a domain in a structured way in order to integrate information from various sources for the creation of a diversity of applications. Furthermore, the semantic characteristic of ontologies require special considerations, such as reuse, alignment and merging. In this section the methodologies mentioned and most frequently used in the literature are described in chronological order.

Methontology was created in 1997, at Universidad Politécnica de Madrid by the Ontology group (Gómez-Pérez & Fernández, 2007). It is applied to the whole ontology development life cycle. It is built upon evolving prototypes, thus each prototype allows adding, changing and deleting terms. Figure. 2.12 shows one cycle of one prototype, when the cycle repeats, the prototype is refined. A schedule is prepared for each cycle, development activities then begin in parallel with other management and support activities.

Management activities include the initial schedule, control and quality assurance. Planning identifies the tasks to be performed, the time required and the resources. Control ensures that planned tasks are completed as they were intended to be performed. Quality Assurance ensures the satisfaction of each product, such as ontology, software and documentation.

The following development activities (Figure 2.11, middle box) lead to the construction of the ontology: During specification, the purpose of the ontology, its intended uses and end-users are defined. In conceptualization, the domain knowledge is structured as meaningful knowledge level models. Formalization converts the conceptual model into a formal model, by defining more components of the model (descriptions, labels, cardinality, etc). In implementation, formal models are built using an ontology language. Maintenance updates and corrects the ontology. Development activities are cyclic, so it is always possible to make modifications or refinements as from any phase the process can be restarted.

Supporting activities are executed constantly in each step of the development activities, however during conceptualization and formalization, knowledge acquisition and evaluation are more active. In the knowledge acquisition phase, the knowledge of a given domain is collected. The integration phase reuses available ontologies when building a new ontology. In the evaluation phase, a technical judgment of the ontologies and software environments is made. The documentation phase records clearly and exhaustively details each phase and generated product. In the configuration management phase all versions of the documentation, software and ontology code are recorded for change control.

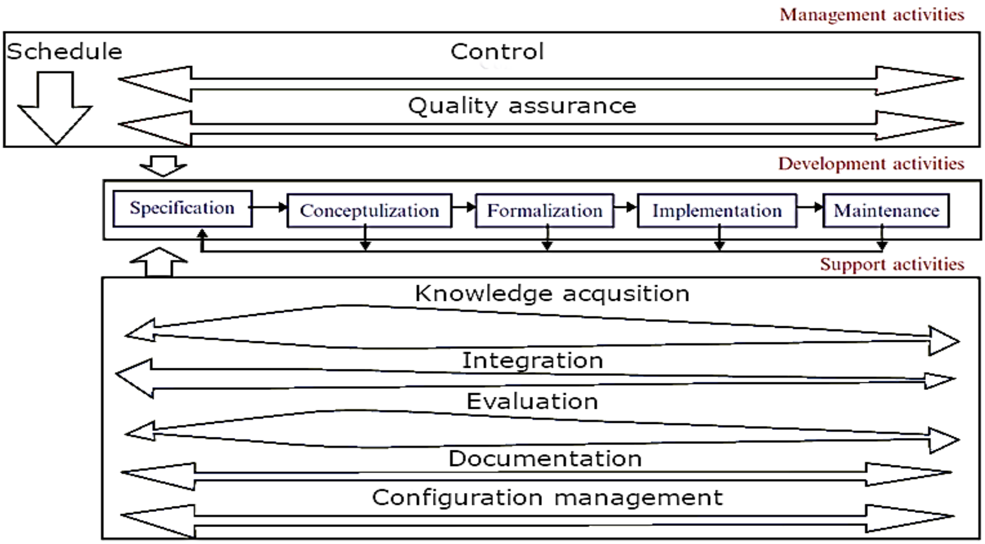


Figure 2.12 Schema representing the activities and steps of Methontology (Corcho et al., 2005). Management, development and support activities are executed in parallel.

On-To-Knowledge was developed by Sure et. al in 2001. This methodology comprises the Knowledge Meta process (Figure 2.12) and the Knowledge process (Figure 2.13). During the Knowledge Meta process an ontology is built, while the Knowledge process manages the population and testing of the ontology. The steps in these two processes can be linked to each other, e.g. each test can lead to an ontology improvement and each change can be tested. This iterative and incremental methodology allows a basic ontology to be refined to an acceptable level.

Five phases belong to the knowledge meta process: The feasibility study identifies the problem, opportunities and possible solutions. With a set of requirement specifications, the kickoff phase searches for already developed ontologies by creating a semi-formal description of the ontology. This semi-formal ontology description is enhanced by adding concepts and describing relations during the refinement phase. At the end of this phase a target-ontology is formalized. In the evaluation, the target-ontology is assessed to ensure it complies with the requirement specifications. In the application and evolution phase, the ontology is implemented and a management plan is established to control its evolution.

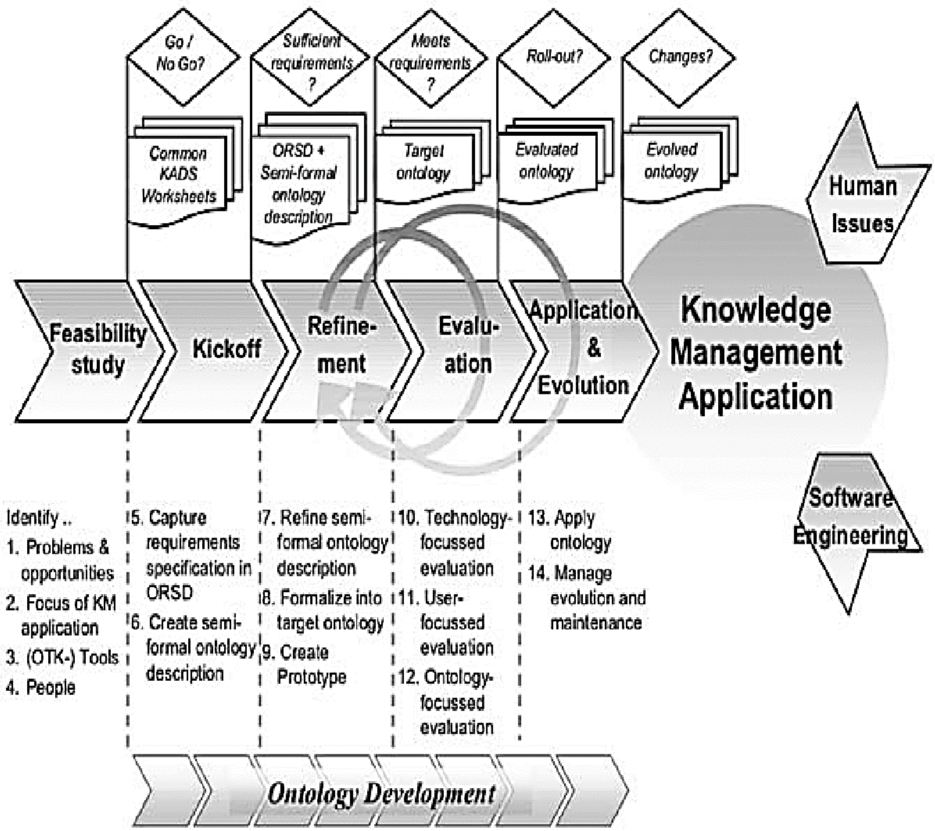


Figure 2.13 Schema representing the steps in the knowledge meta process of the On-to-knowledge methodology (Sure et al., 2009). Five phases lead to the construction of the ontology: feasibility study, kickoff, refinement, evaluation and Application & Evolution.

The knowledge process (Figure 2.14) comprises the following phases: In the creation or import phase, content is added according to the stakeholders' requirements. During the capture phase, previously imported content is interlinked. The retrieval or access phase returns information that satisfies the users' needs. In the last phase, knowledge is retrieved to be further used in a specific context.

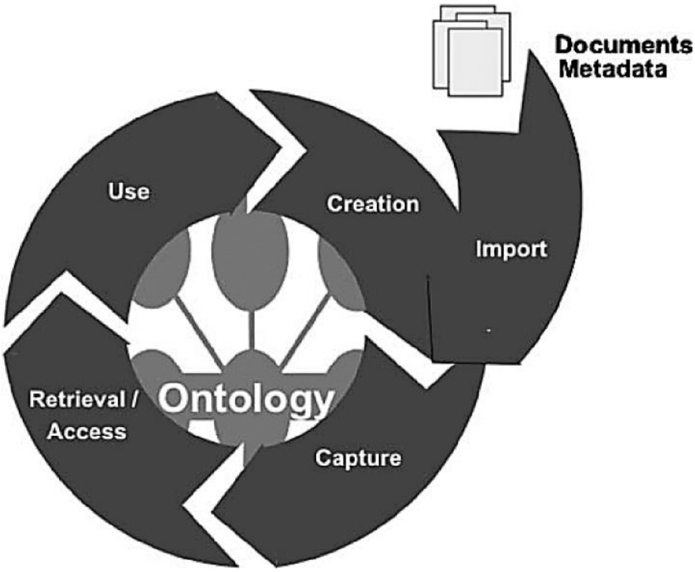


Figure 2.14 Schema representing the phases in the knowledge process of the On-to-knowledge methodology (Sure et al., 2009). The phases of import/creation, capture, retrieval/access, and use lead to population and evaluation of an already developed ontology.

NeOn was developed by Suárez-Figueroa et al. (2015) in 2006 as part of the Neon project. It is based on the idea that ontologies do not work independently, thus the objective is to build an ontology network. It proposes nine scenarios that cover not only the development of ontologies from scratch, but also other common situations such as re-engineering and alignment of available ontologies. Figure 2.14 shows the workflow of the nine scenarios.

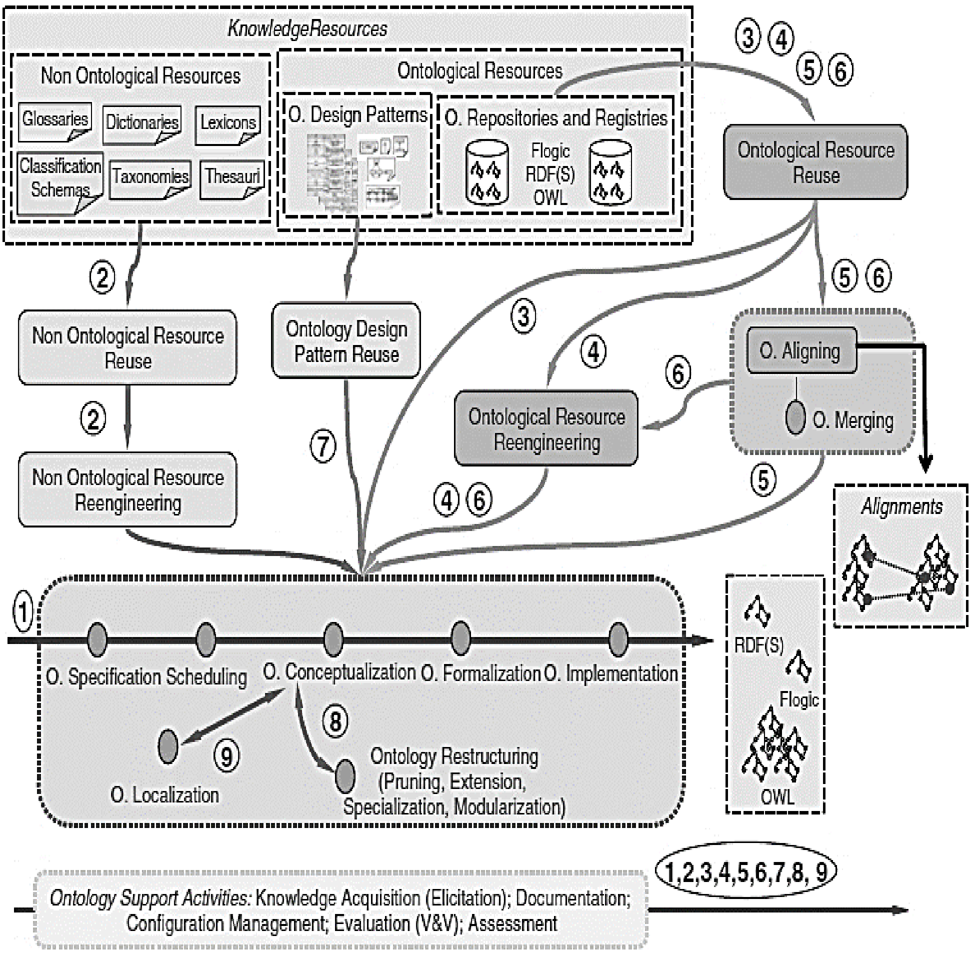


Figure 2.15 Schema showing the workflow among the NeOn methodology scenarios (Suárez-Figueroa et al., 2015).

Scenario 1: From specification to implementation. In this scenario, developed knowledge resources are not available to be reused. The ontology is built from scratch.

Scenario 2: Reusing and re-engineering non-ontological resources. In this scenario, the ontology network can be built reusing non-ontological resources such as glossaries, dictionaries, taxonomies, etc; which are then analyzed and re-engineered.

Scenario 3: Reusing ontological resources. In this scenario, ontological resources such as complete ontologies, modules, or statements are used to build the target ontology.

Scenario 4: Reusing and reengineering ontological resources. Similar to scenario 3 but it also includes ontological resources re-engineering and merging.

Scenario 5: Reusing and merging ontological resources. In this scenario several domain ontological resources are selected for reuse and a new ontological resource is created.

Scenario 6: Reusing, merging, and re-engineering ontological resources. Similar to scenario 5, but in this case the resources will be reengineered before merging them.

Scenario 7: Reusing ontology design patterns (ODPs). In this scenario, repositories of ontology design patterns are accessed and reused.

Scenario 8: Restructuring ontological resources. In this scenario, the ontological resources are restructured by selecting ontology modules or sections to be used. These modules or sections can also be extended or specialized.

Scenario 9: Localizing ontological resources. This scenario discusses the ability to create multilingual ontologies that can be adapted to other languages and culture communities.

This methodology is described in detail in Suárez-Figueroa et al. (2015). This section is limited to Scenario 1 to which all other scenarios are connected. This scenario is an evolution of Methontology, thus some activities are the same. This scenario refers to the core activities that have to be performed in any ontology development: Specification of the ontology network requirements including the purpose, the scope, and the implementation language, the target group, and the intended uses. Then, the competency questions (CQs) and a pre-glossary of terms are created. The activity closes with a search of candidate knowledge resources (ontologies, non-ontological resources, and ontology design patterns) which may lead to the identification of additional scenarios. During the scheduling, the team establishes the ontology network life cycle and the human resources needed for the ontology project. Then, the ontology developers start the conceptualization, in which knowledge is organized and structured into meaningful models at the knowledge level. The formalization, adds more detail to the model. In the implementation the ontology is generated.

UPON was developed by De Nicola et. al in 2009. The unified process for software engineering is used as starting point. It is an iterative method where several cycles are performed. Each cycle (Figure 2.15) is divided into phases and in each phase several workflows are executed.

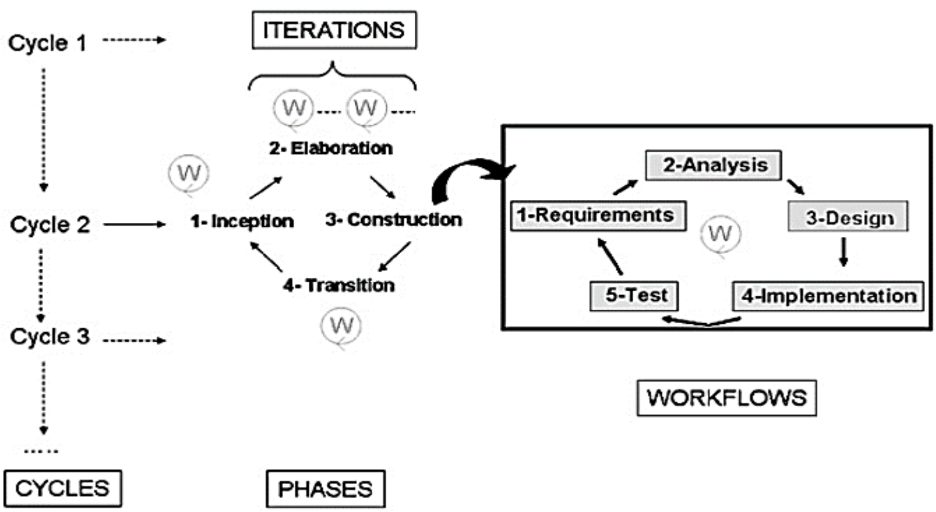


Figure 2.16 Schema representing the cycles, phases and workflows of UPON methodology (De Nicola et al., 2009).

There are 4 phases: In the inception phase, requirements are captured and a basic conceptual analysis is performed without any implementation or testing. In the elaboration phase, the fundamental concepts are identified and briefly structured through a slight ontological blueprint. In the construction phase, most of the design and implementation occurs. In addition, further analysis may be necessary to identify concepts that have been overlooked in previous phases. During the transition phase, the final version of the ontology is created after the corresponding testing.

Figure 2.16 shows the relation between workflows and phases, as well as the involvement of domain experts and the knowledge engineers.

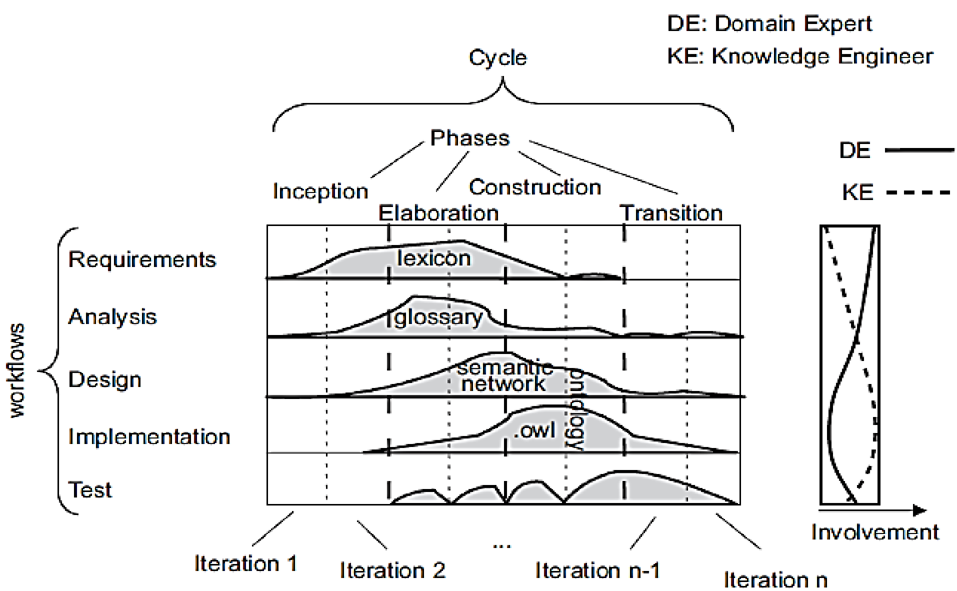


Figure 2.17 Schema depicting the activity of each phase during each workflow in the UPON methodology (De Nicola et al., 2009).

There are 5 workflows: The requirement workflow aims to specify the user's semantic needs. The following tasks have to be completed: the definition of the domain and scope, and the definition of the business purpose (using story boards, application lexicon, competency questions and use cases). In the analysis, the ontology requirements are structured and refined by extending the ontology scope. After adding definitions to the terms, the application lexicon is translated to a reference glossary. During the design workflow, the terms are organized in a hierarchical structure, then attributes, relationships and axioms are added. In the implementation workflow, the ontology is encoded using a rigorous, formal language. The selection of the language takes into account its expressive power, the computational complexity of the reasoning method, and the level of community acceptance. The test workflow evaluates the ontology in relation to the following aspects: syntactic quality, semantic quality, pragmatic quality and social quality. These aspects refer to the way the ontology is written, whether its concepts and relationships are consistent with its intended meaning, the end-users' considerations of its usefulness, and the degree of use and reuse of the ontology.

UPON lite (De Nicola & Missikoff, 2016) was created by De Nicola and Missikoff in 2016. This methodology places end-users at the core of the process. It is simple and agile, reducing the complexity presented by other methodologies. It defines six steps (Figure 2.17) to build lightweight ontologies: In the lexicon, a list of domain terms is generated. In the glossary, the terms are associated with a textual description and synonyms are established. In the third step, a taxonomy is generated that organizes the terms in a hierarchical structure. In the fourth step, predicate terms representing properties are connected to the entities they characterize. In the parthood, the names of complex entities are connected to their components. This step tries to identify all part-whole relationships. The last step produces the formally encoded ontology using a formal language.

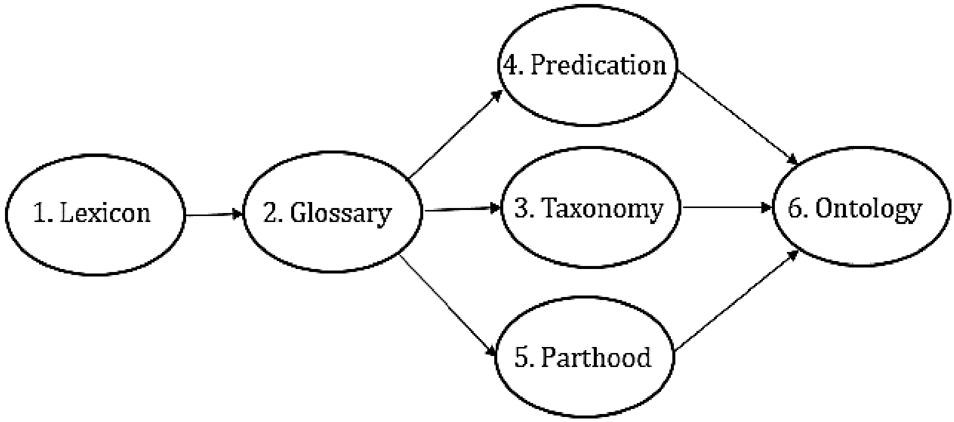


Figure 2.18 Schema depicting the steps of UPON lite methodology. Adapted from De Nicola and Missikoff (2016)

Ontology Development 101 is a simple knowledge-engineering methodology created in 2001 (Noy & Mcguinness, 2001). According to the authors, there is no one "correct" way or methodology for developing ontologies. The model of a domain depends on the application. They offer a possible process for ontology creation which should be applied iteratively. The methodology lists 7 basic steps (Figure 2.18): Step 1. Determine the domain and scope of the ontology. This is the starting point of the development process. Questions as to the domain of the ontology, the type of question the ontology information should answer (CQ), and who will use the ontology have to be considered. Step 2. Consider reusing existing ontologies. Before creating anything from scratch it is worthwhile to consider what has been already done. Step 3. Enumerate important terms in the ontology. A list of important terms of the domain and statements about them are used as input for the next step. Step 4. Define the classes and the class hierarchy. Several approaches can be used: from the most general concepts to the specific ones (top-down), an inverse process (bottom-up) or a mixture of them. Step 5. Define the properties of classes or slots. Classes alone do not provide enough information to answer the competency questions. Thus, it is necessary to define how the classes interact with each other and the features of each class. These features are named slots. Step 6. Define the facets of the slots. Slots can have different facets describing the value type, allowed values, the number of the values (cardinality), etc. Step 7. Create instances. Once the ontology has been created, it is necessary to create instances for each class and its slots.

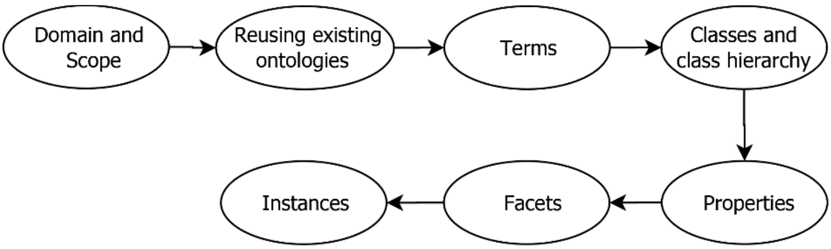


Figure 2.19 Schema depicting the steps of Ontology 101 methodology.

2.2.2 Methodology selection

The methodology used for a developing process is fundamental to ensure a quality product. Table 2.7 summarizes de pros and cons of the previous methodologies.

Table 2.7 Methodologies pros and cons.

Methodology	**Pros**	**Cons**
Methontology	Covers the whole ontology development life cycle. Integrates management, development and support activities.	No extensive documentation. Too many activities to be integrated at each step.
On-To-Knowledge	Covers the whole ontology development life cycle. Distinguishes between ontology construction and ontology use. It is clear and consistent.	No extensive documentation.
NeOn	Supports ontology networks construction. Defines all possible scenarios for ontology development, re-engineering and alignment. Sufficient documentation.	Too many scenarios that make the whole process very confusing.

UPON	Based on a well-known methodology for software engineering. Sufficient documentation.	Relation between phases and workflows is not very clear.
UPON lite	Simple and agile process.	Only suitable for lightweight ontologies. No extensive documentation. Oriented only to the development process, not to the use of the ontology.
Ontology Development 101	Simple and agile process. Sufficient documentation.	Oriented only to the development process, not to the use of the ontology.

There is a wide variety of methodologies for ontology development but there is a gap between simplicity and detail. Ontologies such as Methontology, On-To-Knowledge, UPON and UPON lite, and Development 101 whose simplicity may make them look incomplete are contrasted with NeOn which is overly complicated. For this thesis, On-To-Knowledge has been selected as methodology and is complemented with the definitions of competency questions and the ontology requirements specification document (Suárez-Figueroa et al., 2015). It supports the whole ontology development life cycle by making a distinction between the construction and the use of ontologies. This allows for immediate corrective actions to be taken rather than waiting for the entire cycle to finish. Interestingly, this approach is similar to the preventive conservation cycle. It is clear and consistent without being messy and confusing. Although there is no extensive documentation, there are a couple of examples that can be reviewed that clarify its use.

Without neglecting the simplicity of On-To-Knowledge, existing resources already developed for each phase of this methodology should be listed, taking into account that the semantic web is an emerging technology, so these resources are always changing.

2.2.3 Ontology editors

In the last decades several ontology editors have been developed (Alatrish, 2012; Corcho et al., 2005; Kapoor & Sharma, 2010; Suárez-Figueroa, Gómez-Pérez, et al., 2012; Suárez-Figueroa et al., 2015), but few are still on the market. In this section we describe Protégé (Musen, 2015), and TopBraid Composer (TopQuadrant Inc, 2016).

Protégé (Musen, 2015) was developed by Stanford University in 1999. It is a set of tools for building domain models and knowledge-based applications. It is a free and open source and perhaps the most popular ontology editor. A revision of its evolution was published by Gennari et al. (Gennari et al., 2003). Currently, there are two available frameworks (Stanford Center for Biomedical Informatics Research, 2016): Protégé 5 is a desktop version, and WebProtégé is a web-based system.

Protégé Desktop supports the creation and editing of one or more ontologies in a single workspace. Its latest version 5.5 was released in March 2019. It has a connection with reasoners like HermiT (Glimm et al., 2014) and Pellet (Sirin et al., 2007) that includes inference management. Its mature visualization tools show the ontology sorted by classes, properties or individuals. The OntoGraph view allows graphical visualization of the ontology. It allows automatic integration with GitHub repositories, WebProtégé and supports multiple languages, such as: W3C standards recommendations and SPARQL (Stanford Center for Biomedical Informatics Research, 2007).

WebProtégé version 4.0.2 was released in July 2020 (Stanford Center for Biomedical Informatics Research, 2008). It is not automatically compatible with previous versions but a procedure was established to remediate this issue (Stanford Center for Biomedical Informatics Research, 2008). It is a lightweight ontology editor oriented to better support a collaborative development process. It is open source and works in a web environment. Several users can collaborate on a specific ontology, thus there are features for sharing and permissions. The framework includes discussions panels, threads annotations, change tracking and revision history. New features comprise colourful tagging of instances, query view, graphical visualization on entities, improved multilingual capabilities and dark mode support (Horridge, 2022).

WebProtégé provides a simpler design than Protégé 5, and this web-based version has therefore become more popular than the desktop framework. However, it has some limitations regarding inferencing. It is better suitable for OWL 2 EL ontologies, thus large ontologies with few inferencing and querying. When several instances, querying and inferencing are needed, the desktop version performs better.

Protégé desktop and WebProtégé are tools for basic ontology development and do not have built-in support for spatial data. The GeoSPARQL implementation could be imported into Protégé to enable the representation of spatial data. However, spatial functions such as intersection or union need to be programed through a plug-in, which can be challenging.

TopBraid Composer created by TopQuadrant in 2006 (TopQuadrant Inc, 2016) is a commercial W3C standards compliant tool aiming to develop Semantic Web ontologies and semantic applications. Implemented as an Eclipse plug-in, it allows development of ontology models, conversion to and from RDF/OWL data and models, transformation and integration of data sources, and development of Semantic Web services and applications.

TopBraid Composer provides views for exploring classes, properties, association and instances of the ontology being developed. It also provides a SPARQL interface for queries called SPIN. TopBraid Composer also has a built-in inference engine that works with a syntactic subset of OWL 2 (OWL 2 RL), that allows the implementation of inference rules (W3C, 2013a).

Starting from version 6.4, the TopBraid GeoSPARQL Vocabulary was developed, which enables the representation of spatial data, execution of spatial operations, and the creation of interactive maps. The TopBraid GeoSPARQL Vocabulary gathers concepts from the W3C WGS84 Geo Positioning RDF vocabulary and the Open Geospatial Consortium GeoSPARQL (TopQuadrant, Inc, s. f.).

TopBraid Composer Maestro Edition (ME) was released in 2021 and provides a 30 days test period (TopQuadrant Inc, 2001). In 2022, the TopQuaandran website was updated and downloads were moved to the archive website www.archive.topquadrant.com; indicating that active development has ceased. There is no information about how long the tool will be available.

2.2.4 Ontology editor selection

The framework used to build the ontology is also important. Table 2.8 shows the pros and cons of the tools previously described. The TopBraid Composer provides a limited trial period, thus both versions of Protégé were tested. The desktop version was selected since collaborative work is not needed on this research and this version provides a better user experience. Regarding the handling of spatial data, in the initial stage of ontology development, its use is not required. In section 2.4.3, triple stores that enable the use of the ontology in which the spatial aspect is crucial are explored.

Table 2.8 Ontology editors' pros and cons.

Ontology editors	**Pros**	**Cons**
Protégé	Free and open source. Extensive documentation. Friendly graphical interface. Easy installation. Query support.	Oriented to the development process and very basic use of the ontology. Does not handle spatial data.

WebProtégé	Free and Open source. Extensive documentation. Easy access, no installation required. Query support. Supports collaborative work.	Less user-friendly interface than the desktop version. Does not handle spatial data.
TopBraid Composer	Extensive documentation. Friendly graphical interface. Easy installation. Query support. Support for 2D spatial data representation and query.	Commercial tool, provides a very limited trial period.

2.2.5 Search engines and ontology catalogues

Development methodologies recommend reusing ontologies (Suárez-Figueroa, Gomez-Perez, et al., 2012). Semantic web search engines (Shah et al., 2015) such as Swoogle (Ding et al., 2004), Watson (D'Aquin et al., 2007) and Falcons (Cheng et al., 2008) were created to facilitate the search for already developed ontologies. Currently, these search engines are no longer available. In contrast, Link Open Vocabularies (LOV) has become increasingly popular.

LOV was created by Vandebussche and Vatant at the Ontology Engenieering Group of the Universidad Politécnica de Madrid in 2011. It maintains a catalogue of ontologies. The ontologies stored in LOV must follow the Semantic Web best practices (Swick et al., 2006). In this sense, ontologies can qualify as high-quality ontologies. By July 2023 it contained 808 ontologies (Ontology Engineering Group - UPM, n.d.). LOV displays indicators such as interconnections between ontologies, ontology version history, and past and current editors, which can be individuals or organizations.

LOV searches by vocabulary, term or agent (person or organization). To identify vocabularies, a vocabulary search employing key terms such as historical, cultural, spatial, or geo can be performed. A specific search by terms like historical building, point, line, coordinate, can also be performed. If we know who might have created a vocabulary, a search by agent can be done. For example, one can search for vocabularies created by OGC.

The search algorithm distinguishes a match based on where it was found, local name, primary labels (label, title), secondary labels (description, comment) and ternary labels (all other terms). Each category has a different score, with the local name having the highest score and the ternary labels the lowest. In this way, ontologies are ranked.

In addition, LOV provides a SPARQL end point, thus more specialized queries can be performed. The found ontology can be displayed or saved locally. Several tools have been integrated, such as: OntOlogy Pitfall Scanner (OOPs) (Poveda-Villalón et al., 2014), RDF triple checker (Gutteridge, n.d.), parrot (Tejo-Alonso et al., 2012), vapour (Berrueta et al., 2008) and WebVOWL (Lohmann et al., 2016). Parrot is a documentation tool which displays the ontology in a user-friendly way, but is currently unavailable. WebVOWL provides graphical display of the ontology, and OOPs and RDF triple checker are validation tools.

As part of the methodology, reuse of already developed ontologies is an important step. For this purpose, the LOV catalogue and a literature review are used. At the beginning of this research, search engines were also explored, but they are no longer available at the time of writing.

2.3 Ontology evaluation principles

Ontologies for the same domain can be very different as time, place and cultural environment influence the modeler's perception of the domain (Hlomani & Stacey, 2013). Ontologies are the basis for reaching the Semantic Web, so it is important that they meet a number of standards to ensure their quality. There are several studies (Degbelo, 2017; Fernández-López et al., 1997; Gómez-Pérez et al., 1995; Hlomani & Stacey, 2013; Vrandečić., 2009)on ontology evaluation dealing with terminology, aspects, criteria, methodology and tools. In this section we present the state of the art in this field.

2.3.1 Terminology

Before discussing ontology evaluation, it is important to state what we mean by this term. In 1995, Gomez Perez defines ontology evaluation as the combination of ontology verification and validation (Figure 2.19). Verification ensures the ontology is built correctly, thus the requirements are met. Validation or assessment denotes to what extent the ontology models reality, answering whether the correct ontology has been constructed.

Hlomani and Stacey (Hlomani & Stacey, 2013) state two important perspectives to be evaluated: quality and correctness. Analogous to the above definitions of validation and verification, Degbelo (2017) states the goals of ontology evaluation are to perform technical and user evaluations. Other authors such as Vrandečić (2009) and Fernández-López (1997) have elaborated on Gómez Pérez's initial concept.

Vrandečić (2009) defines evaluation methods as procedures that assess the ontology features and qualities. During this assessment, a set of criteria is used (Degbelo, 2017; Vrandečić., 2009).

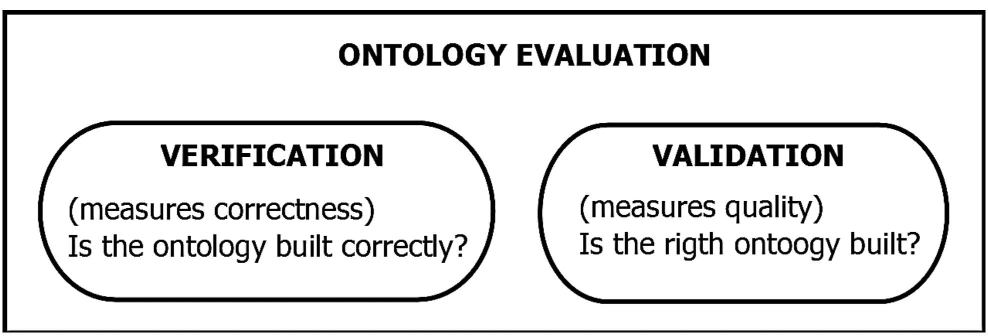


Figure 2.20 Diagram showing ontology evaluation types.

The following sections describe what is evaluated, how it was done and which procedures were used.

2.3.2 Ontology Evaluation Aspects

Several authors (Brank et al., 2009; Dividino et al., 2008; Vrandečić., 2009) agree that ontologies are complex structures and that different aspects can be evaluated depending on user requirements.

Brank et al. (2009) list six aspects that can be evaluated: Vocabulary or data or lexis refers to the vocabulary used to represent concepts, instances, facts, etc. Is this vocabulary correct? Does this vocabulary represent the whole domain?. Hierarchy or taxonomy evaluates the hierarchical 'is-a' relationships between concepts, also known as rdfs:subClassOf. This aspect evaluates if a, 'is-a' relationship is correctly established. Other semantic relations refers to other relationships in addition to the 'is-a' relationship. Context or application level refers to the effects on an application when the ontology is used. Is the ontology suitable for the intended use? Syntactic level considers that the requirements conform to the formal language used to describe the ontology. It includes checking for the presence of natural-language documentation. Structure, architecture and design evaluates whether the ontology was created following some design principles, such as clarity and minimal bias encoding,. These criteria are explained in the following section (Gruber, 1995).

Dividino et al. (2008) define three aspects: The structural level includes topological dimensions and logical adequacy. The former includes criteria such as Depth, Breadth, Modularity, and Connectivity. The latter includes criteria such as Consistency, Complexity, Concept Satisfiability, and Concept Subsumption. The functional level assesses the accuracy of the ontology conceptualization related to its intended use. Including a task assessment based on performance, patterns and condition management, an evaluation of topics based on a corpus analysis, and a modularity assessment which includes the study of reusable components. The usability level comprises both the structural and functional assessment and additionally incorporates annotations (metadata) analysis considering the perspective of a specific user or group.

Vrandecick (2009) lists six ontology aspects: Vocabulary refers to ontology names (URIs, literals). Syntax refers to the particular conditions to correctly represent syntax, such as NTriples or RDF/XML. Structure evaluates graphs' size, depth, presence of cycles. Semantics refers to the formal meaning of the ontology: the model described by the structure, e.g. detection of contradictory axioms. Representation refers to the structure-semantics relationship (formal specification-shared conceptualization), exposing mistakes and omissions. Context refers to the ontology features when compared to other artifacts, e.g. competency questions, data source, etc.

Brank et al., Dinidino et al., and Vrandecick define several overlapping aspects, although the structural and functional definitions of Dividino et. al. coincide quite closely with the above definitions of verification and validation. Other aspects can also be evaluated in this sense. For example, when assessing the vocabulary we could check whether the domain is fully represented, but also whether the terms used are consistent for a user.

2.3.3 Criteria

This section discusses the evaluation criteria defined in literature and how they can be measured.

Accuracy (Leo Obrst et al., 2007; Vrandečić., 2009) measures the degree of agreement between the knowledge in the ontology and the real world.

Higher accuracy is achieved when classes, properties and individuals have correct definitions and descriptions. This criterion can be measured by comparing the terms in the ontology to the opinion of some domain experts or glossaries of the domain.

Completeness/Coverage/Expressiveness (Hlomani & Stacey, 2013; Asunción Gómez-Pérez, 2003; Grüninger & Fox, 1995; Leo Obrst et al., 2007; Noy & Hafner, 1997), reflects how the ontology characterizes the domain. The expected knowledge is either explicitly stated or can be inferred from the ontology. This criterion measures the domain coverage and its richness, complexity, and granularity. According to Kehagias et al. (Kehagias et al., 2008) this criteria is also named congruency and measures the correspondence between a corpus terms and the ontology. This corpus terms can be the initial semiformal hierarchical description of terms. Grüninger and Fox (Grüninger & Fox, 1995) check completeness by verifying whether the ontology can answer competency questions.

Conciseness (Gruber, 1995; Asunción Gómez-Pérez, 2003; Leo Obrst et al., 2007) The ontology should avoid useless, unnecessary, or redundant elements. According to Gruber, a minimal ontological commitment should be used, ensuring that only the essential domain terms are specified. This can be implemented by an expert user assessment detecting if redundant terms are employed.

Consistency/Coherence (Gruber, 1995; Asunción Gómez-Pérez, 2003; Leo Obrst et al., 2007) refers to the definition of logical and consistent axioms and correct inferred statements. The ontology should not include contradictions. The ontology should follow the meta-level integrity principle, which attempts to create an ontology that respects certain ordering criteria used as quality indicators (Gangemi et al., 2005). It measures the number of terms with inconsistent meaning (Hlomani & Stacey, 2013). Inferred statements and logical inconsistences can be checked employing reasoner. Coherence between the formal statements and natural language documentation should be checked manually.

Clarity (Gruber, 1995) refers to how the intended meaning of the ontology terms is communicated. Definitions should be context independent and are preferred over descriptions. Natural language should be used to document entities. Minimal symbol encoding should be used. For example, it is common practice to use abbreviations to represent some well-known fact. By naming a building "HB12" many people might interpret that building as being Historic Building No. 12, which is not true unless there is an assignment or interpretation by a reasoner that verifies the typology of this element. Representation choices should not be made solely for the notation or implementation convenience. Gangemi (2005) refers to this criterion as cognitive ergonomics and transparency and Obrst (2007) as intelligibility. This is checked manually.

Adaptability/Extendibility/Expandability/Reusability/Flexibility (Gruber, 1995; Asunción Gómez-Pérez, 2003; Leo Obrst et al., 2007; Gangemi et al., 2005). This criterion measures the additional ontology uses without the need to remove axioms. Several concepts found in the literature are related to this criterion. The reaction of ontology semantics against small changes in axioms is called sensitiveness (Asunción Gómez-Pérez, 2003). According to Hlomani and Stacey (2013), coupling and cohesion are used to measure adaptability. Coupling refers to the number of imported ontology classes and cohesion refers to the relatedness of ontology elements. An ontology would have high cohesion if its classes are strongly related. Gangemi (2005) states some design principles: ontologies should be compliant to one or more users, and easily manipulated and understood for adaptation and reuse. Expert user assessment usually is used to check this criterion.

Organizational fitness (Gangemi et al., 2005) refers to the facility of deploying the ontology within an organization and the coverage for that context. Legal requirements, sharing among stakeholders, and specific constraints for the application of the ontology in the organization are checked. This is a special case of adaptability.

Computational integrity and efficiency (Gangemi et al., 2005) refers to the ability to successfully and easily process the ontology, particularly the reasoner's speed. This is very dependent on the software, the formal language and the reasoner used to work with the ontology.

2.3.4 Ontology Evaluation Approaches

According to Degbelo (2017) there are two main objectives for carrying out ontology evaluation: following ontology development progress and ontology selection. As part of the ontology development process, several methodologies (Section 2.2.1) include a testing or evaluation phase, although in most cases its description does not provide enough detail to implement such evaluation. Nevertheless, there are several studies in this field due to its importance. In this section, ontology evaluation approaches are presented.

Brank et. al. (2009) organized evaluation approaches according to four categories: Gold standard-based evaluation In this approach, the ontology is compared to a 'gold-standard' which is an instrument of reference, well-constructed and designed according to a specific domain. Then, the number of terms that match are counted. In some cases, the gold-standard is an ontology (Maedche & Staab, 2002), a list of terms created by domain experts, or a list of aspects to be evaluated, etc. Data driven evaluation In this approach, also known as corpus-based evaluation, the ontology is compared with existing data from the domain. For example, Brewster et al. (Alani et al., 2006) compare the concepts and relationships of the ontology with domain documents to select the one that best fits the domain. This approach is a special case of the gold standard approach. Application or task evaluation In this approach, the ontology is evaluated within the context of an application. Examples of this approach can be found in Porzel and Malaka, where a speech recognition software finds synonyms based on the relationships between ontology classes (Porzel & Malaka, 2004). Haase and Sure

(2005) evaluated several ontologies to find the one that performs best in a search scenario. User Evaluation In this approach, the ontology is evaluated through user experiences. The users, as reviewers, determine the criteria and their importance in evaluating the ontology. In Ouyang's work (2011) the user gave weight to coverage, coupling and cohesion according to the importance of these criteria for their purposes.

Hlomani and Stacey (2013) points out the limitations of these approaches. The drawback of the gold-standard approach is that the selection of the gold-standard also has to be evaluated. Finding data or documents fitting the domain is easier than finding an ontology. Data-driven and gold-standard approaches assume that the domain knowledge is constant. However, Nonaka and Toyama (2005), Nlomani and Stacey (2013) argue otherwise. The application evaluation approach is practical when a single ontology is used, i.e. when creating ontologies from scratch. When multiple ontologies are to be compared, the process is challenging. The limitations for the user evaluation are the establishment of objective standards for selecting evaluation criteria and the establishment of the appropriate user.

Obrst et al. (2007) organize evaluation approaches for living science as follows: i) application ontology evaluation, ii) evaluation of domain data sources, iii) human evaluation against a set of criteria, iv) ontology evaluation related to the impact on natural language processing tasks, and v) reality as a benchmark. Some of these approaches are analogous to Brank's: gold-standard is equivalent to v), application-based is equivalent to i), data-driven is equivalent to ii), and user-based is equivalent to iii). The remaining approach, ontology evaluation related to the impact on natural language processing tasks, is analogous to the evaluation in an application. Ontology performance is evaluated on specific tasks such as information extraction and question answering. Wolstencroft et al. (2005) use the Gene Ontology (GO) to find articles that discuss the GO code for a specific protein.

Raad and Cruz (Raad & Cruz, 2015) mentioned four approaches: corpus-based, gold standard, task-based, and criteria based. The first three approaches are in line with the previous authors.

The criteria-based approach measures ontology fit according to specific criteria. This can be related to the structure or to more complex criteria. The former employs structure properties such as the average depth of the taxonomy, the relational density of nodes (Fernández et al., 2009), the presence of cycles (Gangemi et al., 2006), among others. The latter refers to more complex evaluations. Some of them are methodologies in which many aspects are included, for example AKTiveRank (Alani et al., 2006) and OntoClean (Guarino & Welty, 2009).

2.3.5 Ontology evaluation tools

Pinto and Martins (Pinto & Martins, 2004) advise reusing ontologies as much as possible. To this end, evaluation of ontologies is a key activity. However, the gap between theory and practice is still vast. Although there are many theories and methodologies regarding ontology evaluation, in practice the number of developed tools that are currently available is very low and they are limited to verify the formal aspects of the ontologies.

ODEval (Corcho et al., 2004) is an evaluation tool created for inconsistencies and redundancies. It implements syntactic evaluation of RDF(S), OWL, and DAML+OIL ontologies. The tool is accessible through the webpage: https://oeg-lia1.dia.fi.upm.es/odeval/ODEval.html.

OntOlogy Pitfall Scanner (OOPs) (Poveda-Villalón et al., 2012) is a web-based tool developed by the Ontology Engineer Group. The tool is used to detect anomalies in ontologies. It helps developers to automatically detect potential errors, improving ontology quality. The tool is accessible in http://oops.linkeddata.es/. It has also been integrated to LOV catalogue.

The OnTo-knowledge methodology has several phases in which different types of evaluation are required. The verification of the ontology is needed during the meta knowledge process. When constructing the ontology, already developed ontologies have to be assessed for reuse and criteria such as adaptability, completeness and clarity have to be checked. Additional to the criteria used for evaluation other criteria needed when comparing ontologies, such as accessibility, provenance and reputation. Once the ontology is constructed, completeness is checked through an expert opinion assessment and technical evaluation is performed using OOPs which has a comprehensive catalogue of pitfalls and is very easy to use. The validation of the ontology takes place during the knowledge process where some use cases will be implemented. Completeness is checked verifying whether the ontology can answer the competency questions. After showing the use cases to the stakeholders an expert opinion questioner explores adaptability and organization fitness.

Ontological evaluation presents gaps between theory and practice. Very few tools exist oriented to evaluation. In terms of terminology, the one presented in this chapter is the most generally used, but in practice there are many authors who use the terms evaluation, validation, verification, etc. interchangeably. The Aspects, Criteria and Approaches give general indications of what and how can they be evaluated in general terms but not with real implemented methods. This is left to the discretion of each author who in most cases end up making manual comparisons as in sections 4.1.3, 4.1.4 and 4.2.2. It would be very useful to define different evaluation processes for the comparison and selection of ontologies already developed in order to reuse the ontologies that best fit user requirements, as well as to evaluate a newly created ontology with respect to user requirements. Since LOV is currently the most popular ontology catalog, it would be a great contribution to include these kinds of tools. In fact, in recent years OOPs has already been incorporated in LOV, but this tool provides a technical verification only.

2.4 Ontology population

Once an ontology has been created, it is necessary to fill it with data in order to work with it. Usually, the data are already structured, collected and need to be migrated. In this section we explore ways to migrate these data (2.4.1), the tools that can perform the mapping (2.4.2) as well as the platforms on which these data can be stored (2.4.3). Approaches for unstructured data are not explored in this research.

2.4.1 Mapping approaches

According to Michel et. al (2013) mapping approaches can be classified according to the following criteria (Figure 2.20): i) mapping description, ii) mapping implementation, and iii) data retrieval.

Mapping description refers to the amount of expressiveness of the final RDFs. It answers the question: what is mapped? The mapping description approaches are direct mapping and domain semantics-driven mapping.

The direct mapping approach is the only automatic conversion technique. The W3C released the recommendation "A Direct Mapping of Relational Data to RDF" (Arenas et al., n.d.) that specifies good practices for direct mapping. Table names are converted into classes; column names are predicates and cell values are literals or resources (Berners-Lee, 1998). In addition, the R2RML recommendation (Das et al., 2012), released by W3C in September 2012, is a standardized language that describes mappings between a relational database and an equivalent RDF dataset. To apply this approach the database schema has to represent the domain following these rules, which is not always the case (Dolbear & Goodwin, 2007). Thus, other manual alignment techniques involving transformations are available.

The domain semantics-driven mapping approach is used with existing ontologies, for example when a database needs to be aligned with an existing domain ontology. In this approach mapping description languages are used. The main difference is that direct mapping represents the database schema while domain semantics driven mapping represents the domain semantics from the target ontology.

Mapping implementation denotes how database information is translated into individuals. The approach is classified into data materialization and on-demand mapping.

Data materialization is also known as ‘RDF dump’. Through mapping rules, the database content is translated to an equivalent RDF graph. This process is known as Extract-Transform-Load (ETL) approach. The limitation of this approach is that data are not always updated, depending on the frequency that the ETL process is executed.

On-demand mapping provides a run-time solution. The data remains in the relational database and it is accessed through SQL queries. The query results are then converted into RDF datasets. In this approach, the data are updated. The performance of the query may be affected, especially if many data sources have to be integrated. With this approach the mapping is done only at the moment when information is needed and only the part of the information sought is mapped.

Data retrieval approaches refer to how RDF data are used after the mapping is implemented. This approach is categorized into Query-based access and Linked data.

Query-based access uses the SPARQL language to perform a query against the RDF dump. When using the on-demand approach the SPARQL query is translated into SQL queries.

The Linked data approach assigns a URI to each resource during the transformation. The information about the resource should be accessible as if it were a URL instead of retrieving just the information.

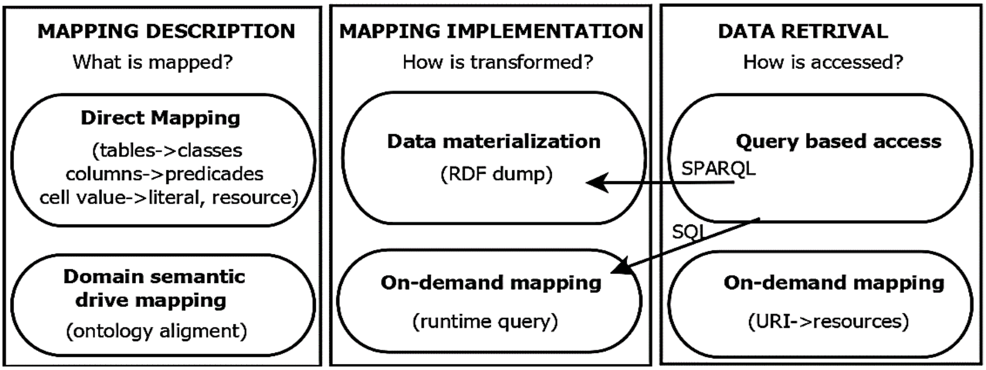


Figure 2.21 shows the approaches for mapping description, implementation and data retrieval.

2.4.2 Mapping tools

Following the approaches described in the previous section, several applications have been developed to manage RDF data creation.

The **D2RQ Platform** was developed as part of the Knowledge Nets project in 2004 (Bizer & Cyganiak, 2006). D2RQ brings together several tools to expose relational database content on the semantic web. In the following paragraphs we describe the platform components, mapping and access methods.

The platform is composed of the D2R Server, the D2RQ language and the D2R Map (Dolbear & Goodwin, 2007). D2R Server is a tool that publishes relational databases information on the semantic web. The D2R Map describes mappings between applications based on relational database schemas and RDF or OWL ontologies. The D2RQ declarative language is used to perform the mappings.

The tool offers two types of mappings: an automatic and a customized mapping (Cyganiak & Bizer, 2006). For each database, the automatic mapping creates a new RDF vocabulary following the direct mapping approach. Class and property names can subsequently be changed to terms from well-known ontologies. The customized mapping uses

ClassMaps and PropertyBridges. The former defines resources and their identifications. The latter sets resource properties which can be database values or URIs to other resources. Conditional mapping is also allowed. The mapping is performed when a condition is met and the resource properties are results of various transformations.

A mapped database can be accessed by RDF dumps, RDF APIs, and SPARQL Endpoints (Bizer & Cyganiak, 2007). RDF dumps create a duplication of the mapped database, stored in N-Triples or RDF/XML. Libraries such as Sesame and Jena allow JAVA applications to access the mapped database. This access is granted through the use of application program interfaces (APIs). SPARQL endpoints are created whereby the mapped database can be accessed remotely. Individual entities are accessed by dereferencing their URIs. The dereferencing process is called Linked data. A simple HTML view is also provided. An important application of this tool is DBPedia, which was first released in 2007 using this platform (Michel et al., 2013).

Morph-RDB has evolved from ODEMapster (Barrasa et al., 2004) developed by Barrasa et al in 2014 (Priyatna et al., 2014). Morph-RDB is an RDB2RDF engine developed by the Ontology Engineering Group, which follows the R2RML specification.

It supports two operational modes: Data upgrade generating RDF instances from data in a relational database such as MySQL, Oracle, PostgreSQL, Comma Separated Values (CSV) files and MonetDB. It supports direct mapping and custom mapping, using multiple configuration files. Query translation, in which users can also write an SPARQL query which is translated to SQL using optimisation techniques. The result is presented in a XML file.

2.4.3 Triple stores

In addition to mapping tools there are other comprehensive applications for RDF management that might include mapping services. Triple stores allow RDF storage and queries execution. Stored data can be native RDF, transformations of DBMS or a combination of both.

Virtuoso Universal Server (OpenLink Software, 2019a) was developed by OpenLink in 1998 (OpenLink Software, 2015). It is a commercial and open-source tool suite. In addition to the transformation from RDB to RDF (Linked Data Views), it also offers other functionalities such as clustering, RDF triple store, data replication, reasoning and integration from multiple data sources (Michel et al., 2013). Virtuoso uses its own declarative language, called Meta Schema Language (MSL) (OpenLink Software, 2019b) which is extended from the SPARQL query language. Results can be saved in several formats, such as RDF-Turtle, JSON-LD, N-Triples, N-Quads, CSV, TSV, among others.

The mapping methods available are on-demand mapping and data materialization (Michel et al., 2013). The on-demand mapping is provided through Virtuoso SPARQL 1.1 endpoint. Data materialization is possible but not the primary goal. Data access standards include Open Database Connectivity (ODBC), Java Database Connectivity (JDBC), ActiveX Data objects for the .NET Framework (ADO.NET), Object Linking and Embedding, Database (OLE DB), and XML for Analysis (XMLA).

The transformation process can be executed automatically or manually (Spanos et al., 2012). The automatic mode translates tables to classes and columns to predicates. The primary key is translated to RDF objects, the column of a table as RDF predicate and the value in a cell as the RDF subject (Sahoo et al., 2009). The manual mode allows for more complex mappings.

RDF data is stored using quads (graph, subject, predicate, object) (Erling, 2008). The access methods provided by Virtuoso are: ETL, SPARQL based and Linked Data (Spanos et al., 2012). A novel feature of Virtuoso is the support for SPARQL-in-SQL (SPASQL) that allows performing mix queries.

Virtuoso provides support for managing spatial data starting from version 6 onward, (OpenLink Software, 2023a) through the implementation of the GeoSparql standard and some additional custom functions (OpenLink Software, 2023b). The default coordinate system is WGS84, and the ST_Transform function can be used to transform coordinates to another coordinate system. While data can be represented in 3D, it has been tested (Section 5.1) that during execution of important functions, such as intersection, and within support just two dimensions.

Apache Jena is a free and open source Java framework for building semantic web and Linked Data applications in 2001 (The Apache Software Foundation, 2011c). It is composed of different Application program interfaces (APIs): The RDF API allows the creation of RDF graphs. ARQ allows querying RDF data. TDB is a triple store that allows data persistence. Fuseki exposes RDF data as a SPARQL endpoint accessible over HTTP. Ontology API allows the integration of RDFs an OWL in order to add semantics to RDF data. Inference API) allows reasoning through inference rules.

Apache Jena also provides the GeoSPARQL API (The Apache Software Foundation, 2011a), either as a standalone component or as part of the Fuseki API, where the GeoSPARQL 1.0 standard has been implemented. This allows for the representation of spatial data and spatial functions, as well as other custom functions (The Apache Software Foundation, 2011b). One drawback is that all these functions need to be executed from the command line as there is currently no graphical user interface available.

AllegroGraph is a graph and document database for complex data and queries (Franz Inc., 2022) created in 2004. AllegroGraph employs a combination of document (JSON and JSON-LD) and graph technologies that process data with contextual and conceptual intelligence. It can be run locally or from the Amazon Web Services (AWS).

AllegroGraph's Entity – Event Data Model places core 'entities' such as customers, patients, students or people of interest at the center and then collects various layers of knowledge related to the entity as 'events'. Predicates can be defined by formulas or conditional logic, allowing for a more realistic representation of the data. Its data model unifies enterprise data with knowledge bases such as taxonomies, ontologies, industry terms and other domain knowledge. It is W3C/ISO standards compliant and supports JSON, JSON-LD, SPARQL 1.1, OWL Reasoning, SHACL, and Prolog rules.

FedShard™ enables the execution of federated queries that are processed against multiple data sources but appear to access a single database. Complex queries combine geo-spatial, temporal and social network analytics.

Early versions of AllegroGraph allow handling of spatial information in 2D (Franz Inc., 2005a), while starting from version 5, the concept of N-dimensional Geospatial information is implemented with proprietary functions (Franz Inc., 2005b). The drawback with AllegroGraph is that it basically handles multidimensional points without clearly defining the concepts of a reference system, and other spatial object types, such as lines and polygons, are not supported. It lacks support for the GeoSPARQL standard, which is the most widely used standard for spatial information. Additionally, indexing of information and inference rules to define some spatial functions must be programmed for each dataset separately, which increases its complexity of use. Due to all the aforementioned reasons, it is not considered a practical solution.

GraphDB is a family of graph databases with RDF and SPARQL support, created by Ontotext (Ontotext, 2022) in 2011. GraphDB uses linked datasets in the cloud, as well as proprietary resources. It offers three editions: Free, Standard and Enterprise. The Free edition is limited to running two queries simultaneously. The Standard edition does not have this limitation. The Enterprise edition provides improved performance in terms of simultaneous loading, querying and inferencing of billions of RDF statements. It has a query optimizer and a reasoner (TRREE Engine) to determine the most efficient way to execute a given query. The Workbench is the web-based administration tool.

GraphDB offers strong support for spatial data, as the GeoSPARQL standard version 1.0 has been fully implemented, enabling the representation of both spatial data and spatial operations in 2D. Additionally, it provides support for formats such as Geography Markup Language (GML), WellKnown Text (WKT) and GeoJSON. Additionally, GraphDB also implements its own functions to extend spatial functionality (Ontotext, 2022).

2.4.4 Triplestore selection

The two most popular triple stores, Virtuoso and GraphDB, were tested as they contain more functionality than Allegro Graph and Apache Jena. The Virtuoso server presented some configuration problems from time to time and its interface was not as user friendly as GraphDB's, so the latter was selected for this research.

Ontology editors and triplestores are built for different purposes. Protégé, for example, has a very didactic interface oriented to represent the different aspects of the ontology but lacks functions for data general management. When exporting the ontology to a serializable file, it does not employ dividers such as tabs to make the final file easy to visualize. GrahpDB, on the other hand, is oriented to data storage and management. An ontology design tool similar to OntoRefine would be desirable in GraphDB to complete its functionality. GraphDB tools certainly provide a lot of useful visual functionality for exploring the data (Annex I).

Mapping approaches and tools were briefly explored since OntoRefine fulfilled the required expectations. However, it is important to further explore these options since a manual import of the data with several transformations was performed. It would be interesting to explore how this process can be implemented more efficiently and automatically.

2.5 Semantic Web for cultural heritage

The integration capabilities of the Semantic Web are very suitable for the cultural heritage domain. In fact, many subdomains already use ontologies for data integration. In this section we explore ontologies developed for the cultural domain and the projects where those ontologies were used.

2.5.1 CIDOC-CRM

The Committee International for DOCumentation (CIDOC) of the International Council of Museums (ICOM) established a Conceptual Reference Model (CRM) in 2000, which became ISO-standard 21127:2006. Since then the CIDOC-CRM Special Interest Group and its working groups constantly review the standard for possible extensions (ICOM, 2015). The scope of this mature ontology is scientific documentation of heterogeneous museum collections and the integration of this documentation in libraries and archives.

One example of a successful implementation of CIDOC-CRM is Europeana (Gradmann, 2010), an internet portal working as an interface to books, films, paintings, museum objects, and archival records from several museums, libraries, and organizations from Europe. Europeana employs CIDOC-CRM with other ontologies such as: SKOS (Simple Knowledge Organization System, to represent taxonomies, thesaurus and vocabularies); ORE (Open Reuse and Exchange specification, standard to define exchanging aggregation); and the FRBR (Functional Requirements for Bibliographic Record) (Peroni et al. 2013).

Even though CIDOC-CRM was created for the documentation of museum artifacts, several extensions have been developed to cover other related domains. The Conceptual Reference Model for Building Archaeology (CRMBA) extension (Ronzino et al., 2015) supports the documentation of standing buildings in an archaeological context. The ARIADNE project focuses on the documentation of archaeological sites (Meghini et al., 2017). And the English Heritage (EH) (English Heritage, 2019) has implemented an archaeological extension called CRM-EH (Binding et al., 2008). The Parcours project (Niang et al., 2017) aims at providing an integrated system making the isolated conservation restoration data more accessible and easy to share and reuse. This project includes new concepts such as alterations, scientic_study and intervention. The Arches project (Crlisle et al., 2014) provides an open source software system for managing and registering inventories of immovable cultural heritage.

2.5.2 The Getty Research Institute vocabularies

The Getty vocabularies were created by the Getty Research Institute (The J. Paul Getty Trust, 2018) organize terminology for the fields of architecture, art, and culture. The Getty vocabularies comprise: The Getty Thesaurus of Geographic Names (TGN), The Union List of Artist Names (ULAN), The Art & Architecture Thesaurus (AAT), The Cultural Objects Name Authority (CONA) and the Getty Iconography Authority (IA). TGN contains information about places of relevance to art and architecture. ULAN includes information about artists and architects. AAT and CONA include information for art and architecture; AAT has more generic concepts and CONA oriented to the representation of artworks. IA represents iconographical information.

The vocabularies are compliant with international standards for thesaurus construction (NISO,ISO), the Categories for the Description of

Works of Art (CDWA) and Cataloging Cultural Objects (CCO)(Getty Research Institute, 2019a).

Researchers and cataloguers have access to authoritative information enhancing access to web sites and databases. AAT, TGN, and ULAN are available as LOD while CONA is being mapped to CIDOC CRM (Getty Research Institute, 2017). By August 2019, information comes from 212 contributors among museums, libraries, galleries, universities, etc (Getty Research Institute, 2019b).

Several projects such as Europeana and ARIADNE have employed the Getty Vocabularies. Europeana is linked to the AAT vocabulary which enriches their data with vocabulary terms that are structured and multilingual (Europeana Pro, 2019). In the ARIADNE project, the AAT vocabulary is the backbone of all the terms (Meghini et al., 2016).

2.5.3 Finland ontology

The National Semantic Web Ontology project (FinnONTO) is an ideal example of ontology application at national level. The project has been directed by the Aalto University (Semantic Computing Research Group) and the University of Helsinki. This project ran from 2003 to 2007 and resulted in the creation of the Finland Semantic Web infrastructure. A project of this magnitude was accomplished with the participation of cultural institutions, libraries, health government, organizations, education, and media (Hyvönen et al., 2008). In this project several tools such as: standards, ontologies, services and application were developed for several domains such as: Culture, Health, Government, Education and Commerce.

In the heritage domain there are two main applications: MuseumFinland and CultureSampo. MuseumFinland (Semantic Computing Research Group, 2004) is a portal based on semantic web for publishing museum collections. The portal integrates information from the National Museum

(Finnish Heritage Agency, 2019), the Espoo City Museum (Museot.fi, 2019a), and the Lahti City Museum (Museot.fi, 2019b). The portal uses seven domain ontologies corresponding to the following domains: artifacts, materials, actors, situations, locations, times, and collections (Hyvönen et al., 2002).

CultureSampo (Semantic Computing Research Group, 2019) is an extension of MuseumFinland. It focuses on applications for intelligent search and browsing, suggesting new searches to the user according to user preferences. For example, if a user searches for a painting of a war, other paintings with the same theme will be suggested. The application can also browse according to related themes. For example, suggesting places and events related to the user search. In the example of the painting, it can suggest more information about the war or the place portrayed in the painting (Hyvönen et al., 2006).

2.5.4 MONDIS

In the framework of the MONDIS research project was developed the Monument Damage Ontology (Cacciotti et al., 2013). MONDIS project aims to develop an ontological framework focus on the coordination of automated reasoning for the documentation of built heritage damages, leading to a diagnosis and possible interventions.

The ontology comprises concepts in five clusters: i) component and construction description, ii) events, iii) risk assessment, iv) measurement and v) other topics. The intended applications of MONDIS include: the implementation of a local or national authorities management system, a tool for learning support for students and owners, and a tool to support the professional practices.

2.5.5 Spatial ontologies

Spatial and three dimensional information is required for the cultural heritage domain and especially for architectural heritage. As described in section 2.4.3, two prominent standards have emerged for the exchange of three dimensional models: CityGML and IFC. In this section we discuss equivalent ontological versions of these standards.

In 2010, the University of Geneva in Switzerland developed the CityGML ontology. Similar to the CityGML stanadard, the Geneva ontology implements in OWL the modules for: Building, Bridge, CityFurniture, Relief, Transportation, Tunnel, Vegetation and WaterBody. It includes 185 classes, 281 object properties, 92 data properties, and 568 logical axioms. It can be applied for the creation of air quality models (Métral et al., 2012) merging the cityGML standard with the urban planning process leading to the creation of the urban planning process ontology (OUPP).

IFC uses the EXPRESS schema as data model; aiming to support the architectural design and construction industry an OWL version of the model has been created by the University of Ghent (Pauwels, 2016). The resulting ontology is as extensive and complex as the original schema. It includes 1313 classes, 1580 object properties, 5 data properties, 13,867 logical axioms, and 1158 individuals. The authors are trying to overcome these issues by working with modules or suggesting less complex semantic structures (Pauwels et al., 2017). For instance, suggesting a more simple representation of coordinate lists.

2.6 Conclusions

Throughout this chapter methodologies and tools are explored and a motivated selection is made. This section presents the selected methodologies and tools and how they relate to each other as shown in Figure 2.21.

On-to Knowledge Methodology

Knowledge Meta Process

Phases	Feasibility	Kickoff	Refinement	Evaluation	Mainteinance
Tools	Cuenca case study (problems, opportunities, possible solutions)	LOV Protégé	Protégé	OOPS, Technical user evaluation	Protégé
Output	Requirements document	Already developed ontologies BCH taxonomy	Prototype BCH ontology	Report of changes	BCH ontology

Knowledge Process

Phases	Import	Capture	Retrieval	Use
Tools	Cuenca stakeholders databases DB Graph	DB Graph	DB Graph QGIS	Further applications user questioners
Output	Independent stakeholders semantic (owl) documents	Interlinked stakeholders semantic (owl) documents	Use cases implemented	Further applications user questioners analysis

Figure 2.22 depicts the methodology, processes and phases with the tool selected in that phase and the corresponding output.

Chapter 3: Cuenca - Ecuador Case Study

This chapter presents the BCH characteristics of Cuenca - Ecuador that makes it a suitable use case for this study and its main stakeholders [Section 3.1], followed by the tools developed by them [Section 3.2]. In an effort to integrate their information, stakeholders created a CityGML ADE model based on a PCA [Section 3.3]; this model is then analyzed and the semantic gaps impeding stakeholder collaboration in Cuenca are presented [Section 3.3].

3.1 Preventive Conservation in Cuenca-Ecuador

Cuenca is located in the canton of Cuenca, province of Azuay, in Ecuador. In July 2022, 1154 places from 167 countries were listed by UNESCO as Cultural Heritage Sites. The Historic Centre of Santa Ana de los Ríos de Cuenca, located in Ecuador, is one of them. The criteria by which Cuenca was nominated a World Heritage Site are the following (UNESCO World Heritage Centre, 1999).

- Criteria II: The renaissance urban planning principles are present in Cuenca.
- Criteria IV: The layout and townscape of Cuenca shows the fusion of different cultures and societies in Latin America.
- Criteria V: Cuenca is a planned inland Spanish colonial city. [2]

[2] Criteria from the Cuenca nomination file. UNESCO.

According to UNESCO, the task of protecting and conserving the heritage situated on a territory belongs to each state and depends on what is considered culturally valuable for the contemporaneous society (UNESCO, 1972). In Cuenca, therefore, valuable BCH is considered as the core of the data analysis. However, a proper management of the BCH of Cuenca requires integrated information from all the management stakeholders which are at several organizational levels.

3.2 Cuenca stakeholders for BCH management

The Constitution of Ecuador (Asamblea Nacional, 2008) is the main legal framework that governs the country. In matters of heritage, Article 3 establishes as the primary duty of the Ecuadorian state to "Protect the cultural and natural heritage of the country." The Ministry of Culture and Heritage is responsible at national level for generating public policies that ensure the fulfillment of this duty. In addition, Article 264, numeral 8, establishes that: "Municipal governments shall have the following exclusive competencies without prejudice to others determined by law... Preserve, maintain, and disseminate the architectural, cultural, and natural heritage of the canton and build public spaces for these purposes"

The Ley Orgánica de Cultura / Organic Law of Culture (LOC) (Asamblea Nacional, 2016) and its regulations (2017) provide for the creation of the Sistema Nacional de Cultura / National Culture System (SNC), which consists of two subsystems: (1) the Subsystem of Social Memory and Cultural Heritage, and (2) the Subsystem of Arts and Innovation. Public policies on cultural heritage fall under the Subsystem of Social Memory and Cultural Heritage, which, according to Article 24 of the LOC, includes: the Instituto Nacional de Patimonio Cultural / National Institute of Cultural Heritage (INPC); Benjamin Carrión Ecuadorian House of Culture; Museums, archives, libraries, hemerotecas, cinematecas, mediatecas, repositories, cultural centers, and entities of heritage and social memory that receive public funds, in addition to those voluntarily joined and approved by the Ministry of Culture and Heritage; Municipal Governments and Special Regime entities; and, those receiving public funds.

The Ministry of Culture and Heritage is the governing body of national public policy generation. The INPC is responsible for research and technical control, and it is divided into several zonal directorates, with the provinces of Azuay, Cañar, and Morona Santiago falling under Zone 6. The Benjamin Carrión Ecuadorian House of Culture serves as a space for common encounters, coexistence, and the exercise of cultural rights, expressing cultural and artistic diversity, social memory, and interculturality. It is located in Quito and has a office in each province (Asamblea Nacional, 2016).

In the Municipality of Cuenca, the mayor is its main representative, and together with the elected councilors, they form the Illustrious Cantonal Council, responsible for shaping public policy at the cantonal level. In matters of cultural heritage, the Municipality of Cuenca has the Direccion General de Areas Históricas y Patrimoniales / General Directorate of Historical and Heritage Areas (DGAHP) and the Commission of Historical and Heritage Areas. The DGAHP is the executing body of public policies, responsible for valuing, conserving, maintaining, and disseminating the tangible and intangible cultural heritage of the Cuenca canton, for current enjoyment and transmission to future generations, through processes of research, planning, and control (Municipality of Cuenca, n.d). The Commission of Historical and Heritage Areas is an advisory body composed of two representatives of the cantonal council, the director of the INPC or their delegate, a delegate from faculties or schools of history, geography, anthropology, sociology, or related fields from the universities of the Cuenca canton, a delegate from faculties or schools of architecture from the universities of the Cuenca canton, a representative of the citizens, and a delegate from the Consortium of Rural Parish Councils of the canton. Among its main activities, the commission serves as a communicator between the DGAHP and the cantonal council (Municipality of Cuenca, 2010).

According to Rodas Espinoza (Rodas Espinoza, 2016), for the specific case of the city of Cuenca, the management of built heritage is legally concentrated between the INPC Zone 6 and the Municipal GAD (Gobierno Autónomo Descentralizado/ Decentralized Autonomous Government) of the Cuenca Canton through the DGAHP (Municipality of Cuenca, n.a) and the Commission of Historical and Heritage Areas. While the DGAHP is the executing unit, the INPC has a supervisory role. Another important stakeholder without legal competence is the Faculty of Architecture and Urbanism of the University of Cuenca which, through its VLaamse Interuniversitaire Raad-City Preservation Management project (VLIR-CPM) (now CPM research group, also known is Spanish as Ciudad Patrimonio Mundial), has directed its research towards issues related to the management of built heritage (CPM research group, 2022).

The CPM research group, part of the UNESCO Preventive Conservation, Monitoring and Maintenance of Monuments and Sites Chair (PRECOM^{3}OS), was created in 2008. The CPM research group has developed several tools and methodologies to support heritage management at multiscale (from building to local and regional level) in line with the PCA in a multidisciplinary (social inclusion, environmental hazards) perspective (CPM research group, 2022). Since 2011, CPM has implemented several campaigns of preventive maintenance in both rural and urban areas, generating a methodology in which teaching moves from the classroom to the heritage in situ, turning the city into a living laboratory where the different actors responsible for the management of the city's cultural heritage interact with each other (Cardoso et al., 2019).

Stakeholder objectives are summarized in the table below.

Table 3.1 Cuenca's stakeholders' aim.

Stakeholder / Jurisdiction	**Aim**
Ministry of Culture and Heritage / National	Generate public policies at national level to protect the cultural and natural heritage of the country. Act as the governing body of SNC.
INPC R6 / Regional	Research and technical control in cultural heritage management for the provinces of Azuay, Cañar, and Morona Santiago. It is governed by the regulations established by the national INPC.
Benjamin Carrión Ecuadorian House of Culture, Azuay headquarter / Regional	Provides spaces to promote cultural and artistic diversity and social memory for the Azuay province. It is governed by the regulations established by the national Benjamin Carrión Ecuadorian House of Culture, located in Quito.
Municipal Government of Cuenca / Local	Preserve, maintain, and disseminate architectural, cultural, and natural heritage at the cantonal level through public policy created by the Cantonal Council. DGAHP is the executing body of public policies and the Commission of Historical and Heritage Areas is an Advisory body between DGAHP and the Cantonal Council.
CPM Research group / No legal jurisdiction but it works at regional level	Develop tools and methodologies for heritage management at different scales. It has implemented several campaigns of preventive maintenance with the involvement of the main stakeholders.

3.3 Cuenca stakeholders tools for BCH management

In line with Rodas Espinoza (2016), the main actors in the management of the BCH are the INCP, the DGAHP, and the CPM research group. Therefore they have been selected for a more in-depth study of their information and tools.

Several information systems and tools were developed for Cuenca by the stakeholders, but there is no explicit relationship between them. Thus, integration of their systems is difficult and can only be developed through an exhaustive data analysis. In the following sections we explore the tools developed by each stakeholder.

3.3.1 INPC

The national INPC is the managing entity of Ecuador's cultural heritage and therefore has developed several useful tools for local governments. There are a variety of manuals, glossaries and methodologies, but its greatest effort has been the development of information systems. The current system is the Sistema de Información del Patrimonio Cultural del Ecuador / Information System of Cultural Heritage of Ecuador (SIPCE) and its predecessor is called Abaco.

SIPCE manages a collection of information from various fields organised in different modules. SIPCE collects information from 5 fields: movable, immovable, intangible, documentary and archaeological heritage. Movable heritage consists of objects with heritage value. Immovable heritage comprises buildings, urban complexes, public spaces and funerary equipment. Intangible heritage consists of cultural manifestations and expressions that transmit knowledge, skills, techniques and practices. The documentary heritage contains manuscripts, printed matter, audiovisuals and photographs. Archaeological heritage includes material remains that allow us to learn about past societies.

SIPCE consists of two modules: a technical module for INPC and government staff, and a public module for the general public. The public module contains four functionalities: search, map, navigation and statistics. The search can be done by keywords such as heritage code, geographic location, container and type of record. INPC manages two types of records: heritage interest and inventory. Inventory records provide more detail on the item inventoried. The map allows the visualisation of heritage assets in their location in the Ecuadorian territory, photographs and a summary of general information (Figure 3.1

right). The navigation allows the search of records first by field and then by categories and subcategories (Figure 3.1 left). Statistics are currently unavailable.

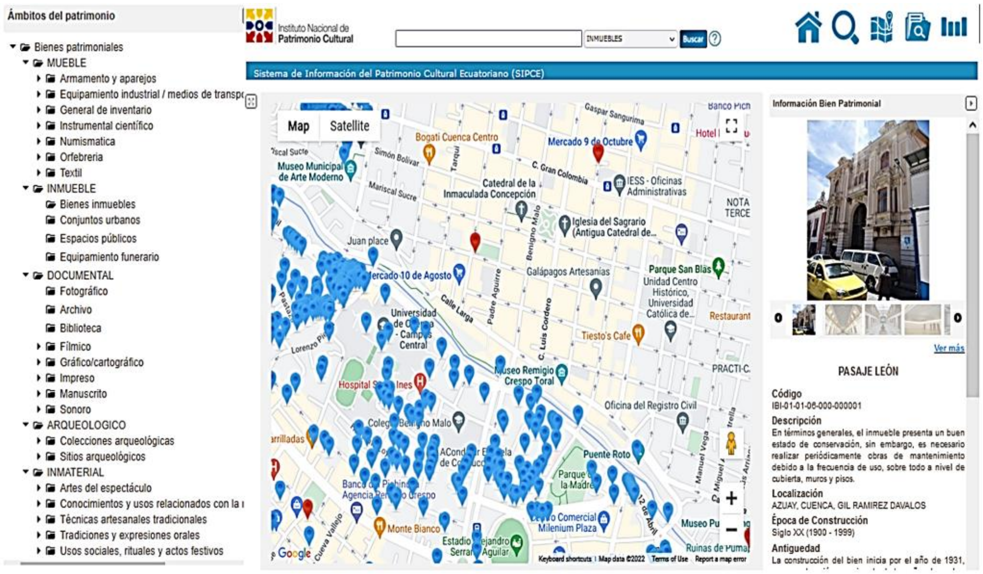


Figure 3.1 SIPCE Navigation categories and Map view (INPC, 2014). The SIPCE Navigation categories (left) allow us to explore the records of registered heritage. The map view (right) displays the heritage location.

Abaco was the previous heritage information system of Ecuador and all its information was migrated to SIPCE. Abaco had a primitive version of the full functionality from SIPCE without the map view. It displayed the full record of an asset while SIPCE displays a summary of it.

The Immovable heritage records of Cuenca from Abaco were exported to a spreadsheet (Figure 3.2) and made available for this research. It contains information related to condition, use, and ownership of buildings. The records are identified using the INPC's own identifier. Additionally the building location is stored as geographic coordinates of a point. This information is the equivalent to the technical module of

SIPCE and is used later in Chapter 5 to elaborate some use cases where information from the different stakeholders is integrated.

B	Z	AA	AD	AE	AF
codigo_t	direccion_t	propietario_t	siglo_c	etapa_s	tipologia
IBI-01-01-01-000-000001	EUGENIO ESPEJO 8-	MEJIA ORDO¥EZ JAIME	XX (1900 - 1999)	II	CIVIL
IBI-01-01-04-000-000001	ANTONIO BORRERO	SECRETARIA DE GESTI	XX (1900 - 1999)	I	CIVIL
IBI-01-01-67-000-000001	VIA PRINCIPAL S/N S/N		XX (1900 - 1999)	S/N	CIVIL
IBI-01-01-66-000-000001	PLAZA PRINCIPAL S/N S/N		XX (1900 - 1999)	S/N	RELIGIOSA
IBI-01-01-63-000-000001	VIA PRINCIPAL S/N S/N		XX (1900 - 1999)	S/N	CIVIL
IBI-01-01-63-000-000002	VIA PRINCIPAL s/n S/N		XX (1900 - 1999)	S/N	CIVIL
IBI-01-01-68-000-000001	N/A n/a N/A	MINSITERIO DE EDUCA	XX (1900 - 1999)	II	CIVIL
IBI-01-01-69-000-000001	VIA A AGUA SANTA	MUNICIPIO DE CUENCA	XX (1900 - 1999)	I	CIVIL
IBI-01-01-65-000-000001A	VIA AL CAJAS/LAGUNA DE LLAVIUCO n/a N/		XX (1900 - 1999)	II	INDUSTRIA
IBI-01-01-04-000-000002	SIMON BOLIVAR n/a	LUIS CORDERO	XX (1900 - 1999)	III	INSTITUCIC
IBI-01-01-65-000-000001B	VIA AL CAJAS n/a N/	CORPORACION MUNIC	XX (1900 - 1999)	II	INDUSTRIA
IBI-01-01-63-000-000003	VIA A BALZAY N/A N	GUERRERO VASZQUE	XX (1900 - 1999)	III	CIVIL
IBI-01-01-56-000-000001	PANAMERICANA NO	MOSCOSO GUERRERO	XX (1900 - 1999)	II	CIVIL
IBI-01-01-07-000-000001	AV. 24 DE MAYO s/n	I.MUNICIPALIDAD DE CU	XX (1900 - 1999)	III	CIVIL
IBI-01-01-11-000-000001	SIN NOMBRE S/N DE	GUTIERREZ FIGUEROA	XX (1900 - 1999)	II	CIVIL

Figure 3.2 Screenshot displaying the Cuenca immovable heritage records from Abaco. Data provided by the INPC.

With respect to spatial information, both SIPCE and Abaco only manage the (2D) location of buildings. INPC Zonal 6 handles information in 2D such as plans and surveys in both CAD and shapefiles for its projects, but they are primarily used for reference as part of the background for new projects.

3.3.2 Municipality of Cuenca

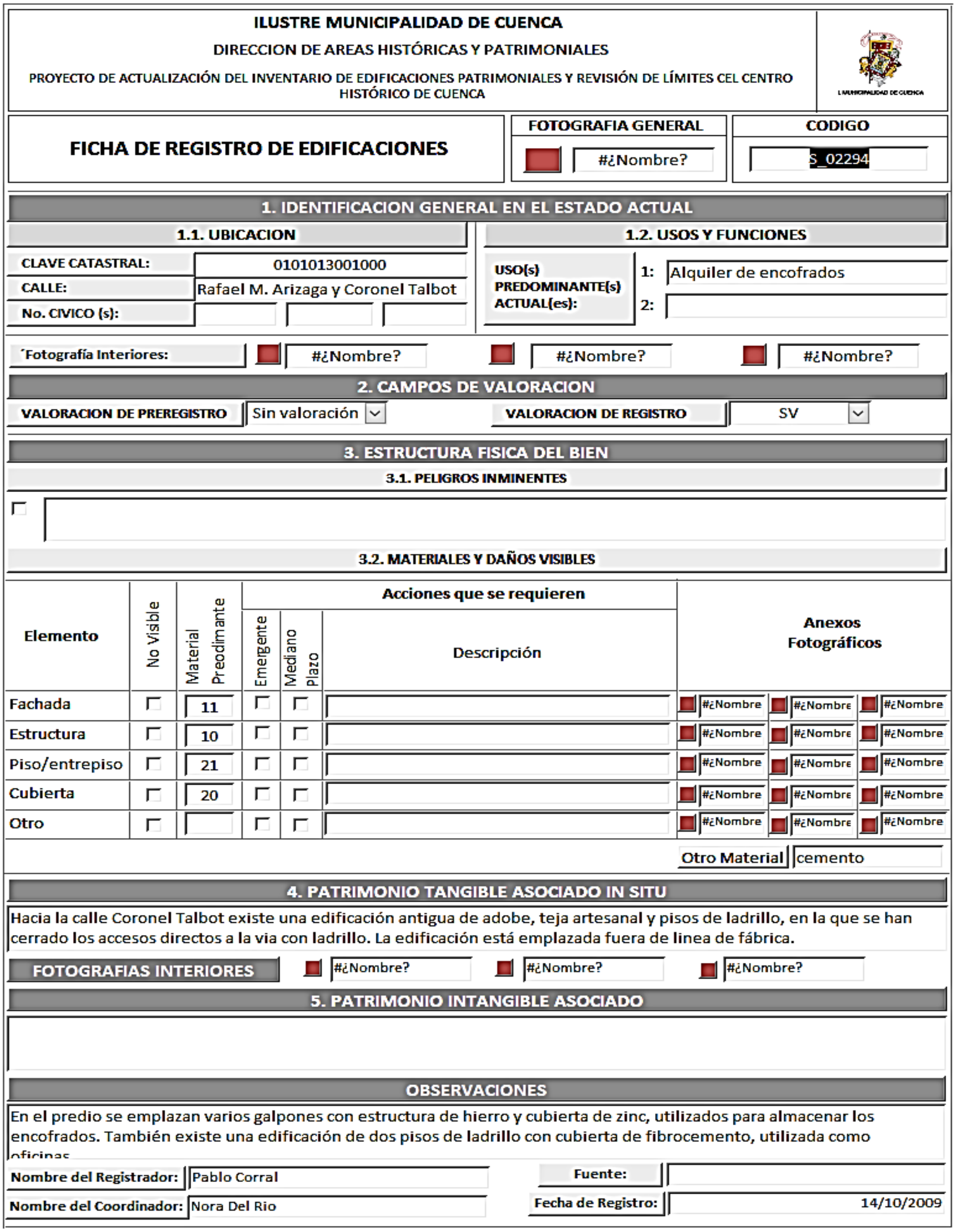
Although the policies for the management of patrimonial assets are dictated at the national level, the care of each asset is carried out at the local level through the municipalities. In this section, some developed tools from the municipality of Cuenca are explored.

A **Geoportal** (Figure 3.3) comprises administrative maps of several municipality departments. The DGAHP has uploaded relevant information to the register of heritage buildings, including requested procedures such as building permits and fines. There are also aerial views of a small sector of the city and 3D representations of particular buildings (Cuenca GAD Municipal, 2016).

a) Construction permits b) 3D building representation c) Aerial view

Figure 3.3 Screenshot displaying the Municipality GeoPortal (Cuenca GAD Municipal, 2016) depicting construction permits, 3D building representations and aerial views.

The **inventory** of a heritage building gives it the status of a protected property. In Cuenca, heritage buildings have been inventoried on four occasions, 1975, 1982, 1999, and 2008-2009. All inventories collect information on the physical characteristics of the property, its state of conservation, and information on the owners. However, the last inventory (Figure 3.4) is the one that presents more and better digital organized information. In this inventory 9338 buildings were inventoried and 3150 of which are identified to have some heritage value. This inventory contains information about location, heritage value, use, tangible and intangible heritage, and elements such as façade, structure, floor, and roof. For each element, materiality and risks are recorded.



ILUSTRE MUNICIPALIDAD DE CUENCA

DIRECCION DE AREAS HISTÓRICAS Y PATRIMONIALES

PROYECTO DE ACTUALIZACIÓN DEL INVENTARIO DE EDIFICACIONES PATRIMONIALES Y REVISIÓN DE LÍMITES CEL CENTRO HISTÓRICO DE CUENCA

FICHA DE REGISTRO DE EDIFICACIONES

FOTOGRAFIA GENERAL: #¿Nombre?

CODIGO: S_02294

1. IDENTIFICACION GENERAL EN EL ESTADO ACTUAL

1.1. UBICACION

CLAVE CATASTRAL: 0101013001000

CALLE: Rafael M. Arizaga y Coronel Talbot

No. CIVICO (s):

1.2. USOS Y FUNCIONES

USO(s) PREDOMINANTE(s) ACTUAL(es):

1: Alquiler de encofrados

2:

´Fotografía Interiores: #¿Nombre? #¿Nombre? #¿Nombre?

2. CAMPOS DE VALORACION

VALORACION DE PREREGISTRO: Sin valoración

VALORACION DE REGISTRO: SV

3. ESTRUCTURA FISICA DEL BIEN

3.1. PELIGROS INMINENTES

3.2. MATERIALES Y DAÑOS VISIBLES

Elemento	No Visible	Material Preodimante	Acciones que se requieren: Emergente	Mediano Plazo	Descripción	Anexos Fotográficos		
Fachada		11				#¿Nombre	#¿Nombre	#¿Nombre
Estructura		10				#¿Nombre	#¿Nombre	#¿Nombre
Piso/entrepiso		21				#¿Nombre	#¿Nombre	#¿Nombre
Cubierta		20				#¿Nombre	#¿Nombre	#¿Nombre
Otro						#¿Nombre	#¿Nombre	#¿Nombre

Otro Material: cemento

4. PATRIMONIO TANGIBLE ASOCIADO IN SITU

Hacia la calle Coronel Talbot existe una edificación antigua de adobe, teja artesanal y pisos de ladrillo, en la que se han cerrado los accesos directos a la via con ladrillo. La edificación está emplazada fuera de linea de fábrica.

FOTOGRAFIAS INTERIORES: #¿Nombre? #¿Nombre? #¿Nombre?

5. PATRIMONIO INTANGIBLE ASOCIADO

OBSERVACIONES

En el predio se emplazan varios galpones con estructura de hierro y cubierta de zinc, utilizados para almacenar los encofrados. También existe una edificación de dos pisos de ladrillo con cubierta de fibrocemento, utilizada como oficinas

Nombre del Registrador: Pablo Corral

Nombre del Coordinador: Nora Del Rio

Fuente:

Fecha de Registro: 14/10/2009

Figure 3.4 Screenshot displaying the 2009 Inventory. It contains information about location, valorization, risks, materiality, associated heritage and registration. Data provided by Municipality of Cuenca.

Through a personal interview, the director of the DGAHP (period 2020-2023) provided us information about the internal systems developed in the department, which are described below (F. Manosalvas, personal communication, December 15, 2022).

In 2004, based on the 1999 inventory, a web application called "**Geographical information system of the historic centre of Cuenca**" was created. This application was created jointly by the historic centre control unit and the undergraduate thesis "GIS for the control of interventions in buildings in the historic centre of Cuenca". The control unit is part of the DGAHP and is in charge of granting construction permits for historic buildings and supervising the construction process in case of complaints. The application manages the procedures within its competence. But only covers the first part of the permit process, after the building permit was granted, the case was transferred to the municipal control department, another municipal body that is not linked to the DGAHP. In 2008, all processes related to heritage areas became the sole responsibility of the DGAHP, so the system became outdated and a series of electronic forms were implemented in its place.

In 2011, the IT Department of the Municipality of Cuenca created a system called "**Control Procedures and Historic Areas" (TAC)** which systematises all procedures that must be fulfilled by the DGAHP, but does not take into account geographic information. In 2018, some of the procedures have been implemented on the web, such as minor construction permits and authorisations for signs and advertisements.

In July 2016, the DGAHP developed a system called **"Tecnologías de la Información para la Puesta en Valor del Patrimonio / Information Technology for the Enhancement of Heritage Value" (TIPVP).** This system has many improvements over its predecessors. Methodologically, it focuses on the "enhancement of heritage", as previous systems were oriented towards facilitating the processing of administrative procedures without considering cultural heritage as a living complex entity that is the originator of all processes. The TIPVP is a web platform that makes all areas of cultural heritage visible: immovable, movable, intangible, documentary and archaeological. The system integrates both alphanumeric and geographic data. The life cycle of a historic building is represented by means of a spiral that demonstrates continuity between the processes as shown in Figure 3.5.

Figure 3.5 TIPVP building interface with 115 processes available. Among the processes is a large amount of information collected from different sources both internal and external to the Municipality of Cuenca. Data provided by Municipality of Cuenca.

One hundred fifteen processes with their own sub-processes are available for each historic building. Although the TIPVP attempts to bring together all the information available for the management of heritage assets, it is also a rather complex system which requires a lot of time to become familiar with as it lacks documentation beyond some general reporting for administrative purposes. One of its shortcomings is that not all the modules present in the spiral are fully implemented, some of them are just for conceptual representation. For example, at the beginning of the spiral, the 'Property Registry' button is intended to integrate domain change information into the system but is not implemented yet since this information is managed by another governmental institution. The TIPVP could also benefit from a categorisation of processes. The different inventories carried out over time are presented with individual buttons when they could be grouped into one and further subdivided. A similar case is when different studies, such as electrical, structural, archaeological, or anthropological, are carried out on buildings.

In addition, there are general tools such as the legal regulations that support the processes, as well as several glossaries of terms organised according to the subject matter.

An interesting part of this system is the inclusion of a module of the planning system in which a methodology for the integrated management of heritage cities is described. This has been developed during the period 2019-2022. Unfortunately, due to the change of local authorities in the Municipality of Cuenca in May 2023, the activities related to the design of the planning system have been stopped.

With regard to the spatial data, there is a large amount of 2D and 3D information, but it is handled in isolation. The spiral part of the TIPVP handles some information such as plans but they are handled as attachments that have to be downloaded for manipulation. Generally each public server handles its own GIS, CAD, OBJ, etc. files. These are deposited in shared folders for access by other personnel who need to consult them, but there is no catalogue or system that allows easy organisation and identification of this data. This functionality is intended to be integrated into the TIPVP. The initial processes of democratisation of geographic information consists of the creation of several 2D and 3D geoviewers.

The main geoviewer is the 'Internal Overview Viewer' which integrates about 500 layers. In this viewer heritage buildings (yellow) and non-heritage buildings (red) can be visually identified by means of a polygon layer. Additionally, a layer of points indicates the buildings registered by the INPC. The text box displayed at the right of Figure 3.6, shows information on photos, owners, areas, DGAHP staff responsible for the control of the properties, etc. It also presents a link to the thematic part of the TIPVP where it is possible to link to the aforementioned processes of the spiral.

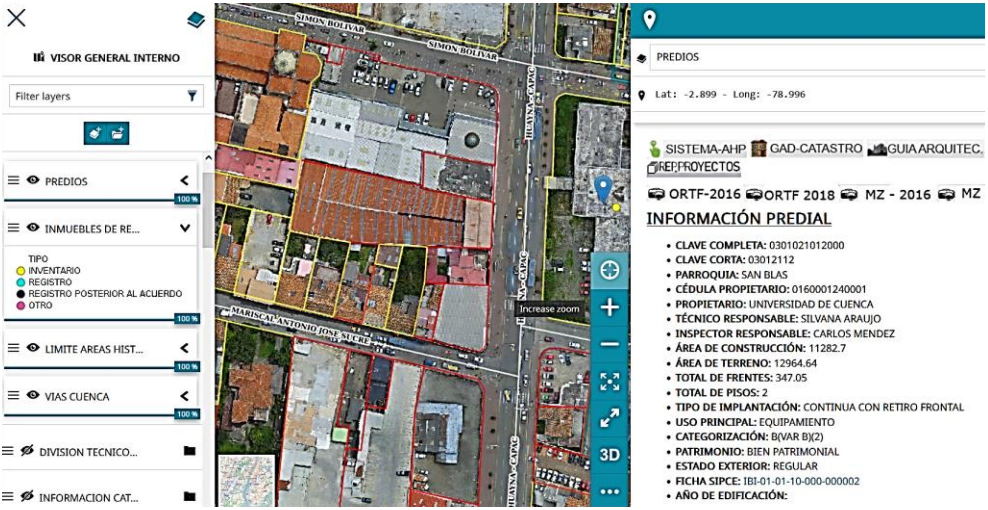


Figure 3.6 2D viewer where heritage buildings and related information are displayed. Data provided by Municipality of Cuenca.

For the management of 3D information, the Cesium platform is being explored, an open source platform that allows the representation of buildings in 3D as well as their context, supported formats are: .obj, fbx, dae, gltf, .glb . By the beginning of 2023, detailed representations of some heritage buildings (Figure 3.7) as well as an overview of the heights of the historic centre of Cuenca have been produced. As it is in an initial exploration stage, this information is not publicly available.

Figure 3.7 representation of a heritage building in Cesium. Data provided by Municipality of Cuenca.

Undoubtedly, the TIPVP is the largest effort made by the Municipality to organize and integrate the heritage information of the city of Cuenca and is intended for the use of DGAHP officials.

However, when it comes to integration with the different heritage management bodies, it still has the same difficulties in updating information and lacks a standardized method for receiving/sending information. For example, among the processes there is information from the cadastre department, which was migrated once and is out of date. This information is manually updated when a new procedure such as a certify request is submitted with inconsistent information. The same happens with the SIPCE information, which is also duplicated in the TIPVP.

3.3.3 CPM research group

The CPM research group develops tools for the city of Cuenca in collaboration with the INPC and the municipality. The tools are tested in small areas. Once the tools have been validated, they are applied at city level by the municipality. The CPM research group has an informative website, however, several aerial images, relational databases, GIS, among others are managed internally.

CPM handles only 2D information of plans and surveys in CAD and shapefile formats. Preventive maintenance campaigns contribute the most to these floor plan surveys, where components, materials, and construction status are represented. Similar to INPC Zone 6, this information is used for documentation purposes, both for assessing a therapy and as background for future interventions.

3.3.4 Normative regulation

Ecuador is a signatory state concerning the application and management of sites on the World Heritage List, of which the secretariat is at UNESCO. UNESCO and the advisory bodies nor the operational guidelines establish or define specific methodologies regarding public access of information. Instead, they respect the methodologies adopted by each state. In the realm of heritage, international standards are seen as a framework of principles and general guidelines (Rodas Espinoza & Contreras Escandón, 2021).

The legal framework aligns with the organization of stakeholders. The national constitution states the protection of heritage as a state duty, with the LOC of 2016 being the supreme law at the national level aimed at defining the competencies, powers, and obligations of the State, the foundations of a public policy oriented towards guaranteeing the exercise of cultural rights and interculturality, as well as organizing the institutions responsible for culture and heritage through the integration and functioning of the SNC (Asamblea Nacional, 2016).

The INPC, the Benjamin Carrión Ecuadorian House of Culture, and the CPM research group are actors involved in project formulation. The Cantonal Council is responsible for approving and publishing public policies at the cantonal level. These policies are generally generated by the DGAHP. Among the current regulations for cantonal management is the Plan de ordenamiento territorial y el plan de uso y gestión del suelo / Development and Land Use Management Plan **(PDOT-PUGS)** in which land use regulations are defined, also a period of 30 working days is defined for the elaboration and presentation of a special management plan for the historic centre of Cuenca (Consejo Cantonal, 2022). The Municipality of Cuenca has a unique opportunity later in 2023 to present the Special Plan for the management of the historic Centre which is composed of a technological plan among others. This is undoubtedly the right time to include the notion of semantic integration and for which the deliverables of section 6.1 are fundamental for the understanding of this topic.

While the Special Plan for the management of the historic centre is being developed, there are certain ordinances that provide guidelines for its management. Rodas Espinoza & Contreras Escandón (2021) offer a detailed study of regulations in the realm of cultural heritage from international to local levels. The following figure provides a summary of the some local ordinances.

Nro	Nombre	Fecha
1	Ordenanza para el control y administración del Centro Histórico de la ciudad de Cuenca	Febrero/1983
2	Ordenanza sobre rótulos y anuncios en el Centro Histórico de la ciudad	Septiembre/1991
3	Reglamento para el uso del color y materiales del Centro Histórico	Octubre/2000
4	Ordenanza especial para preservar y mantener el patrimonio arquitectónico, cultural y árboles patrimoniales del cantón Cuenca	Agosto/2009
5	Ordenanza especial para preservar y mantener el patrimonio arquitectónico, cultural y árboles patrimoniales del cantón Cuenca	Febrero/2010
6	Ordenanza que determina y regula el uso y ocupación del suelo en el área de El Ejido (Área de influencia y zona tampón del Centro Histórico)	Junio/2010
7	Ordenanza de transición para la adecuación de las ordenanzas vigentes a las disposiciones del COOTAD y el ejercicio de las competencias exclusivas establecidas en el Art. 264 de la Constitución	Diciembre/2010
8	Ordenanza para la protección del conjunto urbano arquitectónico de Cristo Rey de Cullca	Mayo/2013

Figure 3.8 Instruments for the management and control of Heritage in the Historic Centre of Cuenca. Adapted from (Rodas Espinoza & Contreras Escandón, 2021).

The table presented above does not include the incorporation of the revision to ordinance number 6, implemented in December 2021. This revision modifies specific clauses related to land use and occupancy within the historic centre. This revision holds significant importance as its annexes establish the necessity for conducting assessments of sections, land use, and volumetric studies before authorizing construction permits. These assessments are conducted through the utilization of GIS technology and 3D models, showcasing the height and volumetric analyses feasible before project execution (Consejo Cantonal, 2021). Despite the regulations stipulating that such analyses should be included in proposals, to our current knowledge, this practice is not consistently observed, probably because there are not enough trained professionals to prepare these models in the proposals. Datasets are not open either, which is unfortunate because if these policies are to be implemented, they must be disseminated and professionals in the area must be trained on a massive scale.

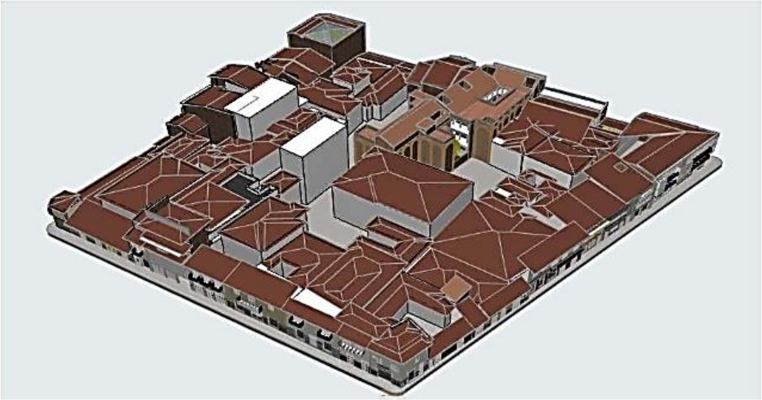


Figure 3.9 3D volumetric representations (Consejo Cantonal, 2021)

In recent years there has also been a shift in mindset with respect to the current regulations for accessing public information, for the first these issues are considered in an efficient way. The open data policy (Mintel, 2022) was published in July 2022, accompanied by a guide which talks about ontological models and the 5-star linked data scheme; however, the lack of trained personnel in these topics prevents their correct implementation.

3.4 Stakeholders collaboration

The tools described in previous sections do not share information among each other. They are informative but none of them allow data downloading. The stakeholders recognized the need to integrate information from these tools. In 2010-2014 as part of a doctoral research (Heras, 2014), the CPM research group in collaboration with representatives of INPC, Municipality of Cuenca, researchers, tourists and citizens developed a city geographic markup language (CityGML) based data model. The model was created through an ADE which is the starting point for this research. The following sections describe the CityGML standard and the ADE classes.

3.4.1 CityGML Building module

Classes in the CityGML-Building module enable a 3D representation of buildings and their components such as walls, roofs, etc. The main class is “AbstractBuilding” (Figure 3.10) which inherits properties from the “_CityObject” and “_Site” classes.

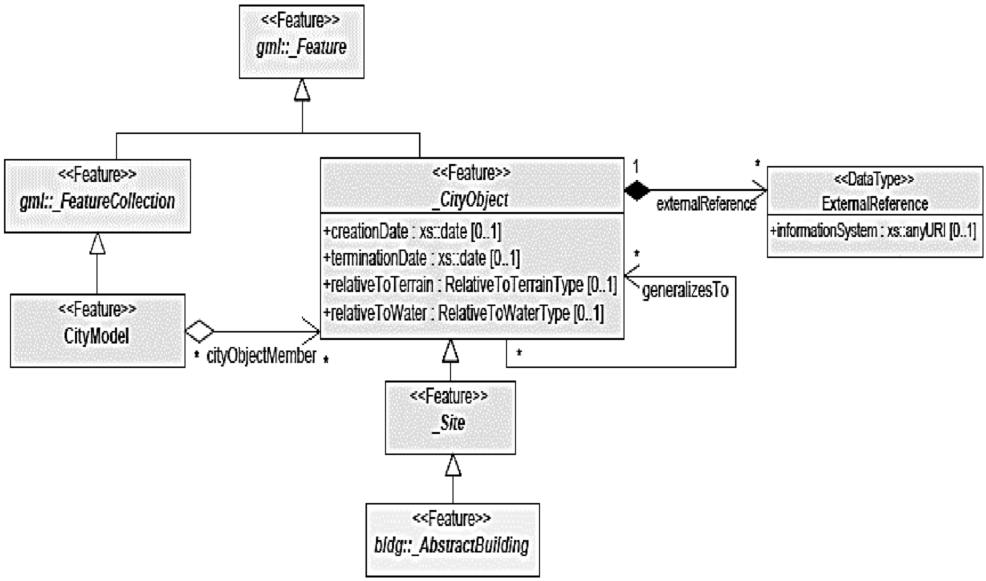


Figure 3.10 UML diagram depicting the Core module of the CityGML standard (Gröger et al., 2008).

Figure 3.11 shows the classes from the CityGML-Building module. The “_AbstractBuilding” class is implemented using the “Building” class or a set of “BuildingPart” classes.

“_AbstractBuilding” classes are bounded by several “_BoundarySurface” classes which can be: “WallSurface”, “RoofSurface”, “GroundSurface”, “ClosureSurface”, “CeilingSurface”, “InteriorWallSurface”, “FloorSurface”, “OuterCeilingSurface”, and “OuterFloorSurface.” Each

“_BoundarySurface” class can have several “_Opening” classes such as “Door” or “Window” classes. Openings, rooms, furniture and installations are represented using the “ImplicitGeometry” class. “_BoundarySurface” classes are represented using the “MultiSurface” class.

The “_AbstractBuilding” is related to “Rooms”, “BuildingInstallations”, and “IntBuildingInstallations” classes. The “Room” class has a relationship with the “BuildingFurniture” class. “BuildingInstallation”, “IntBuildingInstallations” and “BuildingFurnature” classes can also be represented using the “_Geometry” class. Abstract buildings are also represented by solids, curves or surfaces using the different LoD provided by the CityGML standard. Several “Address” classes can be related to one “_AbstractBuildings” class.

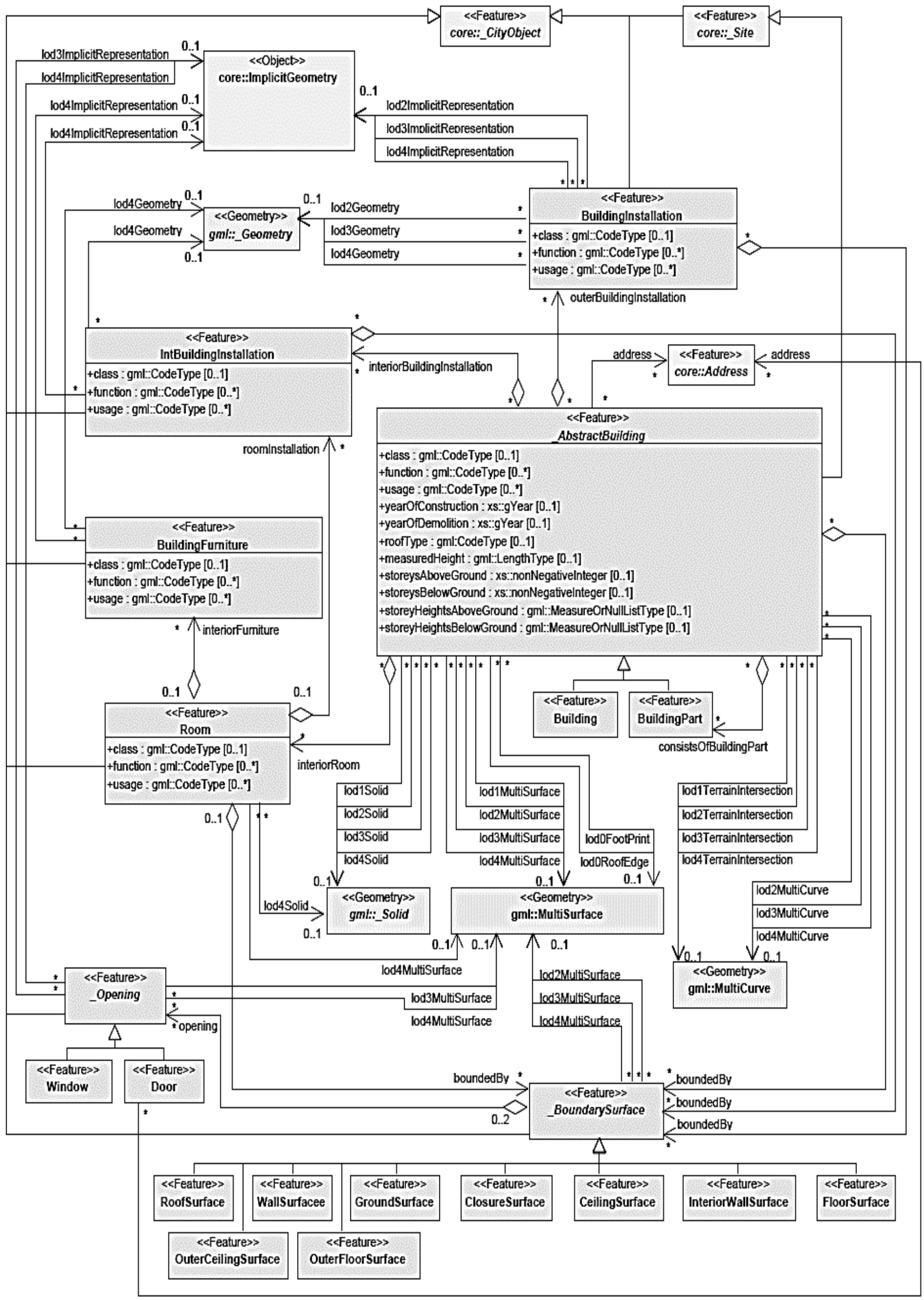


Figure 3.11 UML diagram depicting the CityGML-Building module of the CityGML standard (Gröger et al., 2008).

3.4.2 CityGML-ADE from Cuenca – Ecuador

The CityGML-based data model was developed by Heras (2011) in collaboration with stakeholders through a dedicated ADE. Basically, the CityGML - ADE model merges the specific purpose classes required for implementing a PCA (Figure 3.12 gray) with general purpose classes of the CityGML-Building module (Figure 3.12 white). For readability purposes, Figure 3.13 and onward represent all classes in white. Original figures are used, including some spelling mistakes.

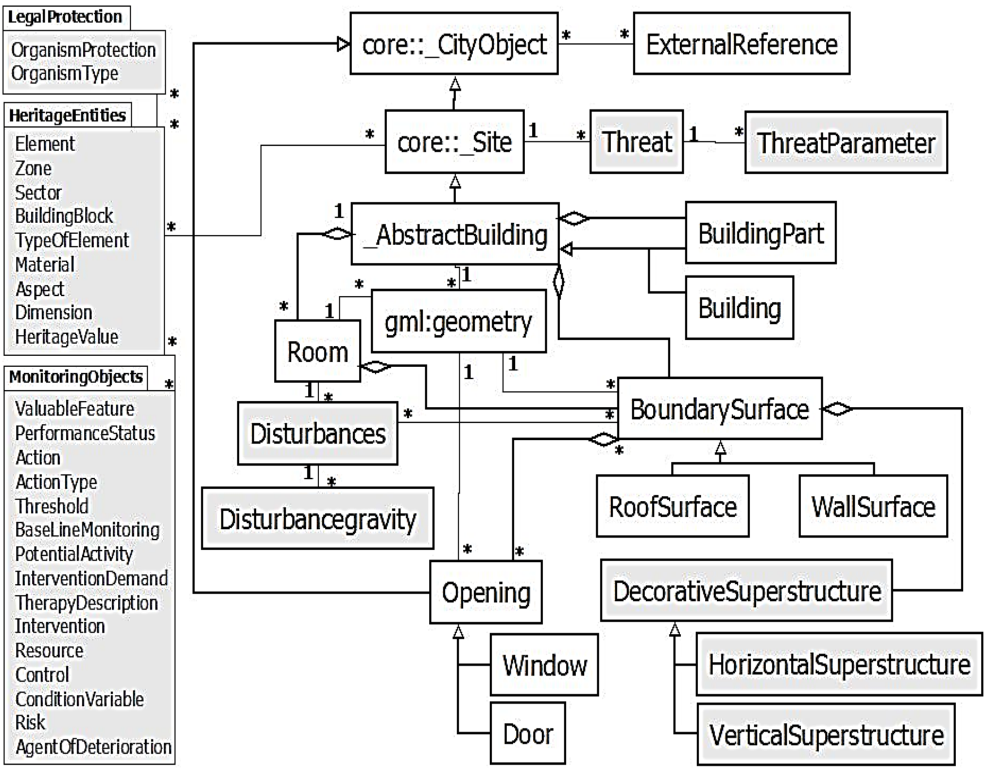


Figure 3.12 UML diagram depicting a summary of the CityGML(white) - ADE (gray). Adapted from Heras et. al (2011).

The preventive conservation classes are organized in heritage entities, legal protection and monitoring stage.

PCA classes - heritage entities

The heritage entities classes (Figure 3.13) encompass the "Element" class which stands for different geographic scales such as those represented by the "Zone", "Sector", "Building block", "Building" and "Constitutive element" classes. For each of these classes, its own attributes are defined.

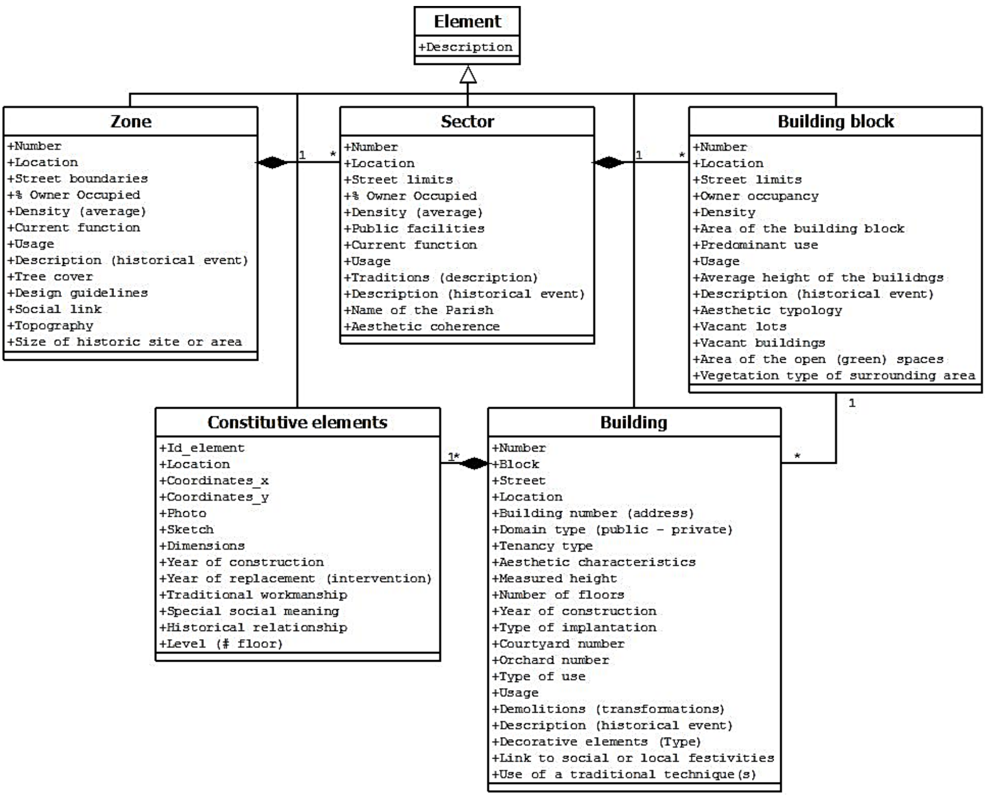


Figure 3.13 UML diagram depicting the heritage entities classes. Adapted from Heras et. al (2011).

Each element such as zone, sector, building block, building or constitutive element may have several heritage values (Figure 3.14). Each "Heritage value" class is associated with one or many "Aspect" and

"Dimension" classes according to the Nara Document on Authenticity (Van Balen, 2008). For the Constitutive elements, a type and materials are recorded. In addition, the workmanship technique applied to the material is also gathered. To this end the "Material" class is used.

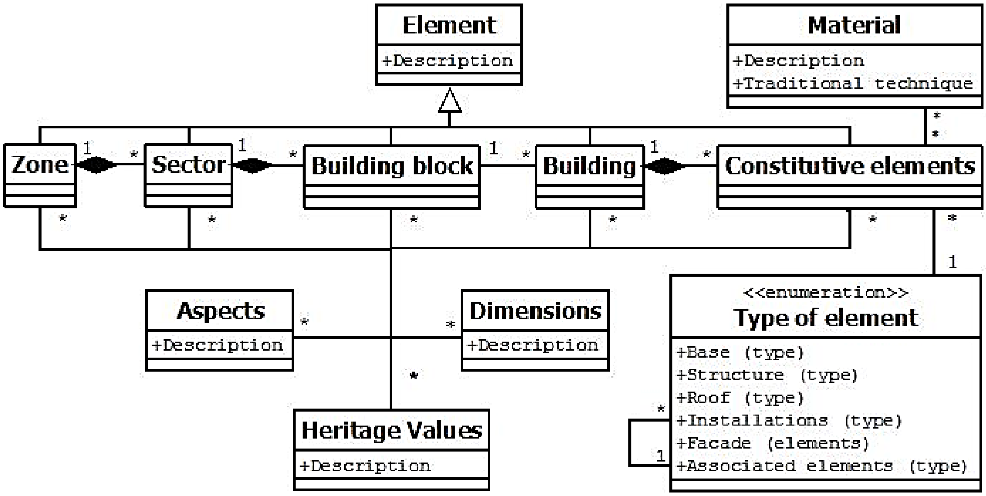


Figure 3.14 UML diagram depicting the material, type of element, aspect, dimension and heritage values classes (Heras et al., 2011).

In order to physically represent some architectural heritage parts of constitutive elements the "_DecorativeSuperstructure" classes are employed (Figure 3.15). The "_DecorativeSuperstructure" class is related to the "HorizontalSuperstructure" and "VerticalSuperstructure" classes. Horizontal superstructures include the "Architrave", "Frieze", and "Cornice" classes. Vertical superstructures include the "Pilastra" class. "_Opening" and "_BoundarySurface" classes are bounded by "_DecorativeSuperstructure" class.

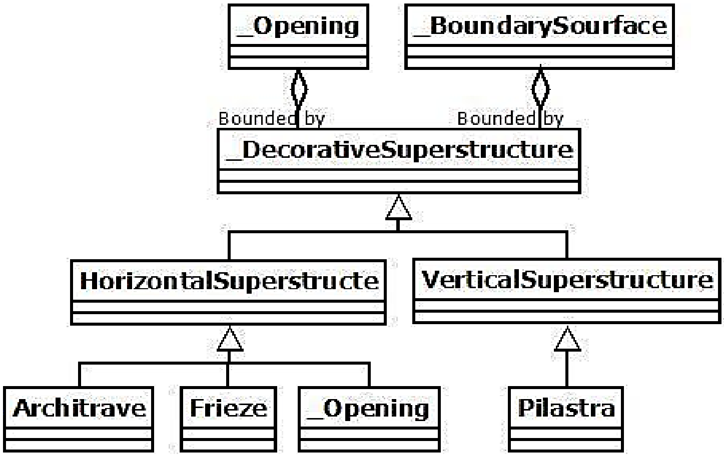


Figure 3.15 UML diagram depicting the decorativeSuperstructure classes (Heras et al., 2011).

PCA classes - Legal protection

The legal protection classes encompass the “Organism protection” and “Type” classes (Figure 3.16) which refer to legal protection of what is considered heritage value. These classes contain information about the organism responsible for management, the scope of the legal protection, and the level of protection. In addition, the “Organism protection” class is related with a “Type” class, which can be international, national, regional or local.

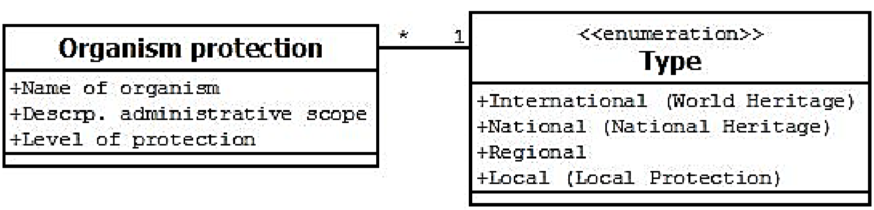


Figure 3.16 UML diagram depicting the legal protection classes (Heras et al., 2011).

PCA classes –monitoring stage

Monitoring stage classes (Figure 3.17) represent the phases from the PCA. The main element to be monitored is a valuable feature. A heritage value existed because there are several heritage features in a component, thus the "Heritage value" class is related to many "Valuable features" classes.

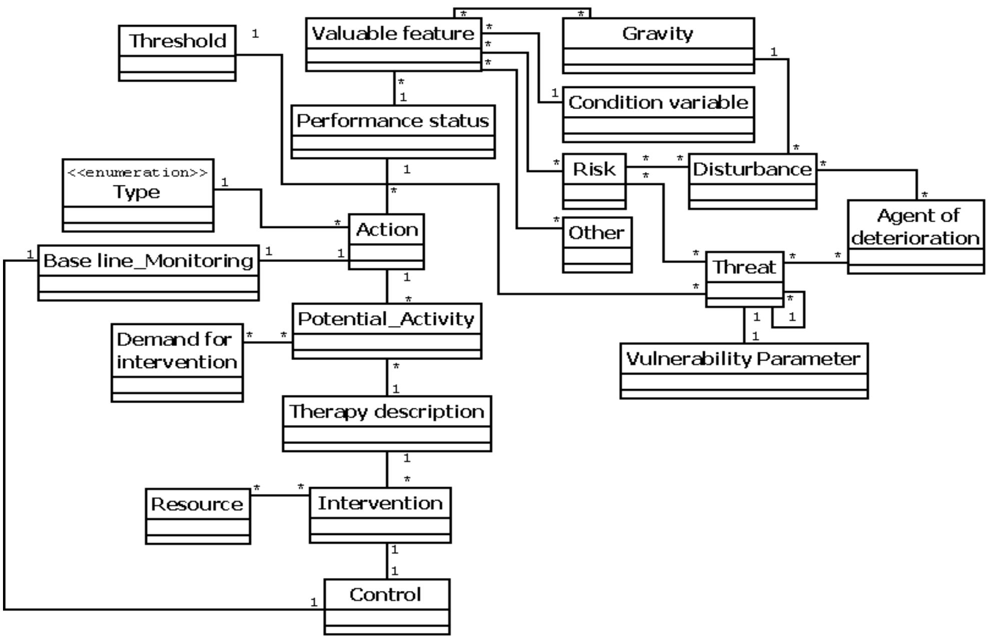


Figure 3.17 UML diagram depicting the monitoring stage classes. Adapted from Heras et. al (2011).

The analysis classes contain information about the valuable features through the "Gravity," "Risk," "Condition variable" and "Other" classes (Figure 3.18). "Other" class refers to external factors such as the population change, the restoration rates and demolition permits. Gravity is computed considering disturbances and the causes of those problems through the "Disturbance" and "Agent of deterioration" classes. Risk assessment is a crucial activity for the preventive conservation management of historical buildings. There are several methodologies (Jimenez, 2001; Paolini et al., 2012; Wang, 2015) for risk assessment but basically the risk is computed by assessing threats and vulnerability. Threats can be sub-classified, thus the “Threat” class has a self-relationship. Vulnerability uses a parameter list represented by the “Vulnerability Parameter” class which allows us to assess if a valuable feature is more or less vulnerable. The condition of a valuable feature is set by computing a list of variables with the “Condition variable” class which defines the condition in a period of time.

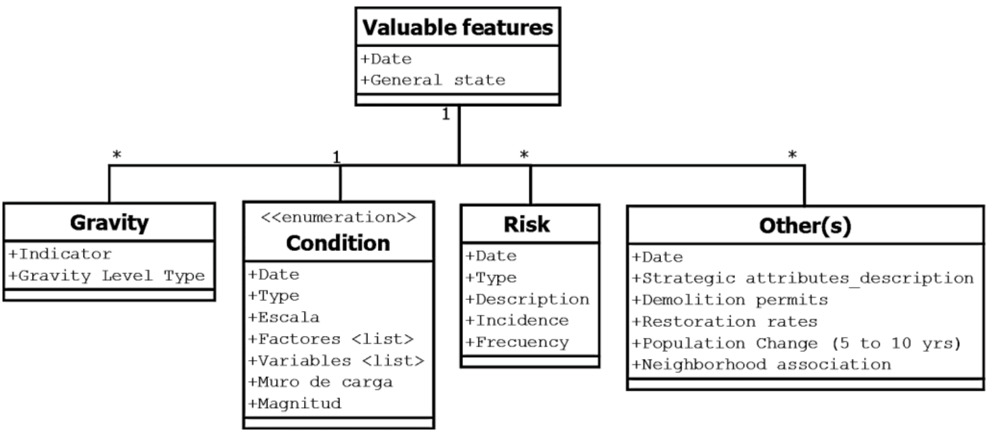


Figure 3.18 UML diagram depicting the analysis classes. Adapted from Heras et. al (2011).

The PCA-diagnosis phase computes the state of heritage features by summarizing the analysis classes. The diagnosis classes (Figure 3.19) comprise the “Performance status,” “Actions,” “Base line_Monitoring” and the “Threshold” classes. Performance status is computed using the effect of consequential damage, the speed of deterioration, the relative importance of damages and the alterations made in the element to be monitored. Then, according to the thresholds and the computed performance status, a set of actions are listed. Actions are curative or preventive (direct, indirect), this typology is represented by the “Type” class. The base line of monitoring sets the period(s) to execute the actions.

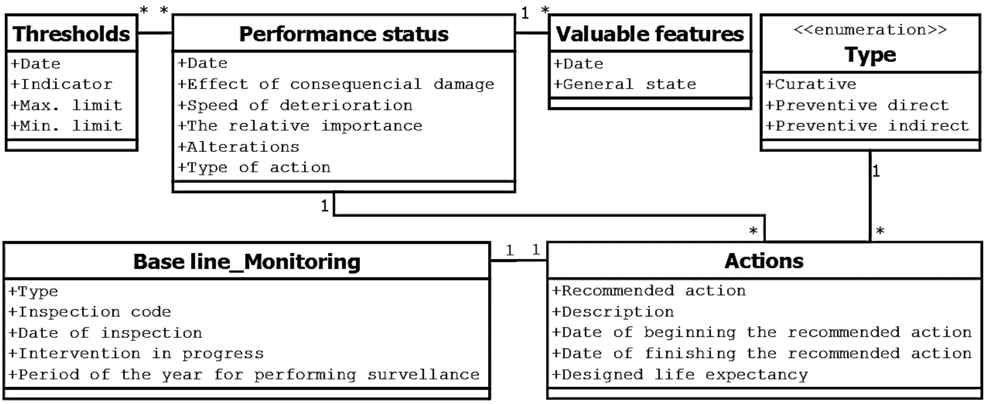


Figure 3.19 UML diagram depicting the diagnosis classes. Adapted from Heras et. al (2011).

Therapy classes (Figure 3.20) include “Potential_Activities,” “Demands for intervention,” “Therapy description,” “Intervention” and “Resources.” Actions are organized by potential activities which are confronted with demands for intervention such as budget, workmanship availability, etc. A therapy for the heritage value is set. Once the therapy is executed, the “Intervention” class is filled, recording the details of the intervention and the used resources.

The Control class uses the information about the intervention and the base line of monitoring to determine whether the conservation objective was accomplished or if another cycle is required.

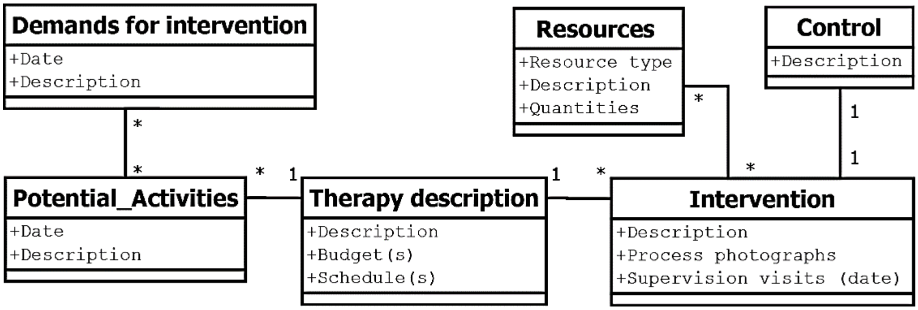


Figure 3.20 UML diagram depicting the therapy and control classes. Adapted from Heras et. al (2011).

Geometry representation classes

In addition to the preventive conservation classes, this section also explains the classes for representing the building's geometries.

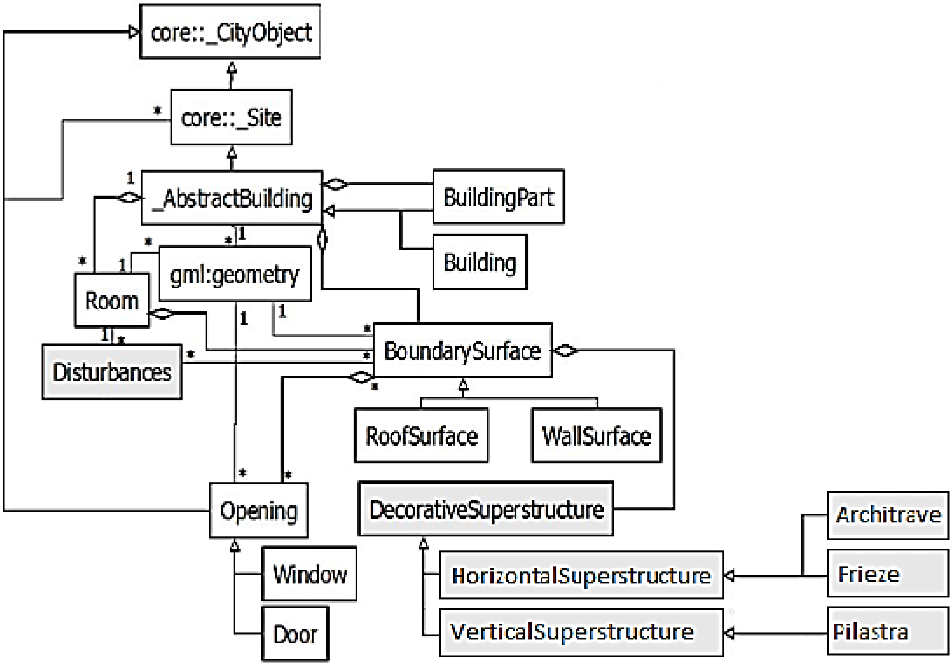


Figure 3.21 Classes for representing the building's geometries. Heras (2011).

The main classes are taken from the CityGML-Building module of the CityGML standard, where a site is composed of buildings, buildings consist of BuildingParts, and rooms. These elements, in turn, have one or more geometries represented by boundary surfaces and openings (windows, doors). Additionally, Heras proposes adding classes to represent disturbances and decorative superstructures for the representation of characteristic heritage elements such as pilasters, friezes, or architraves.

3.5 Semantic gaps

Heras et. al. (2011) propose a good starting point for a proper BCH management. However, the CityGML-ADE model does not provide sufficient semantics for the BCH-management. In this research, the model proposed by Heras et al. has been studied, and the following problems have been identified, which demonstrate the need to implement a semantic model for the management of the BCH of Cuenca.

3.5.1 Challenging modification of traditional structured models

When a structured model is used, further modifications are complex and time consuming. The risk assessment part of the model proposed by Heras et. al (2011) is modelled as follows (Figure 3.22):

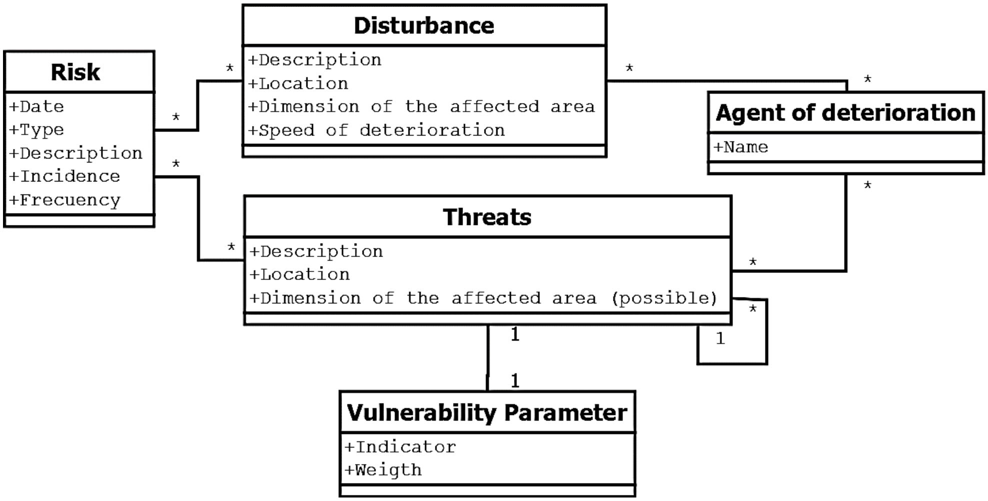


Figure 3.22 Risk assessment model. Heras et. al (2011).

In this model the risk class is computed taking into account the disturbance and threats classes. The threat class is also related to the vulnerability parameter class. This part of the model is based on the research of Jimenez (2001) to compute the vulnerability to earthquakes. The model assumes that another study on e.g., the vulnerability to floods uses the same vulnerability parameters: Indicator and Weight. Otherwise the model should be extended to accommodate the new study and all the applications implemented on said model should also be modified.

The latter inconvenience can be circumvented by an ontology approach in which data is represented and linked between each other. The basic structure is the triple: subject, predicate, object. A triple in this case may represent that 'A risk comes by a threat named earthquakes'. The subject is 'risk', the predicate will be 'has a threat', and the object 'earthquakes'. Another triple may represent 'Risk of earthquakes' is measured by vulnerability parameters" and so on. Therefore, to extend the model a new link can be added representing the fact that "There is a risk named floods" without the need to represent how vulnerability to floods is computed. The software agent knows that there is a way to compute the vulnerability to floods and that by following the links it can be found. In Figure 3.23 the link between Risk and Floods is represented in red to point out that only that initial link is needed to enrich the model with the knowledge about vulnerability to floods.

In this context, other methodologies for risk assessment can be studied and easily integrated into the BCH-ontology, such as the one used by MEGA-Jordan, a GIS inventory to help manage archeological sites. It has been developed through partnerships between the Getty Conservation Institute, World Monuments Fund, and the Jordanian Department of Antiquities (Forster & Kayan, 2009).

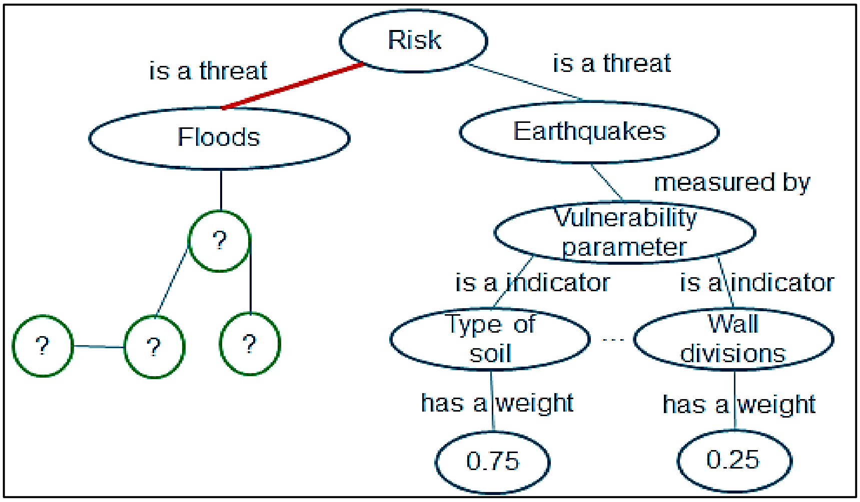


Figure 3.23 Ontology based approach for risk assessment.

By representing the information with triples, the model becomes independent of a fixed structure and discovering new information is a task that can be automated

3.5.2 Inadequacy of Traditional Structured Models for Handling Heterogeneous and Overlapping Data

The integration of information in this case is more complex than in previous paragraphs. In this instance there is a lot of information that is duplicated. When the information is duplicated some agreements have to be done to decide which one is the organization in charge of managing and storing the information. If some organization wants to keep its own version of a piece of information, links have to be established between the organizations to represent the fact that they both are representing the same thing. This can be done, for example, with predicates of the type: “same as”.

In Figure 3.24 two facts are represented:

● The property “IBI-01-01-01-000-000001” according to the INPC is the same property that is identified as “0504051015” by the Municipality.

● The property “0504051015” in the Municipality is the same property as the one in the CPM with zone number 05, sector 04, building block 051 and property number 015.

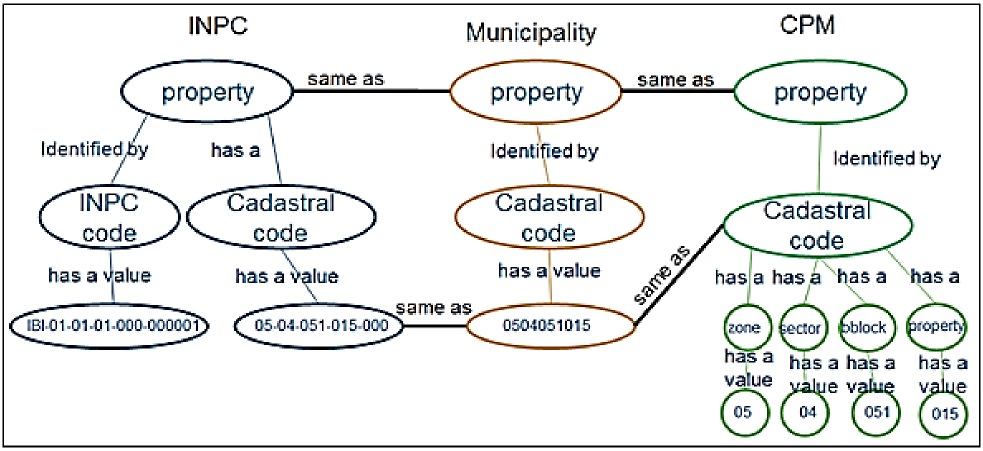


Figure 3.24 Ontology based approach integrating several sources. In this example, information from 3 stakeholders is linked.

For a human reader it is obvious that CPM and INPC deal with the same property. If we populate this information in a relational database the inference that we as humans beings can do has to be explicitly stored in the database. Since ontologies are based on relational calculus, the representation of the first two facts will allow a dedicated software agent to deduce that the CPM and the INPC are also referring to the same object.

3.5.3 Limitations of traditional structured models in retrieving data inferences

A powerful advantage of ontologies is the use of inferences. There is an efficient and practical multilevel inheritance in an ontological structure. Superclasses properties can be used by the subclasses in any level without giving further specification. For example, the property 'built_on' belongs to the class 'Buildings' but the class 'HeritageBuildings' can freely use it because of the hierarchical relationship between the classes. Even if there are hundreds of sub-classifications of 'HeritageBuildings' no action is required since all the subclasses can use the property. In other traditional systems such as databases, an inheritance has to be manually implemented. For example, the column 'built_on' has to be created for each sub-classification of 'HeritageBuildings'.

Additionally, to the multilevel inheritance inferences more complex logical inferences can be constructed. For example: imagine we are integrating information from an external data set where there is not a definition of 'Heritage Building' and the information is just recorded as 'Building' and at some place information such as a component with heritage value is stored. The ontology can establish a logical rule that states: "If a building or a component of it has a heritage value, then the building is a heritage building." When the information from the external data set is integrated into the ontology and the information regarding the component with the heritage value is found, the record is automatically classified as 'Heritage Building.' Other records of no-heritage buildings will be stored as well but only as simple buildings. No additional efforts are needed to organize heritage buildings and simple buildings. If a query is performed, the ontology can make the distinction between these objects and return 'all buildings' or 'heritage buildings' automatically. In other approaches, the same queries can be performed but it is the query builder who has to construct the query knowing where the information of building or heritage building is stored. The query builder needs to be well aware of the stored structure and is the one who knows the logical rule and implements queries according to these logical rules. In an ontological approach on the other hand, the logical rule is stored in the same ontology. The query builder only needs to know that there are buildings and heritage buildings, not where or how they are stored.

3.6 Conclusions

A local view of the management of the BCH of Cuenca - Ecuador allows us to observe the amount of information collected by the stakeholders as well as the lack of coordination among them to share it. The CityGML-ADE model was an effort promoted by the Heras and the CPM research group which, albeit with the collaboration of all stakeholders, was managed as an academic work and was not implemented in any of the institutions. The Abaco and the SIPCE systems show the effort of the INPC to build a national system of heritage management which, due to lack of jurisdiction, is missing specific information as in the case of the historic centre of Cuenca. The TIPVP is the most recent proposal of the Municipality of Cuenca to have a unique system of heritage management that from the definition of 'unique' shows the lack of notion of 'integration'. Although the TIPVP is the best effort compared to its predecessors, it is still a repository where information from different stakeholders is duplicated rather than linked. Regarding the use of spatial information, the majority of stakeholders use only 2D information; even in specific information systems, only the location of buildings is managed. In this context, only the DGAHP is making a significant effort to implement 2D and 3D analyses in the presentation of construction projects for buildings. However, it has not been taken into consideration that there is no trained personnel for the proper execution of these practices.

It is important that these integration processes are enforced by law and disseminate semantic models and their use. Even though the open data policies already talk about ontological models and the 5-star linked data scheme; the lack of trained personnel in these topics prevents their correct implementation. The Ecuadorian July 2022 open data policy and the 2023 Cuenca Special Plan for the management of the historic centre are undoubtedly the right opportunity to include the notion of semantic integration and for which the deliverables of section 6.1 are fundamental for the understanding of this topic.

Chapter 4: Development of the BCH-ontology

This chapter presents the construction of the BCH-ontology for the documentation and management of BCH following the steps of the knowledge meta process [Section 4.1], which is then technically verified through the application of the OOPs tool and a user evaluation [Section 4.2]. The classes and properties of the improved ontology are explained [Section 4.3] and a proof of concept shows how the PCC can be applied to a heritage building using the BCH-ontology [Section 4.4].

Chapter based on the “Merging and expanding existing ontologies to cover the Built Cultural Heritage domain” article publish in the Journal of Cultural Heritage Management and Sustainable Development on 01/01/2018 DOI: 10.1108/JCHMSD-05-2017-0028.

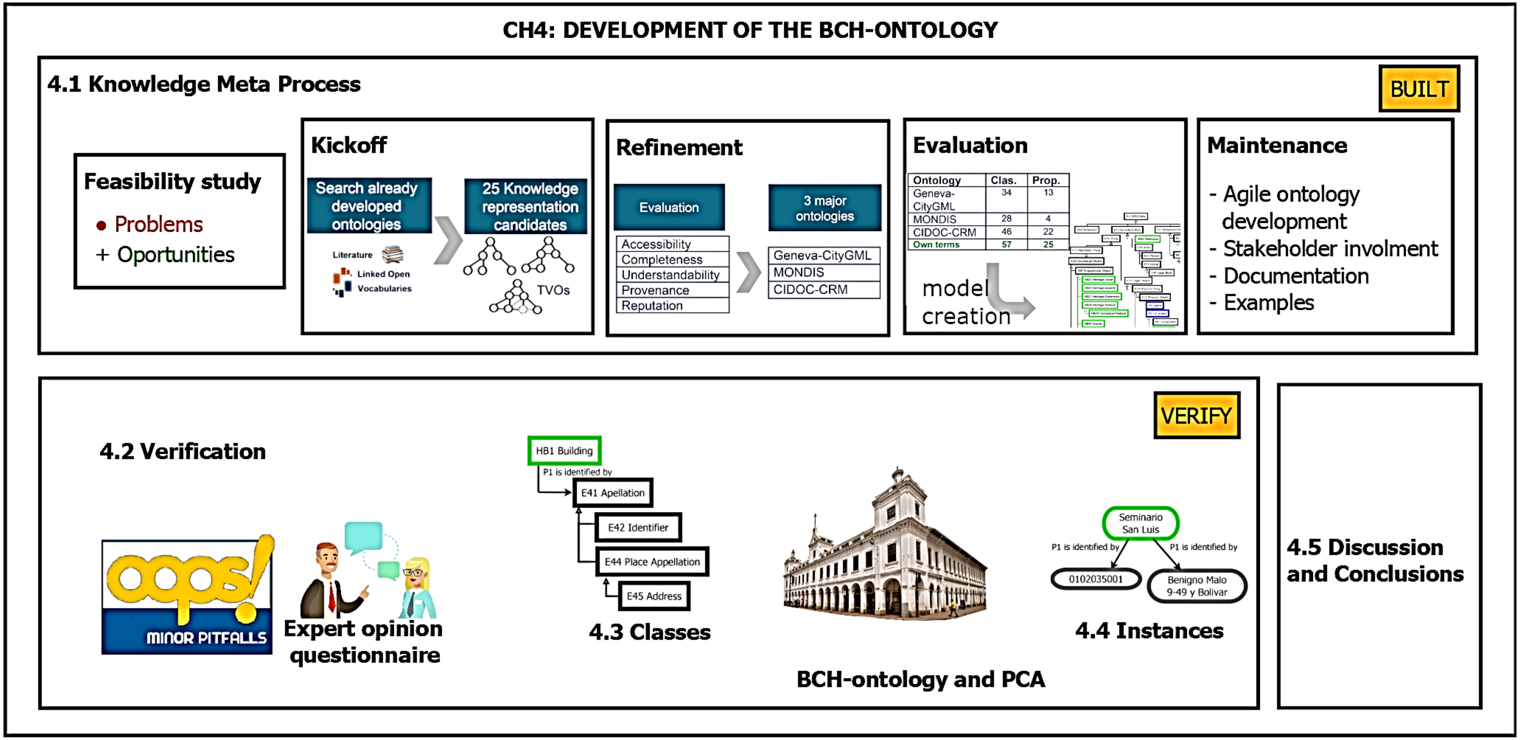


Figure 4.1 Chapter 4 summary.

4.1 Application of the knowledge meta process

In this section the steps of the knowledge meta process (Feasibility study, Kickoff, Refinement, Evaluation) lead to the construction of the BCH-ontology.

4.1.1 Feasibility study

A feasibility study, identifying the problem, opportunities and potential solutions is conducted in this research for the case of Ecuador, in collaboration with the main stakeholders. Stakeholders described in chapter 3 meant to share and integrate their information through a common data model. However, in this research the following semantic gaps described in chapter 3 are found:

- Challenging modification of traditional structured models

- Inadequacy of Traditional Structured Models for Handling Heterogeneous and Overlapping Data

- Limitations of traditional structured models in retrieving data inferences

In the feasibility study of the case of Cuenca-Ecuador which is very similar in other historical cities, the problem consists of closing the identified semantic gaps.

A domain with these issues presents a good opportunity to apply semantic models. The International Committee for Documentation (CIDOC) of the International Council of Museums has already developed the CIDOC Conceptual Reference Model (CIDOC-CRM), an ontology which provides the opportunity to share cultural heritage information. The main drawback of CIDOC-CRM is that its scope is limited to museum artifacts, thus the CityGML-ADE model, described in chapter 3, cannot be represented with this ontology. A possible solution is the extension of already developed ontologies that will cover the requirements represented in the CityGML-ADE model (Heras, 2014).

Section 3.5 shows theoretically how ontologies could help to close these gaps. Chapter 5 shows use cases where these limitations are overcome. Chapter 4 focuses on ontology construction.

4.1.2 Kickoff

During the kickoff phase, the requirements of the different stakeholders are specified, already developed ontologies are explored, and a semi-formal description of the ontology is created.

The first step in this phase is to create the ontology requirements specification document (ORSD) (Sure & Studer, 1999), which describes in general terms the scope and applications of the ontology. (Table 4.1).

Table 4.1 Document depicting the specifications requirements the BCH-ontology must meet.

Name: **Date:**	BCH-ontology 2019/09/09
Domain and Goal: The main goal of this ontology is to represent the principal concepts of the BCH domain following a PCA. The ontology serves as a model for knowledge distribution and integration among the BCH-stakeholders.	
Design guidelines: The ontology will be based in the CityGML-ADE model designed by Heras et. al (Heras, 2014). Axioms will not be implemented. OWL will be used as ontology language. Ontology and instances will be stored in a semantic repository. Ontology should support a multilingual environment including Spanish and English.	
Knowledge sources: CityGML-ADE model. Databases from the CPM research group. Databases from the INPC. Databases from the Municipality of Cuenca.	
Users and use cases: Users: Governmental stakeholders (Municipality of Cuenca, INPC), researchers (CPM research group).	

UC1: Semi-automatic population of the BCH-ontology with data from several sources. UC2: Query and search general information regarding BCH damages pointing out advantages of ontological models.
Potential reusable ontologies: CIDOC-CRM
Competency questions: The aim of use case 2 is to query the ontology to answer some competency questions which are in line with the PCA phases: CQ1: What are the most common damages in historical buildings (Information gathered in the Analysis phase)? CQ2: Where are the most common damages located (Diagnosis phase)? CQ3: What are the most common actions applied during the therapy phase? CQ4: What buildings are on danger due to their proximity to other buildings with damages?

As a result of this phase, a semi-formal description (taxonomy) of the ontology derived from the CityGML-ADE model is created using Protégé (Figure4.1). Initially, the taxonomy includes the 54 classes from the CityGML-ADE model and the “BCHClasses”, “GMLClasses” and “CityGMLClasses” which are added for organizational purposes. The preventive conservation classes are mapped as taxonomy classes and the generalization associations are converted into ontology classes and subclasses. Then, the main attributes from the CityGML-ADE model extend the original taxonomy to 71 classes considering all dates, quantitative and qualitative values as single classes.

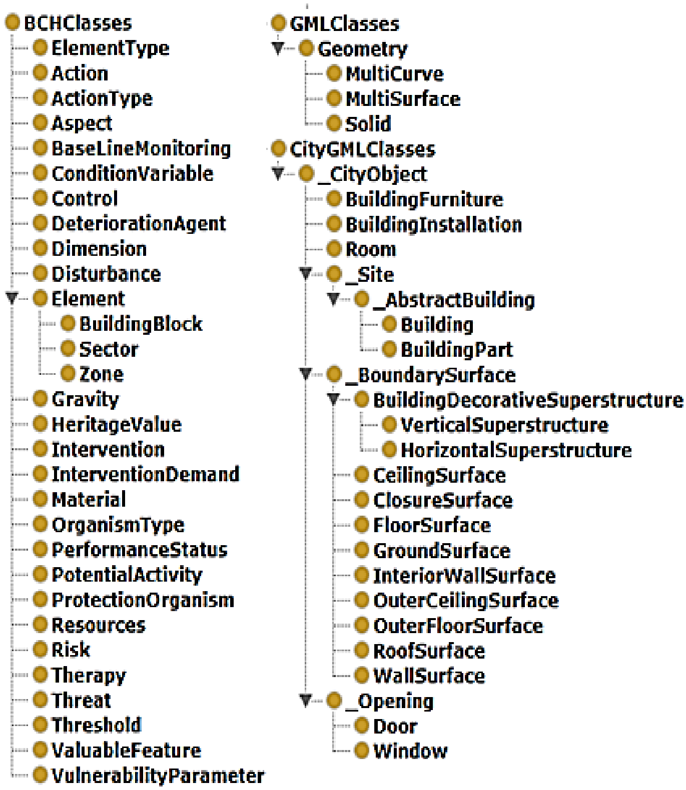


Figure 4.2 Taxonomy for the BCH domain.

Already developed ontologies are searched in the literature, catalogues and search engines recommended by the W3C: Linked Open Vocabularies (Ontology Engineering Group - UPM, n.d.), Swoogle (Ding et al., 2004), Watson (D'Aquin et al., 2007) and Falcons (Cheng et al., 2008). The keywords 'historic building', 'BoundarySurface' and 'Risk' were used for the search. Results from Watson are ignored because the search engine looked for any semantic document and not only ontologies which increase the difficulty level of verifying whether the ontology meets the requirements. At the time of writing, only Swoogle and LOV are still running. The search is concluded with 25 knowledge-based representations (Table 4.2).

Table 4.2 List of BCH domain-related ontologies and descriptions found.

Name	Description
3D ontology	CityGML, IFC and Open Green Building XML Schema (GbXML) standards are implemented and aligned through an intermediate ontology
Bag	Vocabulary for the Dutch base registration of buildings and addresses.
CIDOC-CRM	Encoding approved by CRM-SIG as the official version for the CIDOC-CRM namespace.
Dbpedia-owl	Provides the classes and properties used in the DBpedia data set.
Dogont	Supports device/network independent description of houses, including both controllable and architectural elements.
Ecrm	OWL DL 1.0 implementation of the CIDOC-CRM.
Emergency response	Integration of topographic, cadastre and hydrology data for emergency response
Frbrer	Element set of native RDF classes and properties described in the current text of Functional Requirements for Bibliographic Records (FRBR) entity-relationship model.
Geneva-CityGML	Ontological version of the CityGML standard.
Gndo	stands for "Gemeinsame Normdatei" (Integrated authority file) and offers a broad range of elements to describe authorities. The GND originates from the German library community and aims to solve the name ambiguity problem in the library world.
Gov	The Genealogisches Orts-Verzeichnis (GOV) contains information about current and historical political, ecclesiastical and legal administrative affiliations of settlements and administrative units. In addition several time-dependent values (such as names, populations numbers, postal codes etc.) are given.
Juso	Web vocabulary for describing geographical addresses and features.
Juso.kr	South Korea Extension to Juso ontology.
Km4c	Knowledge Model to describe a smart city, that interconnect data from infomobility service, Open Data and other source.
Lgdo	LinkedGeoData ontology has been derived from concepts defined by Open Street Map.
Lode	Ontology or publishing descriptions of historical events as Linked Data, and for mapping between other event-related vocabularies and ontologies.
Log	Historical ontology used by the cwm command-line tool back in the very early days of the semantic web.
Mtlo	MarineTLO is a top-level ontology for the marine domain (also applicable to the terrestrial domain)
MONDIS	Monument damage ontology representing disturbances and threats in buildings.
Oupp	Ontology of urban planning process, for the integration of air quality models

Oslo	Version of the OSLO Exchange Standard which provides a minimum set of classes and properties for describing a natural person.
Pext	Upper-level ontology with extensions to handle LOD.
Owl	Partially describes the built-in classes and properties that together form the basis of the RDF/XML syntax of OWL 2.
Schema	Search engines including Bing, Google, Yahoo! And Yandex rely on shema.org markup to improve the display of search results, making it easier for people to find the right web pages.
Vaem	Its purpose is to provide, by import, a foundation for commonly needed resources when building an ontology.

4.1.3 Refinement

The refinement step improves the semi-formal ontology description by adding concepts and relations from a subset of the 25 knowledge-based representations found in previous steps. The criteria used to evaluate the knowledge-based representations are described in Table 4.3.

Table 4.3 Evaluation criteria for ontology selection. Description and indicators for each criterion.

Criteria	**Description**	**Indicator**
Accessibility	The ontology is accessible through a server or the ontology can be downloaded	Is the ontology downloadable?
Scope review	Ontologies which scope is not relevant for this research are removed as canditate	Is the scope relevant for our research?
Completeness	Degree at which classes are not missing	Number of matching terms between the taxonomy and the ontology
Provenance	Metadata available to identify the creator of the ontology	Is the creator known?

Reputation	The creator of the ontology is reliable. e.g. Governmental organization, research lab, etc	Is the creator trustworthy?
Understandability	The classes in the ontology have labels that can be interpreted. The ontology is implemented in a known language.	Is the ontology clear?

Accessibility is addressed by verifying if the knowledge-based representations are downloadable. OUPP, 3D ontology and the Emergency response ontology are discarded since they are available in literature but no downloadable or published version is found. Bag ontology is discarded after a visual inspection using Protégé since it is implemented in Dutch and the classes contained by this ontology are not worth the translation efforts.

Scope review is performed. General ontologies to represent semantic web concepts (classes, properties, metadata) were discarded since at this point we are looking for ontologies related to the BCH domain. Thus, OWL, pext, schema, and vaem were discarded. Ecrm is discarded since is a non-official version of the CIDOC-CRM standard and in the remaining ontologies, the official version is listed. The juso.kr ontology is discarded since it is too specific for registration of buildings in South Korea and in the remaining ontologies, the general version of juso is also listed. The description of Log ontology indicates this ontology is very old and not currently used, thus it should not be reused. For this reason, Log is discarded.

GENEVA
Adress
_cityObject
_Site
_AbstractBuilding
Building
BuildingPart
_BoundarySurface
CeilingSurface
ClosureSurface
FloorSurface
GroundSurface
InteriorWallSurface
OuterCeilingSurface
OuterFloorSurface
RoofSurface
WllSurface
_Opening
Door
Window
Foo
BuildingInstallation
BuildingFurniture
LandUse
Geometry
Curve
Point
Solid
Surface
Polygon

CRM
Activity
Address
Collection
Conceptual Object
Condition State
Creation
Date
Destrucion
Event
Identifier
Image
Legal Body
Man-Made Thing
Material
Modification
Part Addition
Part Removal
Physical Feature
Place
Site
Time-Span
Place Name
Attribute Assignment
Identifier Assignment
Document
Condition Assessment

MONDIS
CHObject
ComponentAddition
ComponentMovement
ComponentReplacement
ComponentRemoval
Event
NaturalDisaster
ManifestationOfDamage
Hazard
Agent
Component
Intervention
Material
Risk
Vulnerability
Use
UseAddition
UseRemoval
Quantity
Quality

JUSO
Address
Place

MTLO
BC13_Organization
BC3_Place
BC10_Event
BC43_Activity
BC44_Atribute_Assignment
BC46_Identifier_Assignment
BC16_Man-Made_thing
BC17_Conceptual_Object
BC47_Image
BC48_Database
BC26_Place_Name
BC32_Identifier

FRBRER
Object
Event
Place

OSLO
Building
Address
Geometry
Location
Organization
Site

DBPEDIA
activity
agent
event
buiding
historic building
earthquake
+ list of usages (airport, museum, restaurant, university, etc)
+ file (document, sound, image, movie)

KM4C
Historical buildings
+list of usages (entertainment, environment, financial sercies, government offices, healtcare, industry,et)

LGDO
ProtectedArea
HistoricBuilding
UNESCOWOrldHeritage
Place
+ HistoricThing (Abbey, historic church, etc)

DOGONT
Building
Room
Architectural
Ceiling
Floor
Wall
WallOpening
Door
Window

GNDO
Historic single event or era
Place or geographic name
Building or memorial

LODE
Agent
Event
Object
Place

GOV
none

Figure 4.3 Ontologies in Table 4.2 were eliminated due to availability and scope relevance.

Completeness is measured by visualizing the ontologies classes in Protégé and counting the relevant classes which are selected as possible reusable classes. Gov, Juso, Frbrer, Oslo, Lode, and Gndo ontologies are discarded since they do not have relevant classes. Most of the Mtlo classes are already part of the CIDOC-CRM ontology. Most of the classes from Dogont are contained in Geneva-CityGML ontology. Dbpedia, Lgdo and Km4c do not have a relevant number of classes, however they contain some important classes such as historic(al) building and UnescoWorldHeritage.

Only three ontologies remain suitable for reuse: Geneva-CityGML, CIDOC-CRM and MONDIS which cover most of the classes from the source taxonomy (Figure4.1). From the selected ontologies 68% of the source taxonomy classes are covered. Table 4.4 shows the source taxonomy and the coverage of CIDOC-CRM (C), Geneva-CityGML(G) and MONDIS (M).

Table 4.4 CIDOC-CRM, Geneva-CityGML and MONDIS completeness assessment of source taxonomy.

Source Taxonomy	**C**	**G**	**M**	**Source Taxonomy**	**C**	**G**	**M**
BCH Classes				CityGML Classes			
Action				CityObject		x	
ActionType				Site		x	
Aspect				AbstractBuilding		x	
BaseLineMonitoring				BuildingPart		x	
ConditionVariable	x			Building		x	x
Control				Room		x	
DeteriorationAgent			x	BuildingInstallation		x	
Dimension				BuildingFurniture		x	
Disturbance			x	BuildingDecorativeSuperstructure			
Element	x		x	HorizontalSuperstructure			
BuildingBlock	x			VerticalSuperstructure			
Sector	x			BundarySurface		x	
Zone	x			CellingSurface		x	
ElementType				ClosureSurface		x	
Gravity				FloorSurface		x	
HeritageValue				Groundsurface		x	

Intervention			x	InteriorWallSurface		x	
InterventionDemand				OuterCellingSurface		x	
Material	x		x	OuterFloorSurface		x	
OrganismType				RoofSurface		x	
PerformanceStatus				WallSurface		x	
PotentialActivity	x			Opening		x	
ProtectionOrganism	x			Door		x	
Resources				Window		x	
Risk			x				
Therapy				Important properties			
Threat			x	Usage	x	x	x
Threshold				Address	x	x	
ValuableFeature	x			DomainType			
VulnerabilityParameter			x	TenancyType			
				HistoricalEvent	x		x
CityGML Classes				SocialLink			
Geometry		x		LocalFestivities			
Multicurve		x		TraditionalWorkmanship			
Multisurface		x		Photo	x		
Solid		x		Sketch	x		
				Dates	x		x
				quantitative values	x		x
				qualitative values	x		x

The remaining 32% of the classes and properties from the original taxonomy are partially equivalent to more general classes from CIDOC-CRM and Geneva-CityGML. Thus, the remaining classes and properties can be a specification of these classes (Table 4.5).

Table 4.5 Source Taxonomy classes not found in candidate ontologies. However some CIDOC-CRM and Geneva-CityGML could be extended to cover them.

Source Taxonomy	**CIDOC-CRM**	**Geneva-CityGML**
BuildingDecorativeSuperstructure		_BoundarySourface
HorizontalSuperstructure		_BoundarySourface
VerticalSuperstructure		_BoundarySourface

Action	Activity	
Control	Activity	
InterventionDemand	Activity	
Therapy	Activity	
Aspect	Conceptual Object	
Dimension	Conceptual Object	
Gravity	Conceptual Object	
PerformanceStatus	Conceptual Object	
TraditionalWorkmanship	Design or Procedure	
SocialLink	Event	
LocalFestivities	Event	
HeritageValue	Man-made Feature	
Threshold	Man-made Feature	
BaseLineMonitoring	Man-made Object	
Resources	Man-made Object	
ActionType	Type	
ElementType	Type	
OrganismType	Type	
DomainType	Type	
TenancyType	Type	

Additionally, the "Risk" class can be specified using the "NaturalDisaster" subclass from MONDIS. Table 4.6 shows a set of suggested classes from MONDIS and CIDOC-CRM that might be used to extend the BCH-ontology.

Table 4.6 CIDOC-CRM and MONDIS suggested classes to extend the BCH-ontology.

CIDOC-CRM		
Part Addition	Destruction	Section Definition
Part Removal	Document	Spatial Coordinates
Transfer of Custody	Inscription	Place Name
Curation Activity	Appellation	Attribute Assignment
End of Existence	Identifier	Condition Assessment
Measurement Unit	Actor	Physical Man-made Thing
Physical Feature	Group	Modification
Measurement	Person	Transformation
Acquisition Event	Creation	Beginning of Existence
MONDIS		
ComponentReplacement	ComponentAdditon	
ComponentMovement	ComponentRemoval	

Provenance, reputation and understandability are checked to ensure the selected ontologies are reliable and we are able to work with them.

Provenance is verified by identifying the creator. The Geneva-CityGML ontology developed by the University of Geneva is an ontological version of the CityGML standard developed by the OGC. OGC is an international consortium of more than 530 businesses, government agencies, research organizations, and universities driven to make geospatial information FAIR (Findable, Accessible, Interoperable and Reusable). The Monument Damage Ontology was developed by the Czech Republic University in the framework of the MONDIS research project which was supported by the Ministry of Culture of the Czech Republic. The Conceptual Reference Model (CRM) was created by the International Council of Museums (ICOM) through its CIDOC. ICOM is an organization created by and for museum professionals committed to guaranteeing the conservation, continuation, and protection of cultural goods.

Reputation is checked by categorizing the creators according their role: Governmental organization, Research lab project, Academic units, etc. CIDOC-CRM is ranked in first place since ICOM is a well-known organization recognized worldwide. CIDOC-CRM is also well used in the cultural heritage domain as mentioned in section 2.17.1. Geneva-CityGML and MONDIS are ranked second since both are created by university departments and their use is not as popular as CIDOC-CRM but still come from reliable sources (Table 4.7).

Understandability ensures the knowledge-based representation can be interpreted by both machines and humans. Clarity is labeled ‘High’, ‘Medium’, or ‘Low’. CIDOC-CRM has a more complete documentation about the ontology and all the classes have comments. Geneva-CityGML has comments for some classes and the original standard developed by OGC has a complete documentation. MONDIS has documentation for some classes (Table 4.7).

Table 4.7 Ontology selection - Provenance, reputation and understandability raking.

Ontology	Provenance	Reputation	Understandability
CIDOC-CRM	International Council of Monuments	1st	High
Geneva CityGML	Geneva University / OGC	2nd	Medium
MONDIS	Czech Republic University / Ministry of Culture of the Czech Republic	2nd	Low

4.1.4 Evaluation

In this phase, the usefulness of developed ontologies is proved. This step checks whether the target ontology satisfies the ontology requirements. The indicators used for this evaluation are: consistency, reference frame completion, and properties check.

Consistency is checked ensuring the reusable ontologies do not contradict each other. The remaining 3 ontologies cover different parts of the source taxonomy 4.16. CIDOC-CRM is the ontology with the highest reputation and understandability. Therefore it will be used as the foundation for the construction of the BCH-ontology. Priority of selection will be given to classes from this ontology. Geneva-CityGML allows a 3D representation of historical buildings and their environment. MONDIS includes the classes for risk assessment. Classes from CIDOC-CRM will be used for the representation of dates, qualitative and quantitative values.

According to Gómez-Pérez et al. (1995) a technical judgement is made with respect to a frame of reference. In this case, the frame of reference is the source taxonomy shown in Figure4.1. The selected ontologies cover 68% of these classes (Table 4.4). The remaining classes are implemented in this research.

Properties check Candidate ontologies are checked and properties are selected to be used in the construction of the BCH-ontology (Table 4.8) which is presented in Section 4.2.

Table 4.8 Selected properties from CIDOC-CRM, MONDIS and Geneva-CityGML to be reused in the BCH-ontology.

CIDOC-CRM		
P1 is identified by (identifies)	P56 bears feature	P90 has value
P2 has type (is type of)	P67 refers to (is referred to by)	P91 has unit (is unit of)
P3 has note	P68 foresees the use of	P115 finishes
P4 has time-span	P81 ongoing throughout	P116 starts
P5 consists of (forms part of)	P82 at some time within	P127 has broader term
P43 has dimension (is dimension of)	P83 had at least duration (was minimum duration of)	P140 assigned attribute to (was attributed by)
P45 consists of (is incorporated in)	P84 had at most duration (was maximum duration of)	P141 assigned (was assigned by)
P46 is composed of (forms part of)		
Geneva - CityGML		
bounded by	lod2Multisurface	Opening
lod0Footprint	lod3Multisurface	outerBuildingInstallation
lod0RoofEdge	lod4MultiSurface	lod4Geometry
lod1Solid	lod4Solid	
MONDIS		
isSubjectedTo	refersToHazard	
isRepairOfDamage		isEliminatedByIntervention

CIDOC-CRM is selected as the foundation for the BCH-ontology, based on the results of the evaluation step. CIDOC-CRM classes and properties will have priority to be reused. Geneva-CityGML is priority 2 and MONDIS is priority 3. New ontology classes and properties are developed when they are not covered by either CIDOC-CRM, Geneva-CityGML or MONDIS.

4.1.5 Maintenance

This step is also known as Application and Evolution. Ontologies need to be constantly evaluated and maintained by experts who know the domain and have a technical knowledge as well. In this case the BCH-ontology has been presented to the stakeholders and is publicly available at https://w3id.org/bcho#. The w3id.org domain allows changing the location of the BCH-ontology without changing its URI. In turn, this will allow us to change the management of the ontology through different stakeholders. In the city of Cuenca, the municipality has jurisdiction over the historical buildings, thus is the one that should be in charge of its management, while the ontology is tested at local level. If the ontology were to be implemented at national level, the management of the BCH-ontology should be done by the INPC. The crucial part is to keep the ontology open and accessible so the stakeholders can use it, and organize collaborative workshops in order to update it.

The BCH-ontology is distributed in the different files according to the language while this eliminates complexity of dealing with two languages it also creates the need to maintain both files coupled.

Based on our experience in the development of this work, we provide a list of management tips:

- Before starting the development phase, plan the ontology in several iterations. For example, reusable ontology classes and new classes can be implemented first and then properties could be added in a later iteration. This allows for agile ontology development that can always be improved. Prioritizing competence questions allows focusing on the urgent ones.

- Involve stakeholders at each stage of the process. It is important to receive feedback as early as possible rather than waiting for a full iteration to be completed.

- Document ontology metadata with appropriate ontologies such as dcterms, vaem or vann (Garijo & Poveda-Villalón, 2020).

- Document ontology usage with full explanations and examples.

- Use redirection systems such as W3id. It allows different versions of the ontology to be hosted in different domains over time without changing their original path, so that new versions of the ontology can be managed by stakeholders.

- Check periodically reused terms to avoid inconsistent URIs.

4.2 Verification of the BCH-ontology

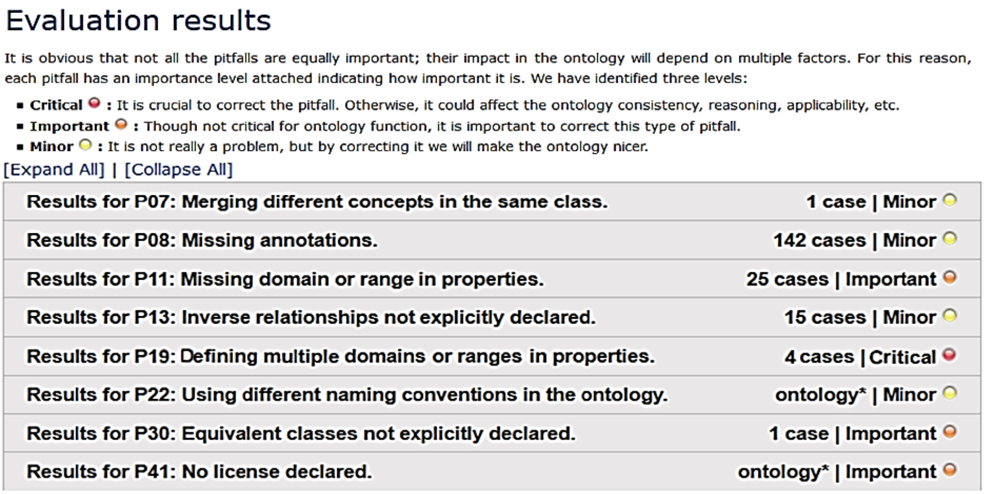
According to Gómez-Pérez et al. (1995) ontology evaluation comprises ontology verification and validation. Ontology verification measures correctness, answering the question: Is the ontology built correctly?, while ontology validation measures quality, looking at how good the ontology models reality, answering whether the correct ontology is built.

After the construction of the BCH-ontology, a verification of the ontology is carried out, which corresponds to a second cycle of the evaluation and maintenance phases of the knowledge meta process. The verification is carried out by means of two processes: the application of the OOPs tool and an expert questionnaire.

4.2.1 OntOlogy Pitfall Scanner (OOPs)

OOPs is a web tool developed by the Ontology Engineer Group (Gómez-Pérez & Fernández, 2007). The tool is used to detect ontology anomalies. It supports developers to automatically detect potential errors, improving ontology quality. The tool is accessible online and independent of any ontology development environment.

OOPs contains a catalogue which comprises 29 pitfalls organized regarding: human understanding, logical consistency, real world representation and modelling issues. The tool classifies pitfalls in three categories: Critical, Important and Minor. The first version of the BCH-ontology is tested using OOPs. 8 type of pitfalls (Figure 4.4) are identified: 1 critical, 3 important and 4 minor.


Evaluation results

It is obvious that not all the pitfalls are equally important; their impact in the ontology will depend on multiple factors. For this reason, each pitfall has an importance level attached indicating how important it is. We have identified three levels:

- **Critical** : It is crucial to correct the pitfall. Otherwise, it could affect the ontology consistency, reasoning, applicability, etc.
- **Important** : Though not critical for ontology function, it is important to correct this type of pitfall.
- **Minor** : It is not really a problem, but by correcting it we will make the ontology nicer.

[Expand All] | [Collapse All]

Results for P07: Merging different concepts in the same class.	1 case | Minor
Results for P08: Missing annotations.	142 cases | Minor
Results for P11: Missing domain or range in properties.	25 cases | Important
Results for P13: Inverse relationships not explicitly declared.	15 cases | Minor
Results for P19: Defining multiple domains or ranges in properties.	4 cases | Critical
Results for P22: Using different naming conventions in the ontology.	ontology* | Minor
Results for P30: Equivalent classes not explicitly declared.	1 case | Important
Results for P41: No license declared.	ontology* | Important

Figure 4.4 Screenshot showing the evaluation of the BCH-ontology using the OOPs tool.

P19: Defining multiple domains or ranges in properties

Some properties are used with several classes. For example the range of the property ‘PG1 bounded’ are the classes ‘G32 Room’ and ‘G19 Building Installation’. As explained in the pitfall this implies a conjunction of these classes but that is not what we want to represent with this class. Thus, the range is replaced by the superclass ‘G14 City Object’ which implies it could be any of the subclasses. The same logic is applied for the property ‘PG11 Lod4Geometry’. Since these properties have been generated by third parties, new generic properties are created.

Results for P19: Defining multiple domains or ranges in properties. **4 cases | Critical**

The domain or range (or both) of a property (relationships and attributes) is defined by stating more than one rdfs:domain or rdfs:range statements. In OWL multiple rdfs:domain or rdfs:range axioms are allowed, but they are interpreted as conjunction, being, therefore, equivalent to the construct owl:intersectionOf. This pitfall is related to the common error that appears when defining domains and ranges described in [7].

• This pitfall appears in the following elements:
› http://www.opengis.net/citygml/building/2.0/boundedBy
› http://www.ciudadpatrimoniomundial.com/ontologias/BCH#PG1_bounded
› http://www.ciudadpatrimoniomundial.com/ontologias/BCH#PG11_lod4Geometry_of
› http://www.ciudadpatrimoniomundial.com/ontologias/BCH#PG11_lod4Geometry

Figure 4.5 Screenshot showing the Pitfall P19: Defining multiple domains or ranges in properties.

P11: Missing domain or range in properties

All properties are checked and missing domain or range are added.

Results for P11: Missing domain or range in properties. **25 cases | Important**

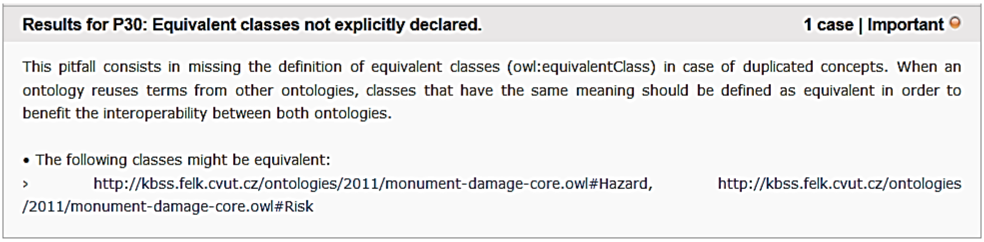
Object and/or datatype properties without domain or range (or none of them) are included in the ontology.

• This pitfall appears in the following elements:
› http://www.opengis.net/citygml/building/2.0/boundedBy
› http://www.semanticweb.org/owl/owlapi/turtle#P138_represents
› http://www.semanticweb.org/owl/owlapi/turtle#P70_documents
› http://www.opengis.net/citygml/building/2.0/lod1Solid
› http://www.semanticweb.org/owl/owlapi/turtle#P71i_is_listed_in
› http://www.semanticweb.org/owl/owlapi/turtle#P71_lists
› http://www.opengis.net/citygml/building/2.0/lod2MultiSurface
› http://www.semanticweb.org/owl/owlapi/turtle#P48i_is_preferred_identifier_of
› http://www.opengis.net/citygml/building/2.0/opening
› http://www.opengis.net/citygml/building/2.0/lod0RoofEdge
› http://www.semanticweb.org/owl/owlapi/turtle#P70i_is_documented_in
› http://www.opengis.net/citygml/building/2.0/lod3MultiSurface
› http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#isRepairOfDamage
› http://www.semanticweb.org/owl/owlapi/turtle#P48_has_preferred_identifier
› http://www.semanticweb.org/owl/owlapi/turtle#P138i_has_representation
› http://www.opengis.net/citygml/building/2.0/lod4Solid

Figure 4.6 Screenshot showing the Pitfall P11: Missing domain or range in properties.

P30: Equivalent classes not explicitly declared

This pitfall refers to the "Hazard" and "Risk" classes but conceptually Hazard and Risk are no equivalent. Risk is computed taking into account hazards and vulnerability; hazard is related to Risk though the "M1 refers to hazard" thus no action is taken in this case.


Results for P30: Equivalent classes not explicitly declared. **1 case | Important**

This pitfall consists in missing the definition of equivalent classes (owl:equivalentClass) in case of duplicated concepts. When an ontology reuses terms from other ontologies, classes that have the same meaning should be defined as equivalent in order to benefit the interoperability between both ontologies.

• The following classes might be equivalent:
› http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#Hazard, http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#Risk

Figure 4.7 Screenshot showing the Pitfall P30: Equivalent classes not explicitly declared.

P41: No license declared

The license agreement is included through the annotation "http://creativecommins.org/ns#license". The type of license selected is http://creativecommons.org/licenses/by/4.0/ which allows the user to share and adapt the BCH-ontology as long as the proper credit is given to the creator and contributors. In this sense creator and contributors are also added through the annotation "http://purl.org/dc/terms/contributor" and "http://purl.org/dc/terms/creator".

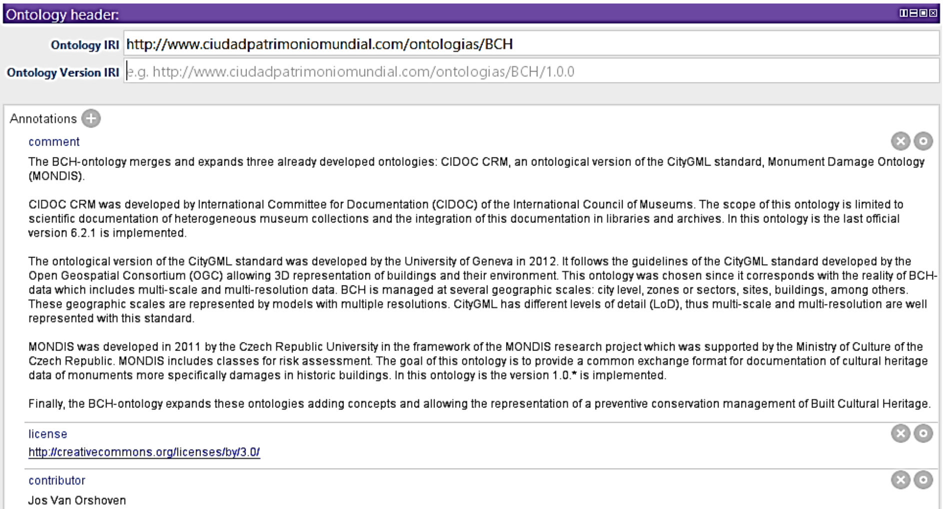


Figure 4.8 Screenshot showing the Pitfall P11: BCH-ontology Annotations.

P08: Missing annotations

Some classes did not contain a description of what the class represents. It is important to recall that classes of the CIDOC-CRM ontology did contain a correct description. In this regard, comments are added to new classes, as well as Geneva-CityGML and MONDIS classes.

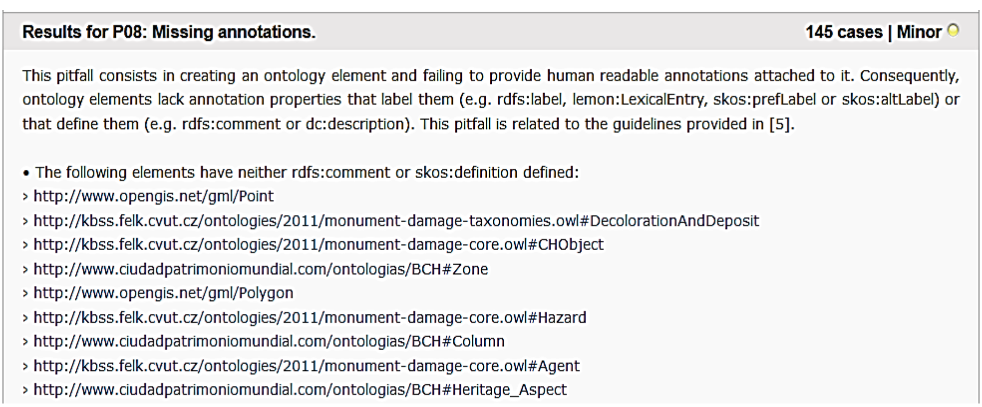


Figure 4.9 Screenshot showing the Pitfall P08: Missing annotations.

P13: Inverse relationships not explicitly declared

Inverse relationships which were not explicitly declared are added. In this regard the number of the property is kept, a letter 'i' is added and the name is slightly changed. For example: the property 'lod4Multisurface' has the label 'GP7 lod4MultiSurface'. The property 'GP7i lod4MultiSurface of' is created as inverse property.

Results for P13: Inverse relationships not explicitly declared. **15 cases | Minor**

This pitfall appears when any relationship (except for those that are defined as symmetric properties using owl:SymmetricProperty) does not have an inverse relationship (owl:inverseOf) defined within the ontology.

- This pitfall appears in the following elements:

> http://www.opengis.net/citygml/building/2.0/lod4MultiSurface
> http://www.opengis.net/citygml/building/2.0/lod0FootPrint
> http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#isSubjectedTo
> http://www.opengis.net/citygml/building/2.0/outerBuildingInstallation
> http://www.opengis.net/citygml/building/2.0/lod4Solid
> http://www.semanticweb.org/owl/owlapi/turtle#P46i_forms_part_of
> http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#isEliminatedByIntervention
> http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#isRepairOfDamage
> http://www.opengis.net/citygml/building/2.0/lod3MultiSurface
> http://www.opengis.net/citygml/building/2.0/lod0RoofEdge
> http://www.opengis.net/citygml/building/2.0/opening
> http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#refersToHazard
> http://www.opengis.net/citygml/building/2.0/lod2MultiSurface
> http://www.opengis.net/citygml/building/2.0/lod1Solid
> http://www.opengis.net/citygml/building/2.0/boundedBy

Figure 4.10 Screenshot showing the Pitfall P13: Inverse relationships not explicitly declared.

P07: Merging different concepts in the same class

This pitfall is ignored. Even though two concepts are merged into one class, the class is reused from the CIDOC-CRM ontology thus we have no right to change the name of these classes. In addition, the class used by the PCA is the new class 'HB21 Traditional Workmanship' which is a subclass of 'E29 Design or Procedure'.

The same pitfall is present in the class 'DecolorationAndDeposit' which is reused from the MONDIS ontology. In the same regard we have no right to change its name.

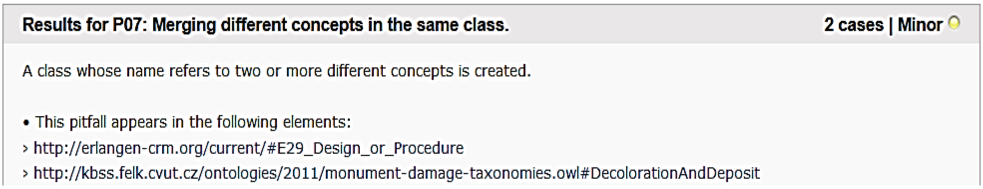


Figure 4.11 Screenshot showing the Pitfall P07: Merging different concepts in the same class.

P22: Using different naming conventions in the ontology

The BCH-ontology is created by merging and expanding 3 already developed ontologies, thus naming of classes and properties are not consistent. Different ontologies employ different domains as shown in Table 4.9.

Table 4.9CIDOC-CRM, MONDIS and Geneva-CityGML domains.

Ontology	**Domain**
CIDOC-CRM	http://erlangen-crm.org/current/
MONDIS	http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl# http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-taxonomies.owl#
Geneva-CityGML	http://www.opengis.net/gml/ http://www.opengis.net/citygml/2.0/ http://www.opengis.net/citygml/building/2.0/

MONDIS employs the ‘#’ to split domain and concepts whilst Geneva-CityGML and CIDOC-CRM employ the ‘/’. New concepts created for the BCH-ontology are located under the domain: https://w3id.org/bcho#.

Even though the ontologies used different naming conventions, the convention described in section 4.3.3 is implemented through labels. This does not fix the pitfall but improves readability.

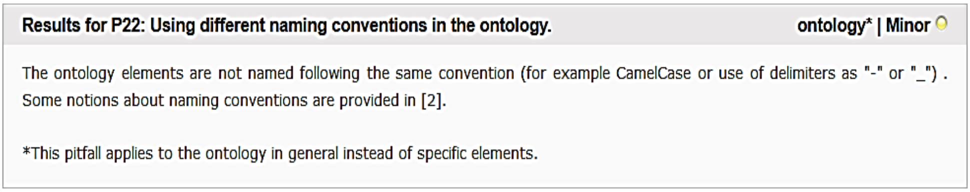


Figure 4.12 Screenshot showing the Pitfall P22: Using different naming conventions in the ontology.

4.2.2 Expert opinion questionnaire

Stakeholder opinion is one of the main axes of ontology verification. To this end, one stakeholder from the Municipality of Cuenca, and three from the CPM research group filled out a questionnaire designed to detect the completeness of the ontology. The questionnaire was also sent to the INPC technicians, but no complete responses were submitted. The INPC and the municipality were selected since they have legal jurisdiction over the heritage buildings in Cuenca; the CPM research group was chosen because of their experience with the PCA, already working since 2008 in Cuenca. These stakeholders collect information through participatory processes with citizens.

Completeness refers to the terminology used in the ontology. A complete ontology should be able to document all relevant information regarding the BCH assets and their management. In order to check completeness of the ontology, commissions and omissions are inquired. Commission refers to classes included in the ontology which comprise redundant or irrelevant information for the BCH-management. Omission refers to classes that are not included in the ontology which comprise relevant information for the BCH-management. Table 4.10 shows their responses regarding to commissions.

Table 4.10 Expert opinion regarding commission.

BCH-ontology class	**E1 score**	**E2 score**	**E3 score**	**E4 score**	**Total score**
Organizational aspects: It contains organizational aspects of a building as the height, type of implantation, number of courtyards and orchards.	5	4	5	5	19
Type of implantation: This class comprises the type of implantation of the building inside the parcel. It could be: frontal, L-shape, C-shape, with interior spaces, etc.	3	3	5	3	14
Performance status: It is a general assessment of the building condition based on the effect of consequential damage, the speed of deterioration, the relative importance of damages, and the type of alterations.	5	4	4	5	18
Inspection: Inspections are supervision visits which aim to verify if the actions suggested during the therapy phase reached the conservation objectives or if further actions are still needed.	5	3	5	4	17
Heritage aspects: According to the Nara-grid, heritage values are classified by aspects and dimensions. Aspects are: form and design, materials and substance, use and function, tradition, technique and workmanship, location and setting, and spirit and feeling.	4	4	5	5	18
Time-Span: Time-Spans are used to define the temporal extent of instances such as the duration of a restoration intervention or the date of a building register, etc.	4	2	4	4	14

Event: This class comprises changes of states in cultural, social or physical systems regardless of scale, including the beginning of existence, end of existence or the execution of some specific activity. Examples of this class are: the construction and demolition of a building, the assignment of an identification code for a building.	5	3	5	3	16
Beginning of existence: This class comprises events that bring into existence persistent items, such as the construction of a building or the creation of heritage management policy.	5	3	5	4	17
Manifestation of damage: visible or detectable damage on components produced by a damaging agent.	5	3	4	5	17
Hazard: The effect of unpredictable and unanalyzable forces in determining events. Some examples are landsides, fires, earthquakes and floods.	5	3	5	5	18
Building: This class comprises buildings in general.	5	1	2	5	13
Window: a sub-classification of openings. Represent windows in elements modelled by a collection of surfaces such as walls or facades.	3	2	1	1	9
Closure surface: virtual surface which can be used to define the volume of geometric objects not totally bounded by real surfaces. For example buildings with open sides like a barn.	1	2	4	3	11
Outer floor surface: horizontal constructions that separate the interior part of a building.	2	2	5	3	13
Solid: This class comprises the representation of buildings or buildings parts modelled as solids.	3	2	4	3	13

15 BCH-ontology classes are randomly selected and the experts are asked to rank them with values from 1 to 5, after which a total score was computed to provide an overall result. For the commissions evaluation we decided only to eliminate something if everyone agreed it was redundant because the information existed elsewhere. However, this was never the case.. After processing the responses, the "Window" class has the minimum score of 9. However one expert considered it important since a value of 3 was given. Moreover, windows are usually an important representations of heritage value. Other classes with a score of 1 are: Building and Closure Surface, which also score values greater than 3 for other experts. Because ontologies integrate heterogeneous information from the stakeholders, opposing opinions can coexist. For all these reasons commissions are not detected.

Experts are also asked if they consider that any important information is missing. Their responses are classified in two groups: information already represented by the BCH-ontology (Table 4.11) and omissions (Table 4.12). Expert opinions lead to a new extension of the BCH-ontology. 6 new classes and 1 new property are added. 7 classes and 9 properties are added from CIDOC-CRM.

Table 4.11 Expert opinion regarding possible missing information. To the right the BCH-ontology classes which represents the missing information.

Expert Opinions	**BCH-Class**
Structure	HB9 Structure
Building block	HB3 BuildingBlock
Relationship with the building block	HB33 Type of Implantation
Ornamental elements	HB31 Decorative Elements
Original use and current use The use of the building, especially if it is linked to intangible heritage Historical and current uses of the recorded property The use of the building, especially if it is linked to intangible heritage	HB58 Usage HB59 Usage Assignment HB29 Conceptual Feature

Tenure, owned, leased, borrowed.	HB56 Domain Type HB57 Tenure Type
Risk level	M3 Risk
The environmental value referred to the presence of elements such as medicinal gardens	HB32 Organizational Aspects PHB2 has courtyard PHB3 has orchard

Table 4.12 Expert opinion regarding omissions. Column Element and Type of element show how to fix the omission.

Expert Opinions (omission)	**Element**	**Type of element**
Type of building block where the building is located.	HB58 Usage HB59 Usage Assignment Building Usage Building Block Usage	Reused class Reused class New class New class
Section. Location on a valuable section. The silhouette context or section in which it is located. Relation to the urban section.	Building Block Section	New class
Urban-architectural assessment. Architectural typology. The architectural style of the building.	Architectural Style	New class
Elements built without a permit on the lot	E11 Modification E12 Production E79 Part Addition E80 Part Removal P108 has produced P110 augmented P111 added P112 diminished P113 removed has permit Construction Permit	Reused class Reused class Reused class Reused class Reused property Reused property Reused property Reused property Reused property New property New class
Basic information on socioeconomic status of owner	Socioeconomic Status	New class

Information about the owners of the building.	P28 custody surrendered by P29 custody received by P30 transferred custody of E10 Transfer of Custody	Reused property Reused property Reused property Reused class
The date of the building	P116 starts	Reused property

4.3 The BCH-ontology

In this section the final ontology is presented, organized according to the cycles of preventive conservation.

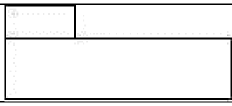
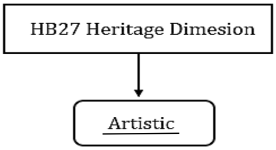
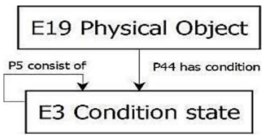
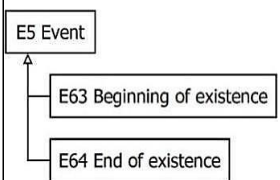
The final model consists of an ontology with 180 classes, out of which 28 are from MONDIS ontology, 34 from Geneva-CityGML, 53 from CIDOC-CRM, and 65 new classes have been added. The ontology also includes 129 properties (57 inverse) (Annex II).

4.3.1 CH-ontology key concepts.

In a later section, the main classes and properties of the BCH-ontology are explained. Key concepts used in diagrams are presented in Table 4.13. Some name classes used in previous sections are changed to synonyms in order to reuse the classes from the selected ontologies.

Table 4.13 Diagrams key concepts used for the construction of the BCH-ontology.

Term	**Description**
Class E19 Physical object	A class represents a category of items that share a number of common features. It is represented by a rectangle.
Package	A package represents a group of classes that share some common characteristics.

	
Instance 	A class is instantiated when a real world value is assigned to it. For example 'Artistic' is an instance of the Heritage Dimension class according to the Nara grid (Van Balen, 2008). The value instantiated is represented by an ellipse. A single arrow points to the instantiated value. The name of the instance is underlined.
Property 	Properties define relationships between two classes. They are formally defined by the specification of a domain class and a range class. Properties are represented by a black arrow starting at the domain and pointing to the range.
Inheritance 	Ontologies are based on taxonomical representations which show the hierarchical relationship among the ontology terms. This hierarchical representation is also known as inheritance and leads to classes acquiring a role of subclass or superclass. All instances of the subclass are also instances of its superclass, and the properties of the superclass are also applicable to the subclass. Inheritance is represented by a white arrowhead where the subclass is pointing to the superclass.

4.3.2 CH-ontology packages

BCH-ontology Classes Packages have been used in Figure 4.13 for readability reasons. Figure 4.14 through Figure 4.16 show the classes included in each package.

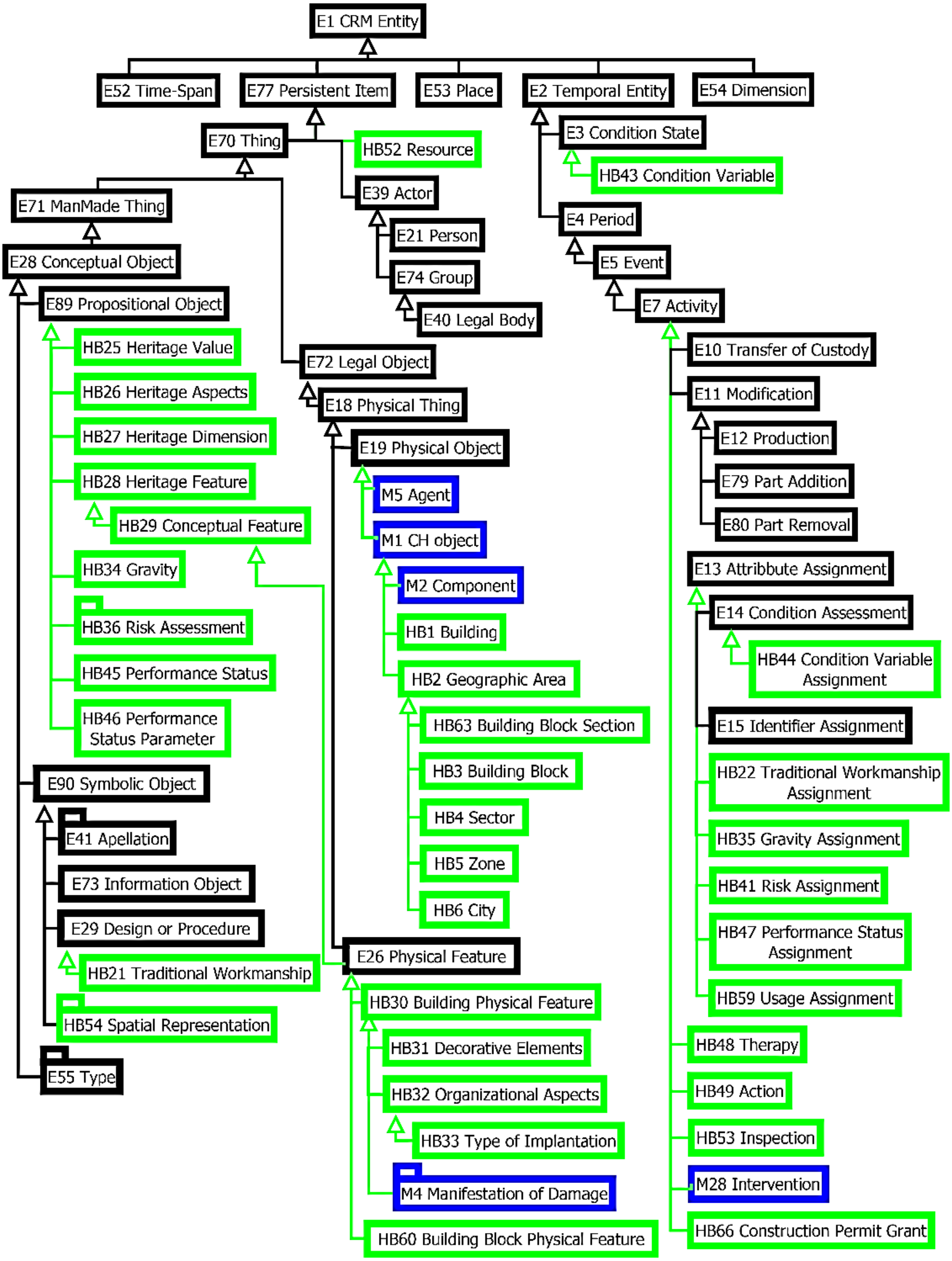


Figure 4.13 Diagram depicting the main BCH-ontology classes and packages. Classes from CIDOC-CRM are in black, MONDIS in blue and new classes in green.

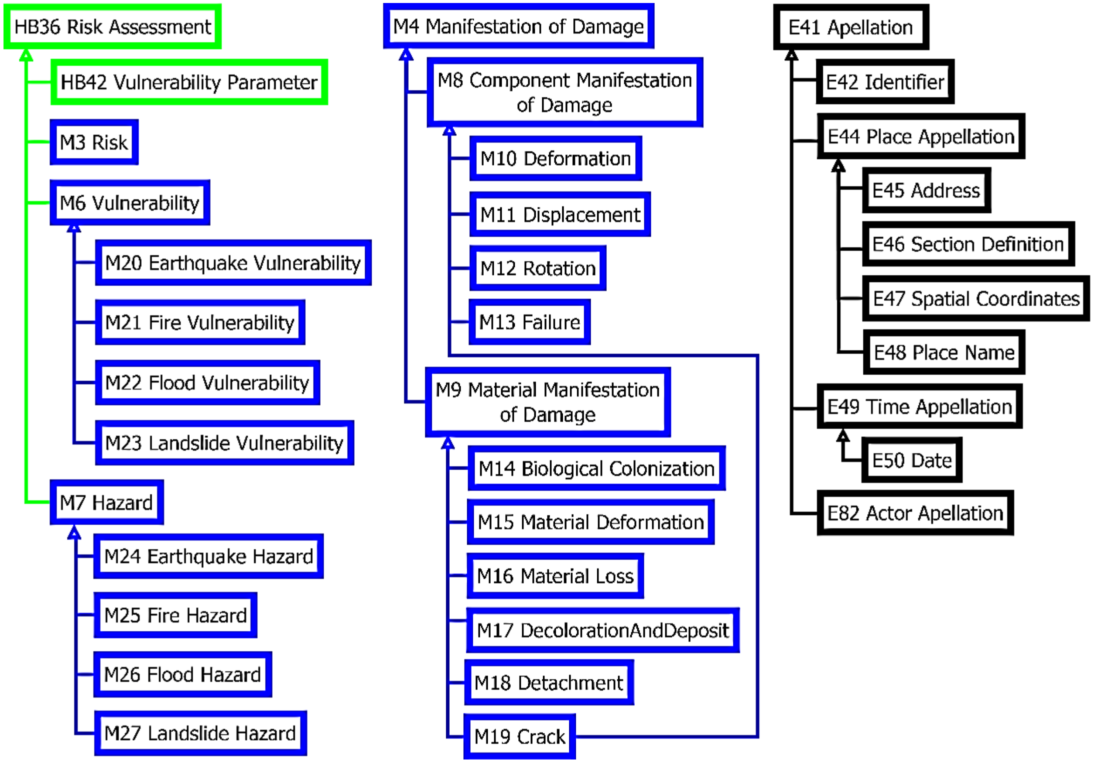


Figure 4.14 Diagram depicting the BCH-ontology packages: Risk, Damages and Appellation. Classes from CIDOC-CRM are in black, MONDIS in blue and new classes in green.

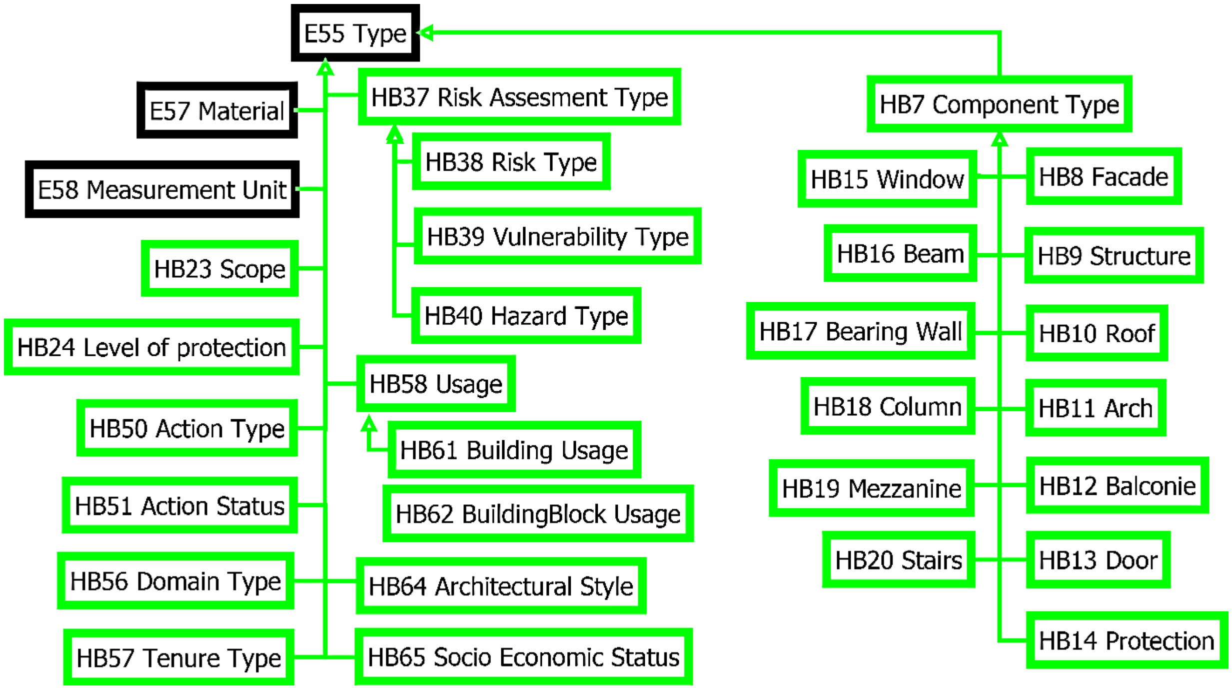


Figure 4.15 Diagram depicting the BCH-ontology package: Type. Classes from CIDOC-CRM are in black and new classes in green.

Figure 4.16 Diagram depicting the BCH-ontology packages: Spatial representation. Classes from Geneva-CityGML are in yellow and new classes in green.

4.3.3 Naming convention

The naming of CIDOC-CRM classes can be translated into any language as long as the identifying codes are preserved. The CIDOC-CRM identification codes for classes start with the prefix 'E' which stands for 'entity', followed by a sequential number and the name of the class (ICOM, 2015). CIDOC-CRM properties use the prefix 'P'. Geneva-CityGML, MONDIS and new classes and properties are named respectively 'G', 'PG', ‘M’, ‘PM’, ‘HB’, and ‘PHB’. HB stands for ‘historical buildings’. Each word of the class name is followed by a blank space and starts with upper case, except articles and prepositions. Properties are written with lower case.

4.3.4 CIDOC-CRM basic structure

The CIDOC-CRM ontology groups the classes into two super-classes: “E2 Temporal Entities” and “E77 Persistent Item.” “E2 Temporal Entity” instances happen over a limited continuous period of time and have a location. This class includes the following: periods, events, the condition state of a heritage unit, and activities in general. The “E77 Persistent Item” class encompasses those classes whose identity remains unchanged for a longer period of time. The class encompasses either physical entities, such as people, animals or material things, or conceptual entities such as ideas, concepts and products of the imagination or common names. We also adopted this structure as the root for the BCH-ontology.

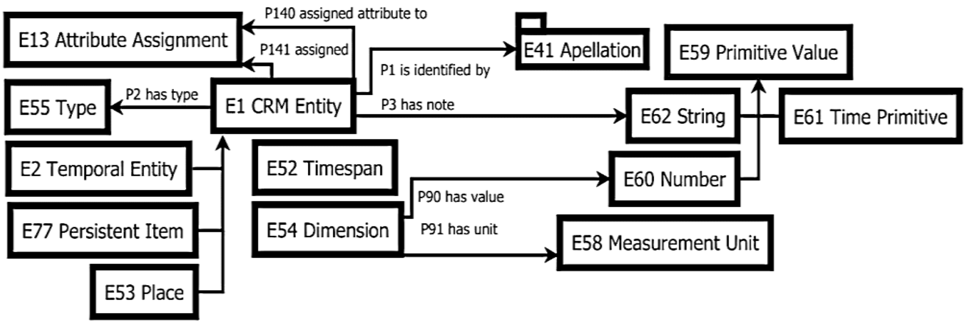


Figure 4.17 Diagram depicting the CIDOC-CRM basic structure.

The “E53 Place”, “E52 Timespan” and “E54 Dimension” classes represent location, temporal features and measurements. Dimensions have value and measurement units, which are represented by the “P90 has value” and “P90 has unit” properties. Every “E1 CRM Entity” instance has appellation, type, notes and attributes. Appellation identifies the entity. The class “E55 Type” supports the classification of entities and the assignment of qualitative values; the class “E62 String” can be used to record comments regarding the entity; and the “E13 Attribute Assignment” class allows to assign attributes such as identifiers, condition, measurements or types.

Primitive values as numbers, string and time are enclosed in the “E59 Primitive Value”, which, together with the “E1 CRM Entity” class, are at the root of the CIDOC-CRM ontology.

4.3.5 The BCH-ontology and the preventive conservation approach

An important goal of the BCH-ontology is to be able to represent the PC approach. In this section we go over all the preventive conservation phases and highlight the BCH classes relevant to each phase.

Analysis

In the analysis phase, information regarding heritage entities is collected through the “M1 CH Object” class; from now on heritage entities are referred as cultural heritage objects (CH objects). CH objects can be: components, a single building, bigger geographic areas (building blocks, sectors, zones) or the whole city. Single buildings are represented using the “HB1 Building” class. The “HB2 Geographic Area” class contains the “HB3 Building Block”, “HB4 Sector” and “HB5 Zone” subclasses. The city is represented by the “HB6 City” class.

CH Objects have constitutive elements, represented with the “M2 Component” class. MONDIS provides a list of 122 classes and subclasses to represent components. This classification is too complex for our case study and still does not accommodate all required concepts. For this reason we have created a simpler typology under the “HB7 Component Type” class which is a subclass of “E55 Type.” The “P46 is composed” property is used to show the relationship between CH objects and components.

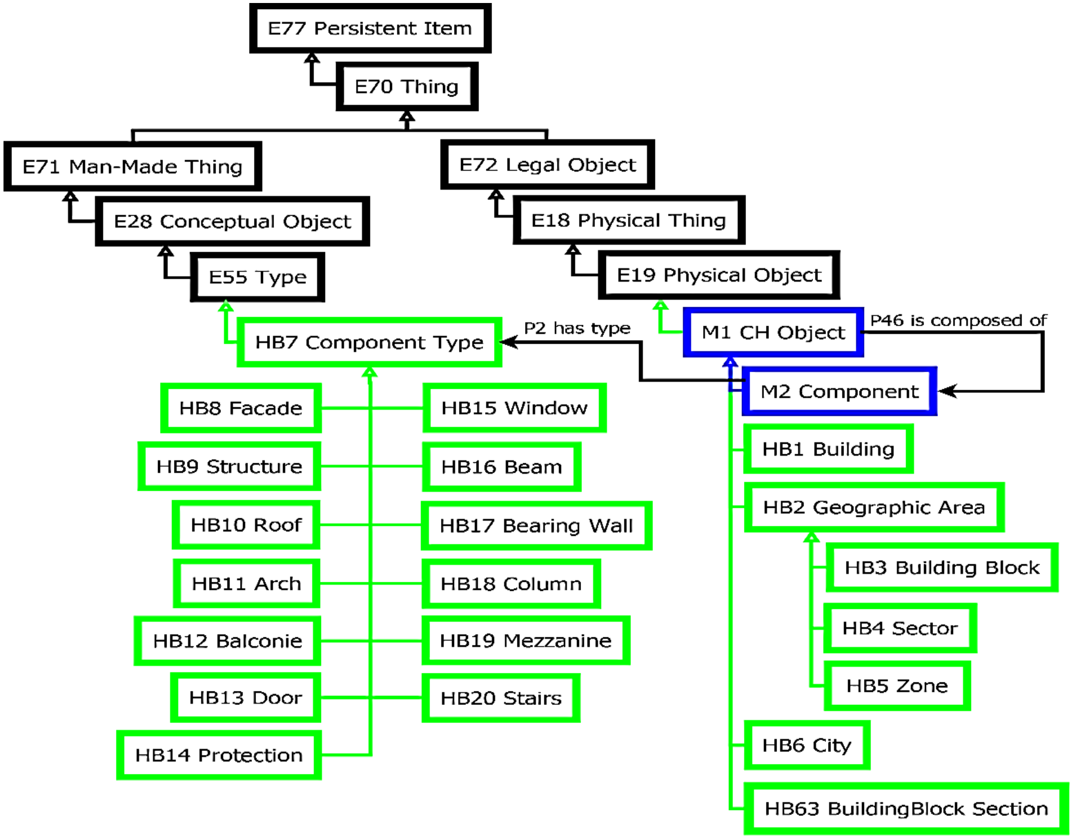


Figure 4.18 Diagram depicting the Analysis phase classes: CH Object and Component classes.

Materials and traditional techniques used in components are also gathered. “E57 Material” and “HB21 Traditional Workmanship” classes are used for this purpose. The latter is included as subclass of the “E29 Design or Procedure” class. The “P127 has broader term” property allows to have classifications of materials. The “P45 consist of” property links components with their materials. The “P68 foresees use of” property links the traditional workmanship with the component material. The “HB21 Traditional Workmanship Assignment” class has been created under the “E13 Attribute Assignment” class. Properties “P140 assigned attribute to” and “P141 assigned” are used to link the traditional workmanship with the CH object.

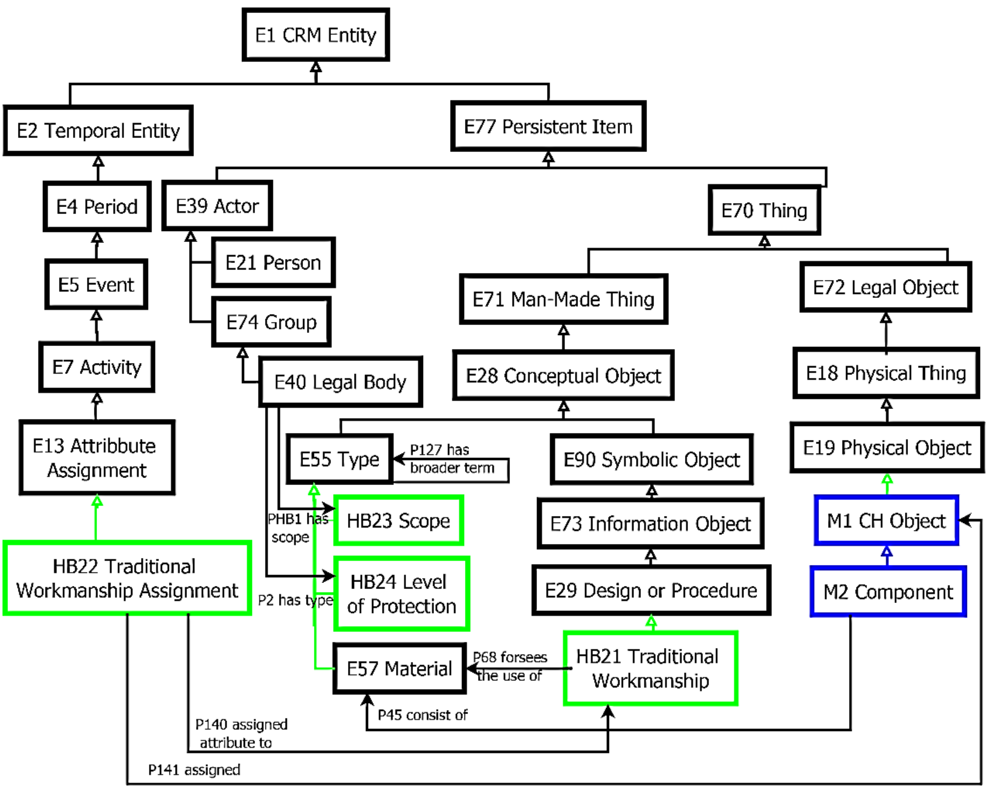


Figure 4.19 Diagram depicting the Analysis phase classes: material, traditional workmanship and legal body.

Legal protection is represented by the “E40 Legal Body” class. “HB23 Scope” and “HB24 Level of Protection” classes are added to the “E55 Type” class. “PHB1 has scope” and “P2 has type” properties link the “E40 Legal body” class with the scope and the level of protection.

CH Objects have heritage values associated with one or more heritage aspects and dimensions according to the Nara Document on Authenticity (Van Balen 2008). The “HB25 Heritage Value”, “HB26 Heritage Aspect” and “HB27 Heritage Dimension” subclasses are added to the “E89 Propositional Object” class, which comprises intangible items that represent propositions about real or imaginary things and that are documented as single units. The “P67 refers to” property is used to link the heritage value to the CH object, and aspects and dimensions to the heritage value. The “P3 has note” property can be used to add a description of the heritage value. Instances of heritage aspects are: Form and design, Materials and substance, Use and function, Tradition, Technique and workmanship, Location and setting, and Spirit and feeling. The heritage dimensions instances are: Artistic, Historic, Social and Scientific.

A heritage value is set according to several valuable features represented by the “HB28 Heritage Feature” class. Heritage features can be represented by the “E26 Physical Feature” or “HB29 Conceptual Feature” classes which are related with the “P67 refers to” property. The “E26 Physical Feature” class comprises identifiable features that are physically attached in an integral way to particular physical objects. The “HB29 Conceptual Feature” class represents immaterial features related to a persistent item. The “P67 refers to” property also links the heritage value and features with the physical object.

When the heritage unit refers to a building, some physical features are already established, such as “HB30 Building Physical Feature”, “HB31 Decorative Element” and “HB32 Organizational Aspect” classes. “HB33 Type of implantation” is a subclass of the “HB32 Organizational Aspect” class. “PHB2 has courtyard” and “PHB3 has orchard” properties link the

"HB32 Organizational Aspect" class with its value. Other physical features have to be defined for different heritage units, for example for the "HB60 Building Physical Feature" class.

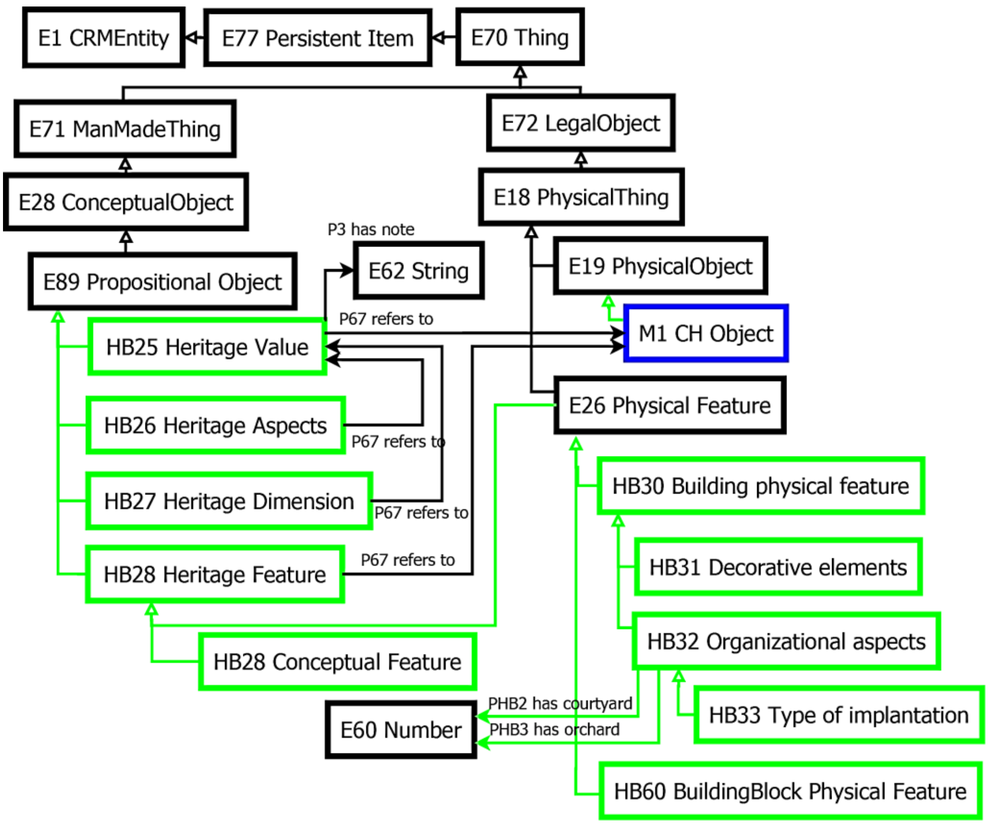


Figure 4.20 Diagram depicting the Analysis phase classes: heritage values and heritage features.

Other collected information regarding valuable features are Gravity, Risk, and Condition represented by the "HB34 Gravity", "M3 Risk" and "E3 Condition State" classes. Gravity is composed of damages (disturbances) and deterioration agents. The "M4 Manifestation of Damage" class from the MONDIS ontology is positioned under the "HB30 Building Physical Feature" class.

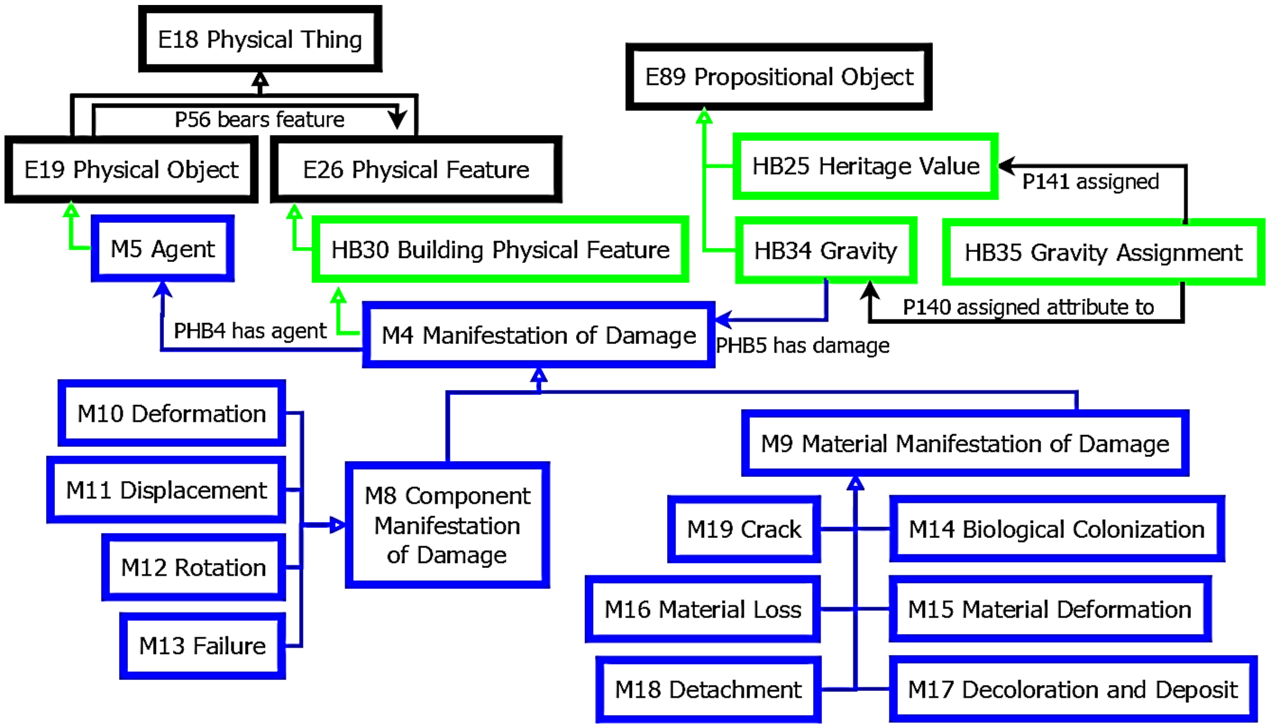


Figure 4.21 Diagram depicting the Analysis phase classes: manifestation of damage.

MONDIS classifies damages present in a component or in the material covering the component (Figure 4.21). Deterioration agents are instances of the “M5 Agent” class which is a subclass of “E19 Physical Object.” The property “PHB4 has agent” relates damages to deterioration agents. The “PHB5 has damage” property relates gravity to damages. The property “P56 bears feature” links damages with the CH object. The “HB35 Gravity Assignment” class and properties “P140 assigned attribute to” and “P141 assigned” are used to link gravity with the heritage value.

Risk is computed taking into account threats and vulnerability. The MONDIS ontology provides the “M3 Risk” and “M6 Vulnerability” classes while threats are represented with the “M7 Hazard” class. The “HB36 Risk Assessment” class is created as a subclass of “E28 Conceptual object” class and comprises risk, vulnerability and hazard concepts. “HB36 Risk Assessment” classes can have a quantitative or qualitative value.

Qualitative values are added using the “E2 Type” and “HB37 Risk Assessment Type” classes. In this case the qualitative values for the risk assessment classes are: ‘Low,’ ‘Medium,’ and ‘High’. If each class has different qualitative values the “HB38 Risk Type,” “HB39 Vulnerability Type,” and “HB40 Hazard Type” classes will be used. A quantitative measure can be added through the “E54 Dimension” class and the “P43 has dimension” property.

“MP1 refers to hazard” property links hazard with risk. Risk is related to the heritage value through the “HB41 Risk Assignment” class and “P140 assigned attribute to” and “P141 assigned” properties. “MP2 is subject to” property links vulnerability with hazard.

MONDIS also further classifies vulnerabilities and hazards with respect to earthquakes, fire, floods and landslides. To compute the vulnerability a new class “HB42 Vulnerability Parameter” is created. These parameters are accompanied by a weight, since not all the parameters have the same importance. To this end the “PHB6 has weight” property has also been added. The “PHB7 has parameter” property relates parameters to vulnerability.

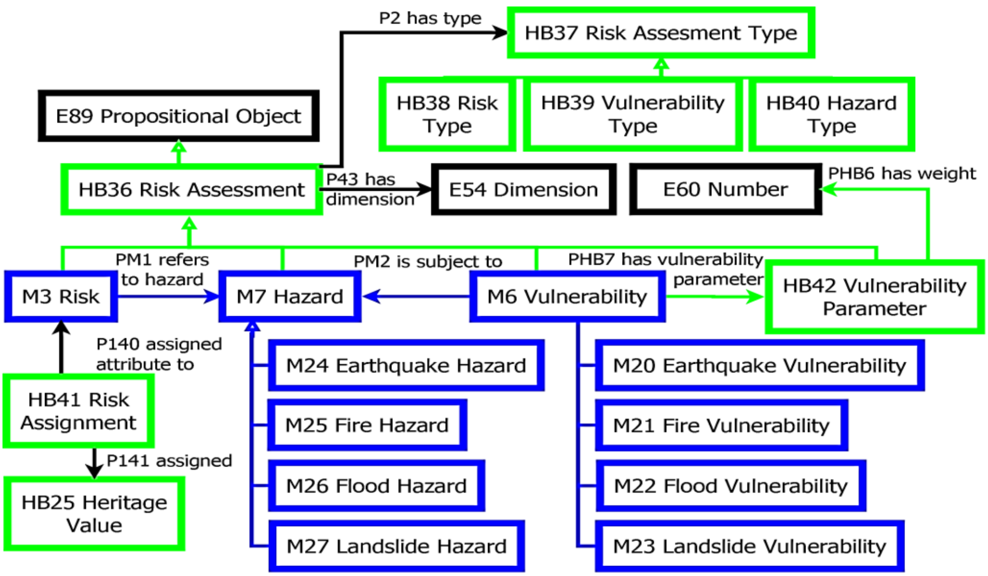


Figure 4.22 Diagram depicting the Analysis phase classes: risk, vulnerability, hazard.

The condition is recorded with the “E3 Condition State” class, through a list of variables represented by the “HB43 Condition Variable” class. The “HB44 Condition Variable Assignment” class is created under the “E14 Condition Assessment” class and links condition variables with their value and the weight through the “PHB8 has condition value” and “PHB9 has condition weight” properties. The “PHB10 has condition variable” property links the condition variable to the assignment. The condition variable assignment is linked to the general condition with the “P5 consist of” property; general condition is linked to the heritage value with the “PHB11 refers to value” property.

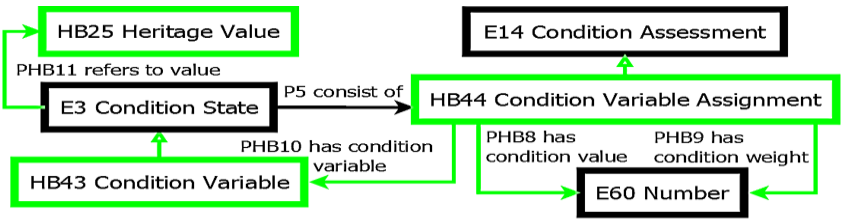


Figure 4.23 Diagram depicting the Analysis phase classes: condition state.

Diagnosis

In the diagnosis phase (Figure 4.24), the "HB45 Performance Status" and "HB46 Performance Status Parameter" classes are added under the "E28 Conceptual Object" class. The effect of consequential damage, the speed of deterioration, the relative importance of damages and the alterations are instances of the performance status parameters. The "PHB12 has parameter" property links the performance status with its parameters. The "PHB13 has max limit" and "PHB14 has min limit" properties establish thresholds for the performance status parameters. Quantitative values to the performance status and each parameter are assigned through the "E54 Dimension" class and the "P43 has dimension" property. The "HB47 Performance Status Assignment" class links the performance status with the heritage value.

According to the performance status a therapy with some actions is suggested. The "HB48 Therapy" class is created under the "E7 Activity" class. The "PHB15 has therapy" property links the suggested therapy with the performance status. The "PHB16 has suggested action" property links the therapy with the suggested actions. Actions in general are represented by the "HB49 Action" class. The "HB50 Action Type" and the "HB51 Action Status" classes are created under the "E55 Type" class. Instances of the "HB50 Action Type" class are curative or preventive (direct, indirect). The status of the action can be "suggested action" and "executed action." The "PHB17 has status" property links the action status to the suggested action. The type of action is assigned through the "P2 has type" property.

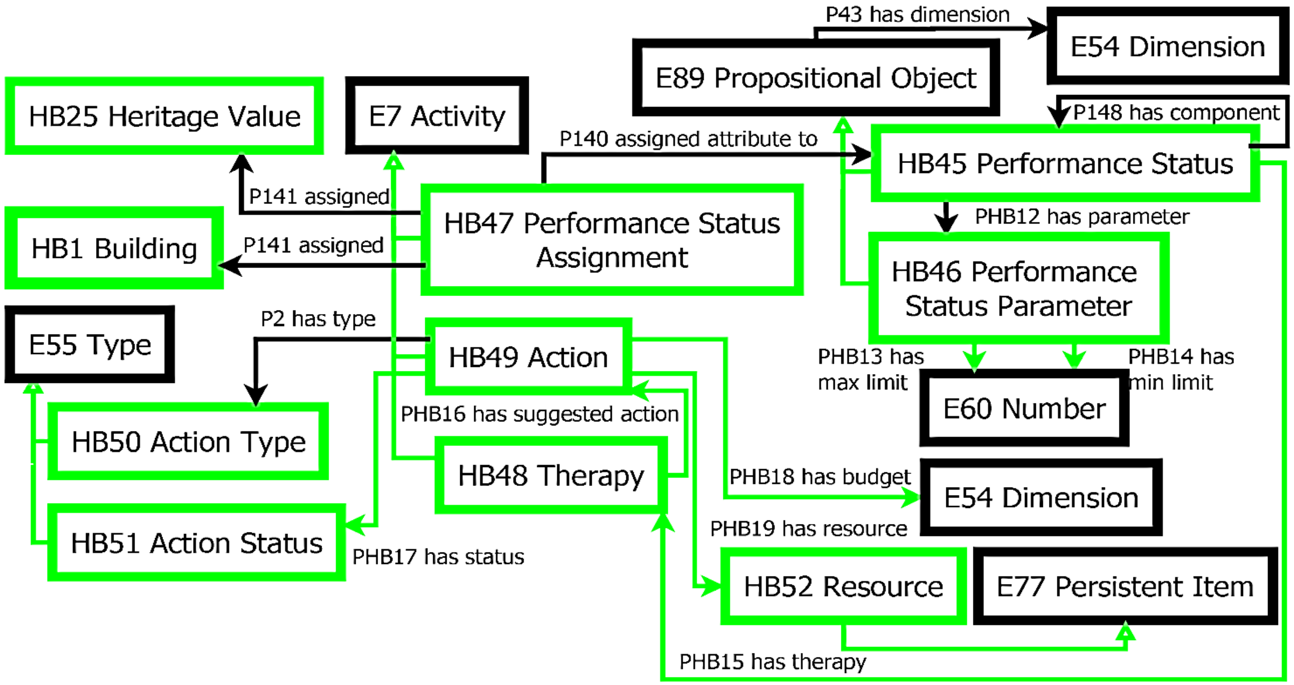


Figure 4.24 Diagram depicting the classes of the Diagnosis phase.

The “PHB18 has budget” and “PHB20 has resource” properties associate a budget and the resources needed for the execution of the suggested action. The budget can be represented by the “E97 Monetary Amount” class. The “HB52 Resource” class is created under the “E77 Persistent Item” class.

Therapy

During the therapy phase an intervention is executed. The MONDIS “M28 Intervention” class is used to keep track of the suggested actions used in the intervention. The suggested therapy is linked to the intervention through the “PHB20 has intervention” property.

An individual action used during the intervention is recorded through the “HB49 Action” class. The “PHB21 has intervention action” property links the intervention with the action. The “HB51 Action Status” class instantiated as “executed action” means that the suggested therapy action was executed in the intervention.

The “MP3 is eliminated by intervention” and “MP4 is repair of damage” properties link the agent and damage that are tackled by the intervention.

Control

The control phase ends with one or more inspections to verify whether the actions reached the conservation objective. The “HB53 Inspection” class is created under the “E7 Activity” class. The “PHB22 requires further inspections” property means that more control activities are required. The “PHB23 conservation objective reached” property points out whether the conservation objective has been reached. Additional notes can be added through the inherited property “P3 has note.” The therapy is linked to the inspection through the “PHB24 has inspection” property.

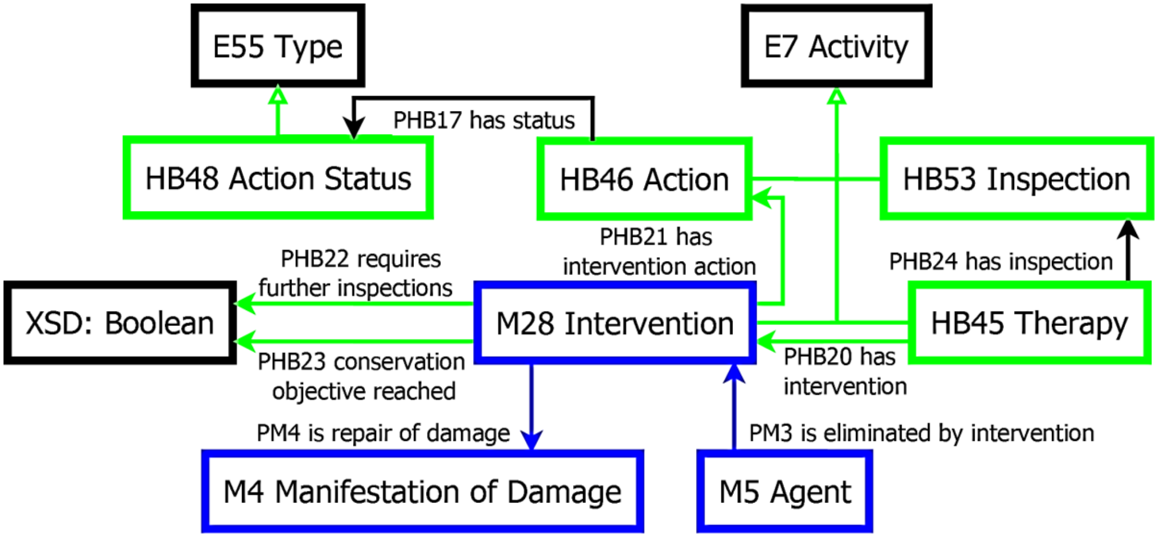


Figure 4.25 Diagram depicting the classes of the Therapy and Control phases.

4.3.6 The BCH-ontology and spatial representation

In this section we describe the employed classes from the ontological version of the CityGML standard developed by the University of Geneva (Métral & Cutting-Decelle, 2011). These classes are used to represent spatial information.

In order to represent geometries from the different objects the "G1 Geometry" class is used. Geometries can be represented by the "G2 Geometric Primitive" class or the "G3 Abstract Geometric Aggregate" class. Geometric primitives are classified into the "G4 Point," "G5 Curve," "G6 Surface," and "G7 Solid" classes. Surfaces are classified into the "G8 Polygon" class. Abstract geometric aggregates are classified into the "G9 Multipoint," "G10 Multicurve," "G11 Multisurface," "G12 Multisolid," and "G13 Multigeometry" classes.

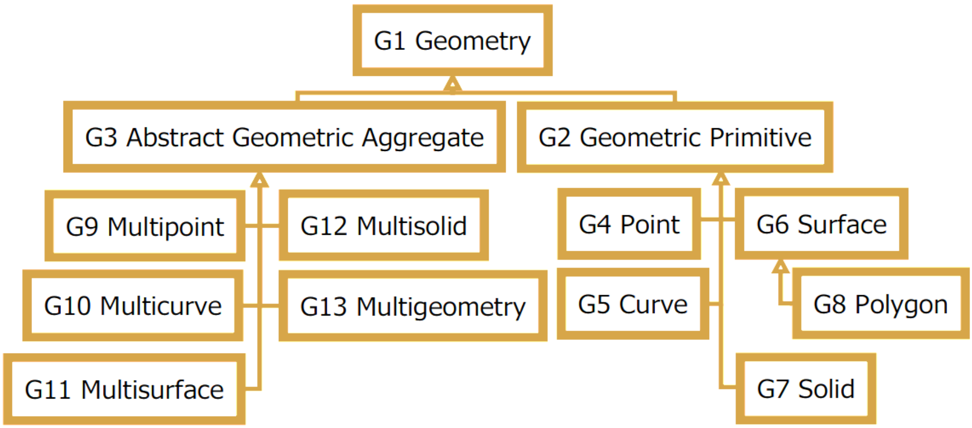


Figure 4.26 Diagram depicting the geometry classes for spatial representation.

The "G14 City Object" class contains all the CityGML standard classes except the "G1 Geometry" classes. The "G1 Geometry" and the "G14 City Object" classes are subclasses of the "HB54 Spatial Representation" which in turn is a subclass of the "E90 Symbolic Object" class.

The “G15 Site” class contains the “G16 Abstract Building” class which comprises the “G17 Building” and “G18 Building Part” classes. The “PHB25 has geographical representation” is used to link “HB1 Building” “M2 Component” classes with their spatial representations. The "HB1 Building" and "G17 Building" classes are related with the "same as" property so they can be used as equivalent objects. This means that the features of the CityGML classes can also be used with the “HB1 Building”. They have not been used in this first version of the ontology but can be extended by means of Geneva-CityGML class properties as was done with other selected properties in Table 4.8. Figure 4.27 shows the features of the class "_AbstractBuilding” that can be used for this purpose; the same methodology can be applied for the features “function” and “usage” of the BuildingInstallation, IntBuilidingInstallation, BuildingFurniture and Room classes.

In general, a building or component can have several representations, with different or the same LoD. Most commonly there is a conceptual instance of the object stored in the class “HB1 Building” whose geometry is bound with the property “PHB25 has geographical representation”. However, if required for some reason, it is possible to have only the geometry being part of the class “G17 Building”, which, due to the property “same as”, implicitly already has an empty instance of the class "HB1 Building".

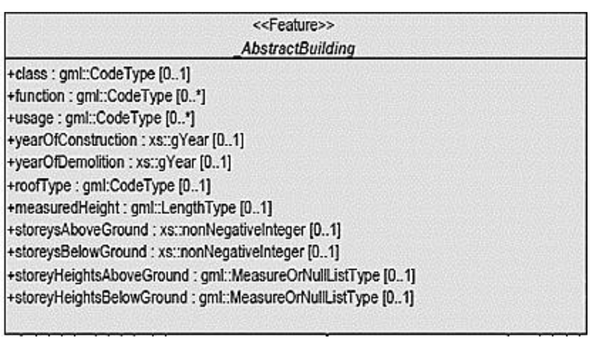


Figure 4.27 Possible properties to be reused from the CityGML standard (Costamagna & Spano, 2013).

The CityGML standard has different LoDs to represent its elements. The first level LoD0 uses 2.5-dimensional surfaces (elevation models) to represent the footprint and the roof edge of a building. Surfaces are represented with the "G11 MultiSurface" class. The "PG1 lod0 footprint" and "PG2 lod0 roof edge" properties are used to link the abstract building to the multisurface.

The outer shell of the building is represented in the second level of detail LoD1 as a block by the "G7 Solid" class. The "PG3 lod1 solid" property links the solid with the building.

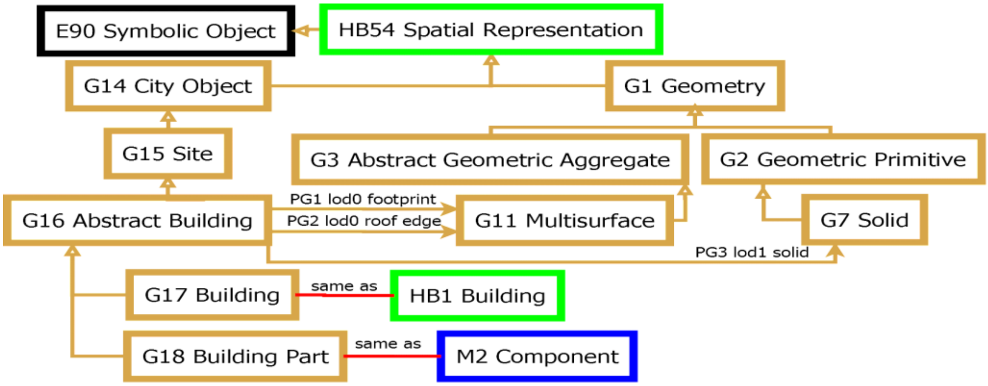


Figure 4.28 Diagram depicting the spatial representation classes for buildings and their components.

The representation of architectural details (Figure 4.29), like roof overhangs, columns, or antennas is made in in the level of detail LoD2 through the "G19 Building Installation" class. The "PG4 outer building installation" property links the abstract building with the building installation. The geometry of architectural details is represented using multisurfaces. The "G20 Boundary Surface" class comprises "G21 Roof Surfaces," "G22 Wall Surface," "G23 Ground Surface," "G24 Ceiling Surface," "G25 Interior Wall Surface," "G26 Floor Surface," "G27 Outer Ceiling Surface," "G28 Outer floor surface" and "HB55 DecorativeSuperstructure" classes. Building installations are linked to boundary surfaces through the "PG5 bounded by" generic property and boundary surfaces are linked to multisurfaces through the "PG6 lod2 multisurface" property.

Openings are represented in LoD3 by the "G29 Opening" class and the "G30 Door" and "G31 Window" subclasses. The geometry is represented by multisurfaces through the property "PG7 lod3 multisurface". An opening in a boundary surface is represented using the property "PG8 opening".

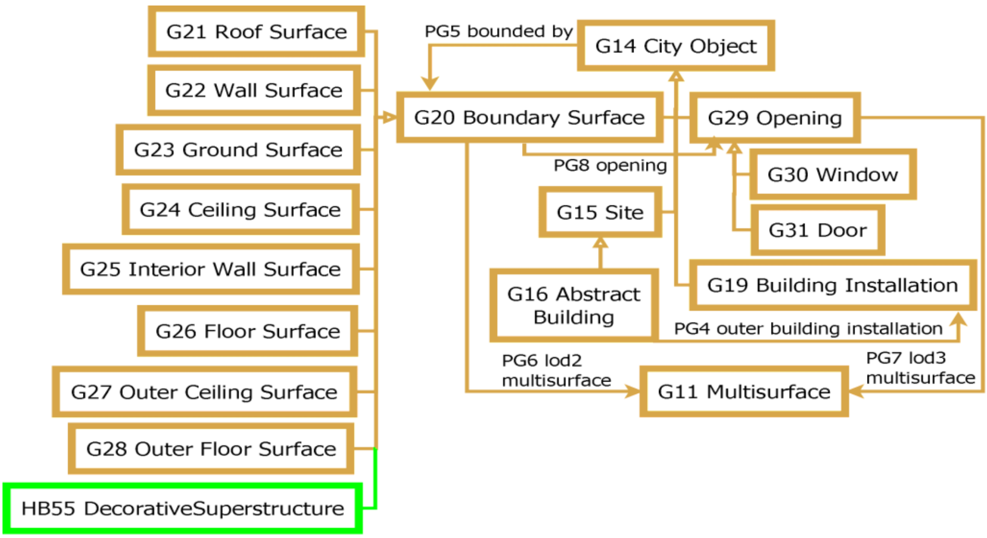


Figure 4.29 Diagram depicting the spatial representation classes for surfaces, openings and building installations.

Elements of the building interior such as rooms, furniture, and interior building installations are represented in LoD4 through the "G32 Room," "G33 Building Furniture" and "G34 Int building installation" classes. Room geometry is represented by solids or multisurfaces through the "PG9 lod4 solid" and "PG10 lod4 multisurface" properties. A boundary surface is linked to a room with the "PG5 bounded by" generic property. Furniture and interior building installations are represented using any set of geometries through the "PG11 lod4 geometry" generic property.

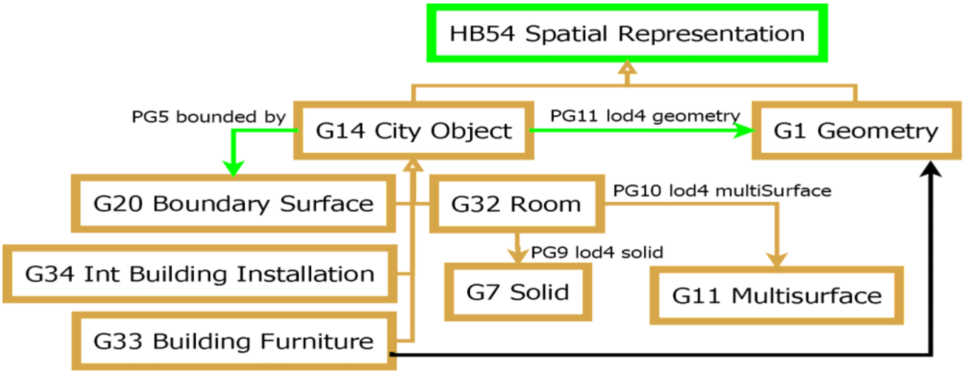


Figure 4.30 Diagram depicting the spatial representation classes for interior building installations, building furniture and rooms.

4.3.7 The BCH-ontology and temporal representation

Phenomena that happen over a limited period of time are represented by the “E2 Temporal Entity” class. Periods of time are described with the “E52 Time-Span” class. The “P4 has time-span” property relates a period of time with the temporal entity.

The “P81 ongoing throughout” property links the time span with the “E61 Time Primitive” class. Time primitives are not further developed by the CIDOC-CRM ontology since there are specific ontologies for this, such as the time ontology developed by W3C and OGC (2017). For the purpose of this research, we will assume the “E61 Time Primitive” class is defined by the W3C/OGC time ontology.

Other important properties are “P115 finishes” and “P116 starts” which define the beginning and end of temporal phenomenon. Maximum and minimum durations are represented using the “P83 had at least duration” and “P84 had at most duration” properties, which link “E52 Time-Spans” with the “E54 Dimension” class. The “P82 at some time within” property describes a period of time which happened at some point during a longer period of time. This property is very useful in case of uncertainty.

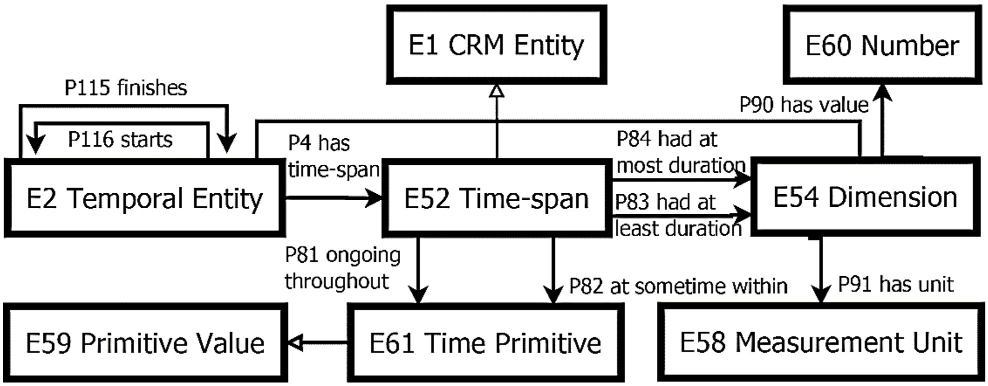


Figure 4.31 Diagram depicting the BCH-ontology temporal classes.

4.4 Proof of concept

The San Luis seminary building from the city of Cuenca is selected to verify if the BCH-ontology is able to represent the PCA phases, in this case only thematic information has been used. For visibility reasons only the initial code of the properties is used in the following diagrams, their full name can be found in Annex IV.

Figure 4.32 Photo of the historical building of San Luis seminary in Cuenca-Ecuador (CPM research group).

4.4.1 Analysis

The reference name ‘SemSL’ is assigned to the seminary whose type is a building. The cadastral code "0102035001" is used as identifier and its address is "Benigno Malo 9-49 y Bolivar". The address is represented by the reference name ‘AddSemSL’.

The seminar consists of two facades with the reference names "SemSLF1" and "SemSLF2". The first facade contains 15 arches, 7 windows and 6 doors. Figure4.30 shows the description of the first arch, the other components are described in the same way.

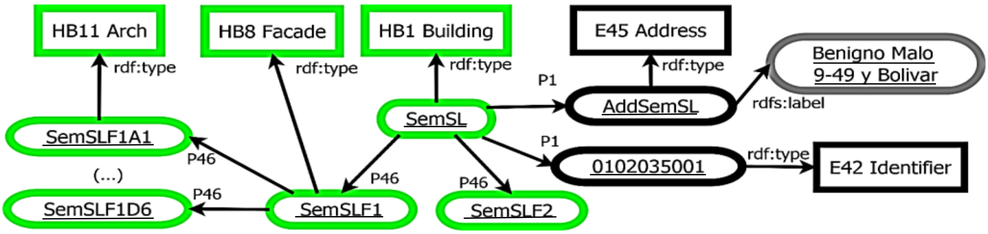


Figure 4.33 Diagram depicting building components and heritage values of San Luis seminary.

The facade has heritage features such as ‘central axis symmetry’, and the ‘homogeneous vertical distribution’ which increases the heritage value of the building. These characteristics are linked to the "Form and Design" aspect and the "Artistic" dimension.

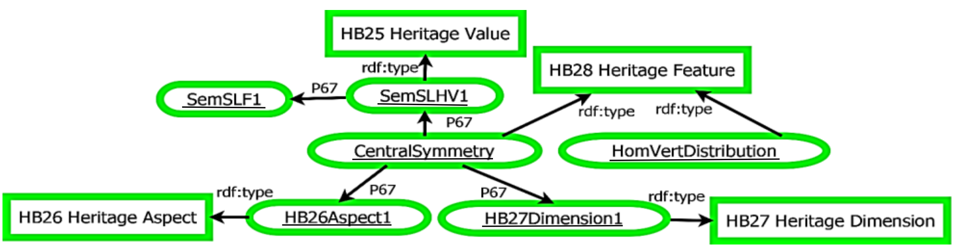


Figure 4.34 Diagram depicting heritage values, features, aspects and dimensions of San Luis seminary.

4.4.2 Diagnosis

In the diagnostic phase, the performance status of heritage values is calculated, based on condition, gravity and risk. A general performance status of the building is computed taking into account all performance status of heritage values.

In this case, the condition is set as a qualitative value 'Stable', although it can also be set as a quantitative value or a list of parameters.

The gravity value is calculated by taking into account damages which increment the risk of losing the heritage value of a component. For the documentation of damages, a detachment of the facade caused by the agent of deterioration water, has been represented.

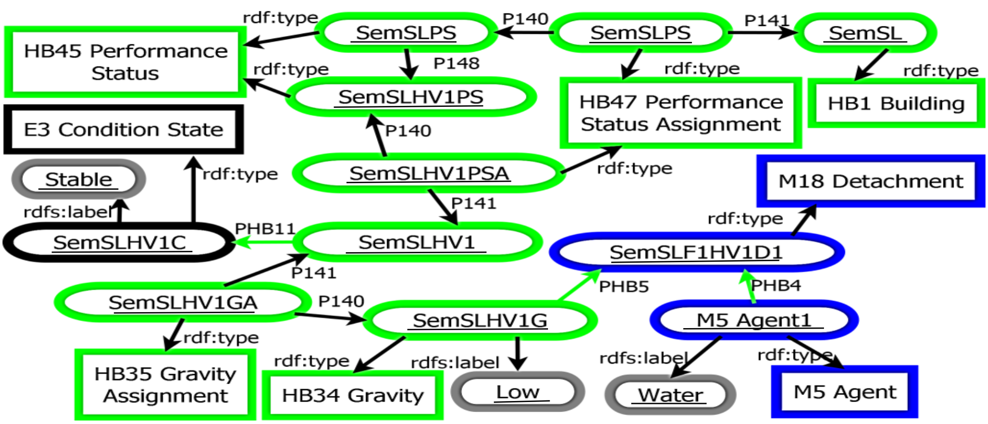


Figure 4.35 Diagram depicting performance status, condition and gravity of San Luis seminary.

Risk is calculated taking into account hazards and vulnerability. Quatitative values have been set for this classes as follows: 'low' vulnerability, 'medium' hazard, and 'medium' risk.

Risk, gravity and performance status are linked to the heritage value through the “HB41 Risk Assignment”, “HB35 Gravity Assignment” and “HB47 Performance Status Assignment” classes.

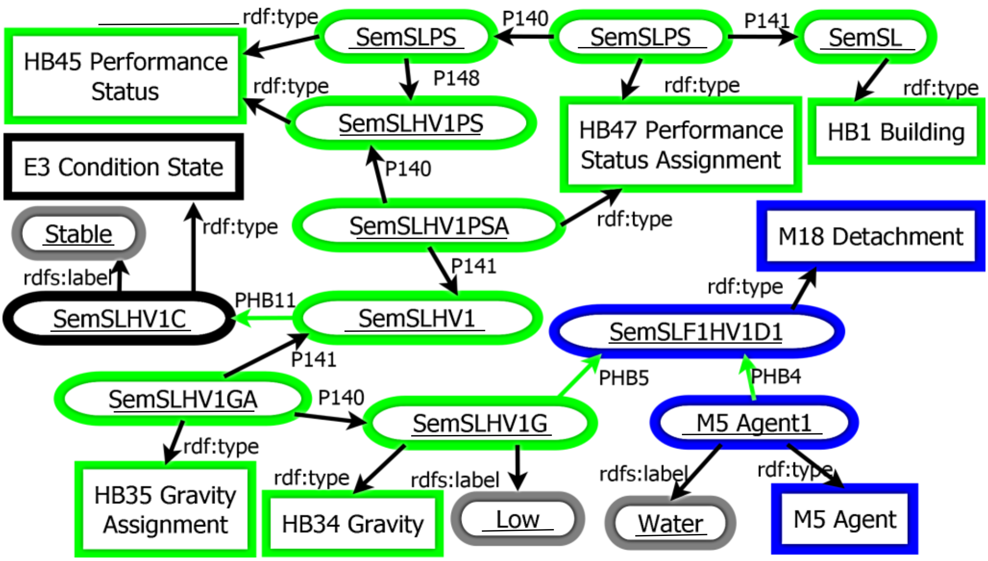


Figure 4.36 Diagram depicting risk management of San Luis seminary.

4.4.3 Therapy

The performance status can be a quantitative, qualitative value or a visual examination of severity, risk and condition.

According to the performance status a therapy is established consisting of a set of suggested actions. In this case, the indirect action 'Special_plans_or_campaigns' with a budget of 100 euros. The actions can be curative or preventive (direct, indirect).

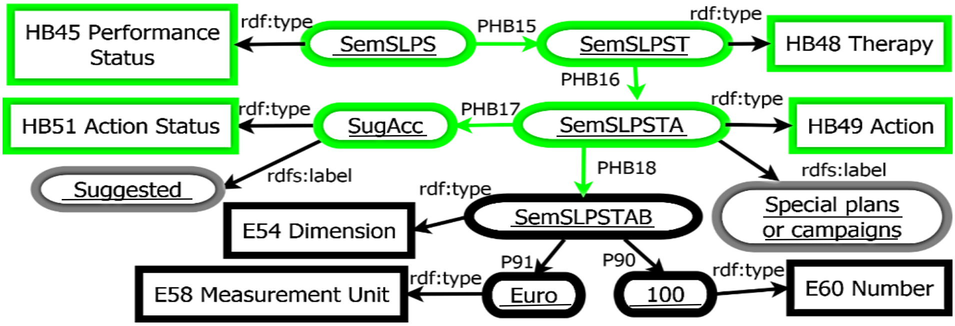


Figure 4.37Diagram depicting the suggested therapy for San Luis seminary.

4.4.4 Control

After suggesting a therapy, an intervention can be executed, where the executed actions change their status. The class “HB35 Inspection” verifies whether the conservation objective was reached after the intervention.

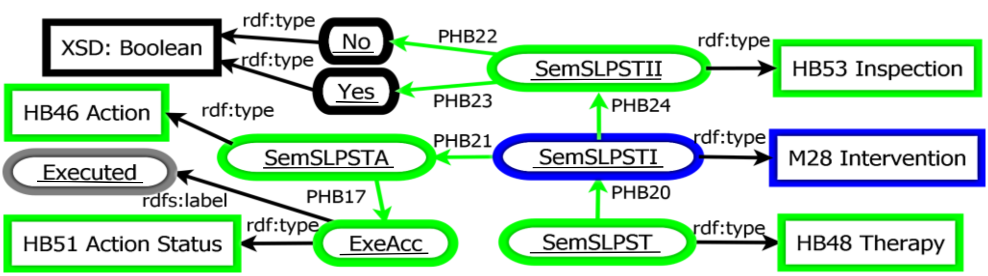


Figure 4.38 Diagram depicting the control phase of San Luis seminary.

Finally, the BCH-ontology has been presented. The proof of concept shows that the ontology is able to represent the PCC. An evaluation of the actual use of the ontology is still needed to evaluate its functionality.

4.5 Discussion and Conclusions

The BCH-ontology presents a model that increases the interoperability of the different data necessary for a correct management of BCH. Sections 4.3.5 and 4.4 show that the BCH-ontology is able to represent the different cycles of preventive conservation, but it is also able to represent other approaches.

The BCH-ontology allows the integration of spatial and thematic information of a heritage area. Section 4.3.6 describes the classes that can be used for 2d and 3d spatial representation. Section 5.1 shows the limitations of semantic models for analyzing 3D models, however more detailed work is required on specific examples of the different LoDs that can be represented.

The BCH-ontology is bilingual and is published in English and Spanish versions in different files, eliminating the complexity of working with two languages but also allows working with all files if necessary.

The BCH-ontology is based on 3 reused ontologies: CIDOC-CRM, Geneva-CityGML and MONDIS. At the time of development these three ontologies were evaluated as adequate. Accessibility and scope review ruled out most ontologies. Then their terms (completeness) were manually compared and the ontologies with the highest number of terms were selected (Geneva-CityGML, MONDIS, and CIDOC-CRM). When checking provenance, reputation and understandability allowed us to identify CIDOC-CRM as the backbone of the BCH-ontology. At the time of writing some other ontologies which have been published, such as the ontological model for the representation of damage (DOT) to construction, where a set of modular ontologies are provided and more detailed types of damages are defined such as damage areas, patterns and elements (Hamdan et al., 2019). A preliminary evaluation allows us to observe that it contains only the general classes to represent damage. The classes of damage area, pattern and element are significant for the maintenance of the BCH. DOT does not provide a classification of damage as such, instead it offers two other ontologies that can be used for this purpose such as the MDCS (Monument Diagnosis and Conservation System) which is no longer online and the Monumentenwacht Vlaanderen Damage (MWV-D) which specifies damages to timber, paper and textile. This classification is interesting, but for the case of Ecuador, where most of the historic buildings are made of earth, this issue is still not well defined.

The development of an ontology, while a useful contribution, has to go hand-in-hand with practical examples of its use. A clear example is the CIDOC-CRM that presents a detailed documentation of each class and property that includes small examples of its use. In this sense, sections 4.3.5 and 4.4 show descriptions and examples of the complete PCC. This documentation is complemented with the uses cases of chapter 5.

Chapter 5: Validation of the BCH-ontology

In this chapter the limitations working with 3D data are illustrated [Section 5.1], then BCH-ontology is validated through use cases where data provided by the stakeholders are translated into semantic means and are linked so that some basic queries can be executed [Section 5.2-5.5]. Further applications are then explored by workshops developed with the stakeholders [Section 5.6]. The general advantages of using ontologies are then discussed with examples from the BCH-ontology [Section 5.7]. The final part of the chapter focuses on the necessary considerations to use BCH-ontologies within the Cuenca stakeholders [Section 5.8].

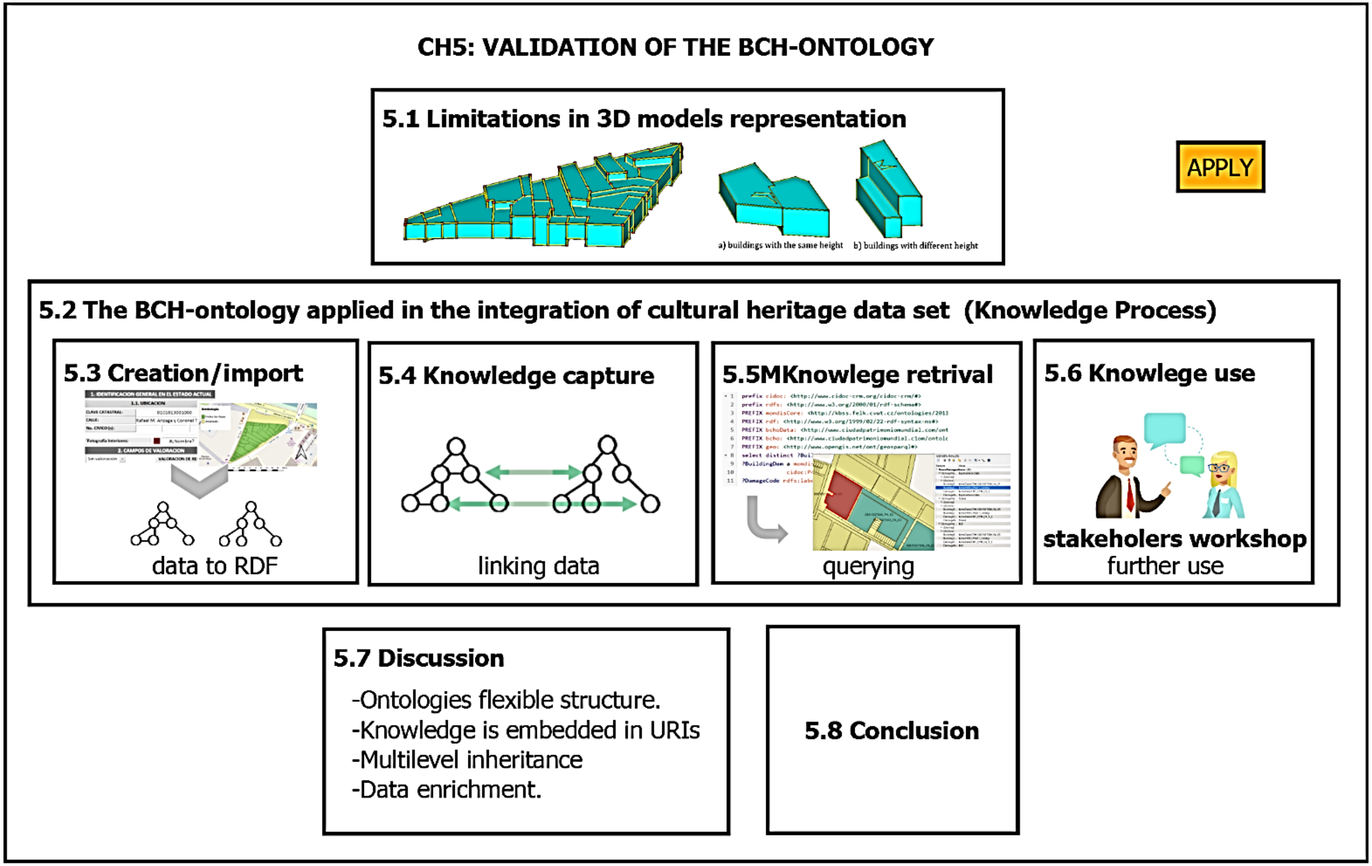


Figure 5.1 Chapter 5 summary.

5.1 Limitations in 3D models representation

Preventive conservation management of Built Cultural Heritage (BCH) comprises vast amounts of disparate data which is represented by different scales and resolutions and where the need of 3D analysis is becoming more necessary. In this use case the aim is to use the BCH-ontology to store a conceptual 3D representation of a building block and make an analysis regarding damage propagation. For this use case Virtuoso Universal Server is employed.

BCH-ontology employs the CityGML's building model which enables a 3D representation of buildings and their components. Protégé was used to instantiate some buildings represented using sets of surfaces. This encoding is then visualized (Figure 5.2) using the FZKViewer (KIT, 2016).

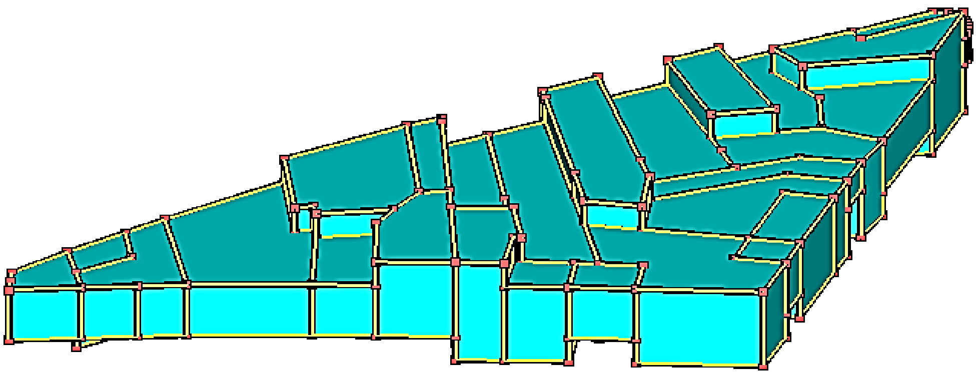


Figure 5.2 3D representation of a San Roque building block using the CityGML standard and visualized in FZKViewer.

The representation of simple buildings with damages is elaborated for discussion of the advantages of using 3D models for BCH-management. In this case, 3D models can be used to identify other elements on risk. Let's assume the following buildings have detachments produced by water filtration. This is a common damage that can be expanded when walls are next to each other.

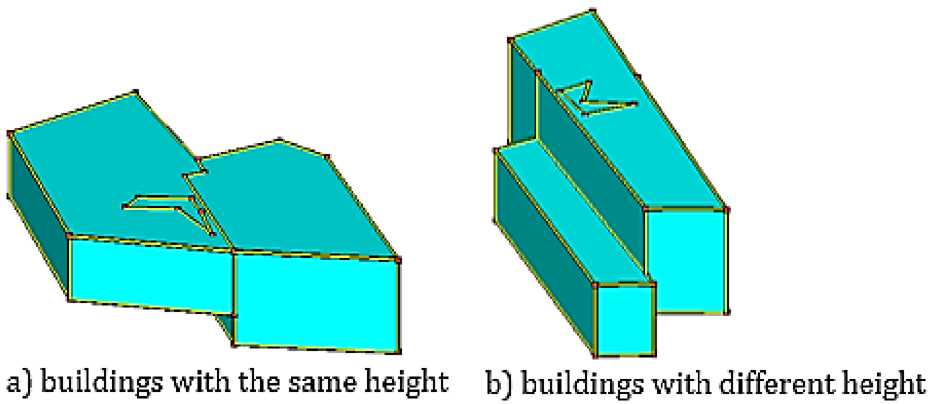


Figure 5.3 Damages on neighbor buildings.

Building in Figure 5.3a has a type of damage that could extend to the neighbor building because they have the same height. Figure 5.3b shows damage which rarely can be extended to the neighbor building since the buildings are of different heights.

Virtuoso Universal Server was chosen for this use case while testing the different triple stores, however it presented some configuration problems from time to time and its interface was not as user friendly.

The data about buildings and damages was input into the triple store; the probable affected areas were computed; and a query was performer asking for buildings on risk. Virtuoso manages quads on the DB.DBA.RDF_QUAD table which consisting of 4 columns: subject, predicate, object and graph. The following code (Figure 5.4) is used to input a damage on the DB.DBA.RDF_QUAD table. Similar code is used for the building.

```
INSERT INTO DB.DBA.RDF_QUAD (G, S, P, O)
  VALUES (
    iri_to_id ('3DUC'),
    iri_to_id ('http://www.ciudadpatrimoniomundial.com
                    /ontologies/BCH#Damage1'),
    iri_to_id ('http://www.ciudadpatrimoniomundial.com
                    /ontologias/BCH#PG11_lod4Geometry'),
    ST_GeomFromText('POLYGONZ((    721046.5 9679337.5 9.2,
     721047.5 9679339.5 9.2, 721048.5 9679337.5 9.2,
     721051.5 9679339.5 9.2, 721049.5 9679336.5 9.2,
     721046.5 9679337.5 9.2))', 32717));
```

Figure 5.4 SPARQL for input a damage in Virtuoso.

The possible affected area is computing assuming that this type of damages can be expanded about half a meter around it. Several approaches were tested:

- The function ‘ST_intersects (G1,G2,error)’ computes if two geometries intersects each other allowing for a margin of error. In this case, the error will be half meter. However, the function didn’t run in Virtuso. After several test we probed that the function only works without using the error parameter.

- Ideally the ST_buffer could be used but it is not supported by the GeoSPARQL. One way around it could be to use the Virtuoso spatial function ST_Translate (shape, dX, dY , dZ) which returns a copy of a shape with all coordinates shifted by the provided dX, dY and dZ parameters. X and Y coordinates are shifted half a meter up, down, right and left, and then a union is made with these polygons. Unfortunately, the ST_union function is not implemented in Virtuoso.

- Finally, the ST_buffer function on postGIS was used. The function removes the Z coordinate while doing the buffer, thus the coordinate was manually added afterwards and then the polygon was added to the DB.DBA.RDF_QUAD table.

The following code (Figure 5.5) shows the intersection between the buildings and the buffer of the damage:

```
PREFIX my:
<http://www.ciudadpatrimoniomundial.com/ontologias/BCH#>
PREFIX geof:
<http://www.opengis.net/def/function/geosparql/>

SELECT
my:Damage1B, ?f2
WHERE {
my:Damage1B my:PG11_lod4Geometry ?fGeom .
?f2 my:PG11_lod4Geometry ?fGeom2 .
FILTER (my:Damage1B != ?f2 and
bif:st_intersects(?fGeom,?fGeom2)=1)
}
```

Figure 5.5 SPARQL query to show damages located next to buildings.

callret-0	f2
http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Damage1B	http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Damage1
http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Damage1B	http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Building8
http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Damage1B	http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Building7

Figure 5.6 SPARQL query results Damage1.

callret-0	f2
http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Damage2B	http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Building10
http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Damage2B	http://www.ciudadpatrimoniomundial.com/ontologias/BCH#Damage2

Figure 5.7 SPARQL query results Damage2.

Figure 5.6 shows the results of intersecting the buffer of Damage1 where there is a building with the same height next to the building with the damage. The buffer intersects with Damage1 that it is the area without the buffer, Building8 which is the building where the damage is located, and Building 7 which is the building that could be affected by the damage.

Figure 5.7 shows the results of intersecting the buffer of Damage2 where there are no buildings of the same height next to the building with the damage. The buffer intersects with Damage2 that it is the area without the buffer, and Building10 which is the building where the damage is located.

This is a simple example of how semantic web can be used in an example of 3D modelling. However, the limitations of GeoSPARQL regarding the functions that are currently implemented and the lack of 3D management limit the usefulness of 3D modelling as a support tool for decision making. In this case, the procedure works because the heights are referential according to the number of floors of each building so two buildings with the same number of floors have the same height. Additionally, roofs are represented as planar surfaces when in reality they may have several heights. For these reasons, for the following use cases the GraphDB triple store was used.

Other researchers have worked on this issue. (Hamdan et al., 2019) presented an ontology to represent damages in heritage buildings using 3D. In this research a network of ontologies was managed in which each one is used to represent an important aspect, such as buildings or damages. Additionally it worked with various formats, such as GIS and BIM. This work could be considered to complement the BCH-ontology with 3D representations.

5.2 The BCH-ontology applied in the integration of cultural heritage data set

In the following sections we illustrate how the steps of the knowledge process (Creation/Import, Knowledge capture, Knowledge retrieval and access, and knowledge use) lead to the validation of the BCH-ontology employing thematic information and two dimensional data. This use case's aim is to answer the competency questions set in the ontology requirements specification document (Table 4.1). Building block 0801007 (Figure 5.8) in the San Roque neighborhood has been selected as study area; it is composed of 28 properties for which information is available from different stakeholders.

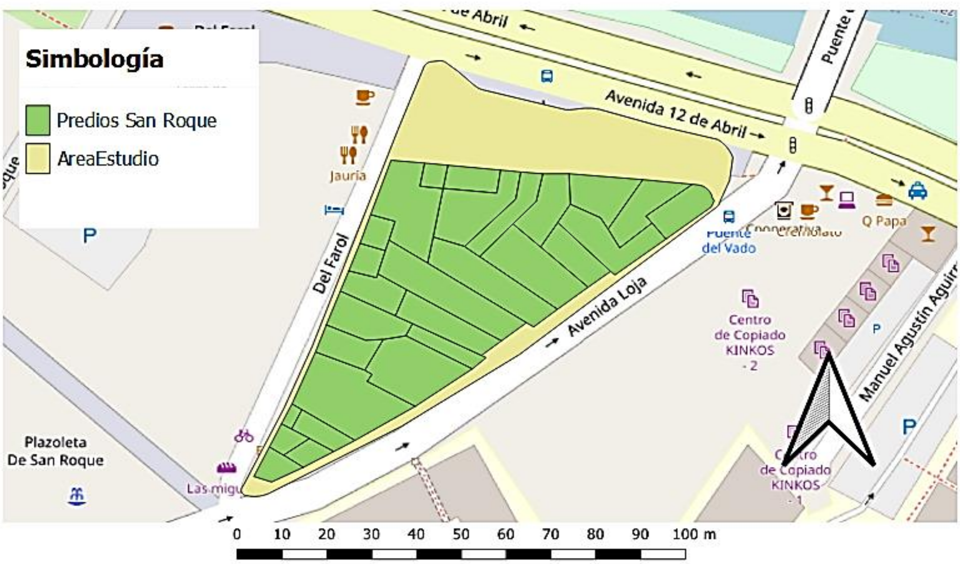


Figure 5.8 Study area, building block 0801007 composed of 28 properties for which information is available from different stakeholders.

Table 5.1 summarizes the available data sources for the study area.

Stakeholder	Data	Description
Municipality of Cuenca	Inventory 2010; Microsoft Access database	This is the last official registry of historic buildings
Municipality of Cuenca	Building shapefiles (plots)	2d plots of the properties where the buildings are located
CPM research group - San Roque maintenance campaign	Workbook; Microsoft Access database	In 2014 a maintenance campaign was carried out in a block of the San Roque neighborhood so it is a good example to obtain data on the activities carried out during the campaign and the damages recorded in components of the buildings.
CPM research group - San Roque maintenance campaign	Elements shapefiles	2d drawings of each of the floors
INPC	Abaco inmueble dataset; Microsoft Excel	It contains the location of the buildings by means of coordinates (points), architectural style, etc

This use case aims to integrate the thematic information in the Inventory of 2010 and the damages and activities carried out in the San Roque maintenance campaign with the 2D shapefiles of the CPM research group and the Cuenca City Council. The different file formats are translated into RDF and populated into the BCH-ontology using GraphDB triple store.

5.3 Creation/import step

In the creation or import phase, stakeholder information has to be migrated to a semantic environment. According to Table 5.1 there are 2 types of data: alphanumeric information (Microsoft Access, Excel) and spatial information (shapefiles).

5.3.1 Migration of alphanumeric data

Alphanumeric data are mapped using BCH-ontology classes and properties. As an example Figure 5.9 and Table 5.2 shows this mapping for the inventory database of the municipality of Cuenca.

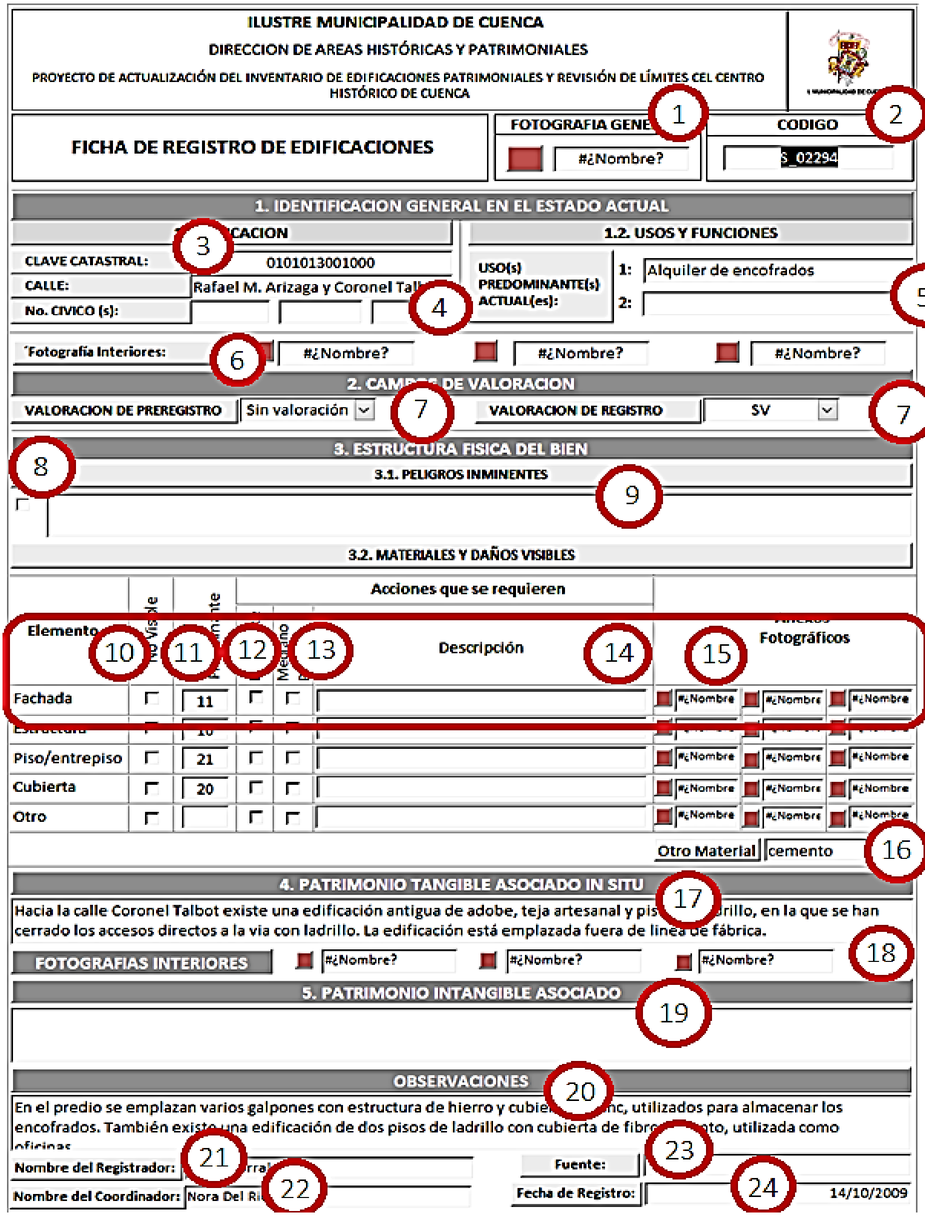


Figure 5.9 2010 Inventory. Each section is enumerated to be further linked with BCH-ontology classes and properties.

Table 5.2 Inventory 2010; properties and classes of the BCH-ontology with which the sections in Figure 5.8 can be represented.

Nro.	**Municipality Dataset**	**BCH-ontology property**	**BCH-ontology class**
1	Foto general	P138 represents	E38 Image
2	Codigo	P1 is identified by	E42 Identifier
3	Clave Catastral	P1 is identified by	E42 Identifier
4	calle num_civ_1 num_civ_2 num_civ_3	P1 is identified by	E45 Address
5	Uso 1 Uso 2	P140 assigned attribute to P141 assigned	HB58 Usage HB59 Usage Assignment
6	Foto interior	P138 represents	E38 Image
7	Valoracion preregistro Valoracion registro	P140 assigned attribute to P141 assigned	HB25 Heritage Value
8	Peligro	P140 assigned attribute to P141 assigned	M7 Hazard
9	Peligro descripción	rdfs:comment	String
10	Fachada visible	rdfs:comment	String
11	Fachada material	P45 consist of	E57 Material
12	Fachada emergente	rdf:type	HB50 ActionType
13	Fachada mediano plazo	rdf:type	HB50 ActionType
14	Fachada descrip	rdfs:comment	String
15	Foto fachada	P138 represents	E38 Image
16	Otro Material	P45 consist of	E57 Material
17	Tangible	P129 is about	E26 Physical Feature
18	Foto tangible	P138 represents	E38 Image
19	Intangible	P129 is about	HB29 Conceptual Feature
20	Observaciones	rdfs:comment	String
21	Registrador	P14 carried out by P14.1 in the role of P107 has current or former member	E7 Activity E21 Person E55 Type E40 Legal Body
22	Coordinador	P11 had participant P14.1 in the role of	E21 Person E55 Type
23	Fuente	P11 had participant P14.1 in the role of	E21 Person E55 Type
24	Fecha	P4 has time span	E52 Time Span

The address is stored as a composite attribute combining the street and the identification number. In case the building has several numbers, an equal number of addresses are registered. Descriptions can be documented with the ‘P3 has note’ property of the CIDOC-CRM ontology or in general with ‘rdfs:comment.’ In our case we selected the second option as it will be easier for those who are not familiar with CIDOC-CRM.

Photos taken with each inventory register were not provided to us so these fields have been ignored, however if they exist they can be documented as indicated in Table 5.2, row 1.

Rows 10-15 are repeated for each building element. The inventory form is poorly designed since other materials are recorded but are not always linked to any element, in which case they can be associated with the building in general. Additionally, other elements of interest are recorded, but the description of each one must be processed manually to know which element is being discussed. However, an element whose type is unknown can be created to associate this information to.

The mapping table (Table 5.2) is undoubtedly a good guide to start mapping. The mapping tool OntoRefine (Figure 5.10) integrated in GraphDB has been selected to make the necessary transformations; it allows direct connections with PostgresSQL, MySql and MariaDB databases. Additionally the tool allows mappings on structured data such as TSV, CSV, Excel (.xls and .xlsx), JSON, XML, RDF as XML, and Google Data documents. Other formats can be added with OpenRefine extensions. In our case it is simple to export the Microsoft Access database to Microsoft Excel.

Although all the data can be mapped, in our experience it is important to do so in an incremental way to facilitate error control. We start with the creation of the conceptual building and the inventory activity to which all other information will be linked. The "RDF Mapping" option allows us to create mappings in a graphical way, as shown in Figure 5.11.

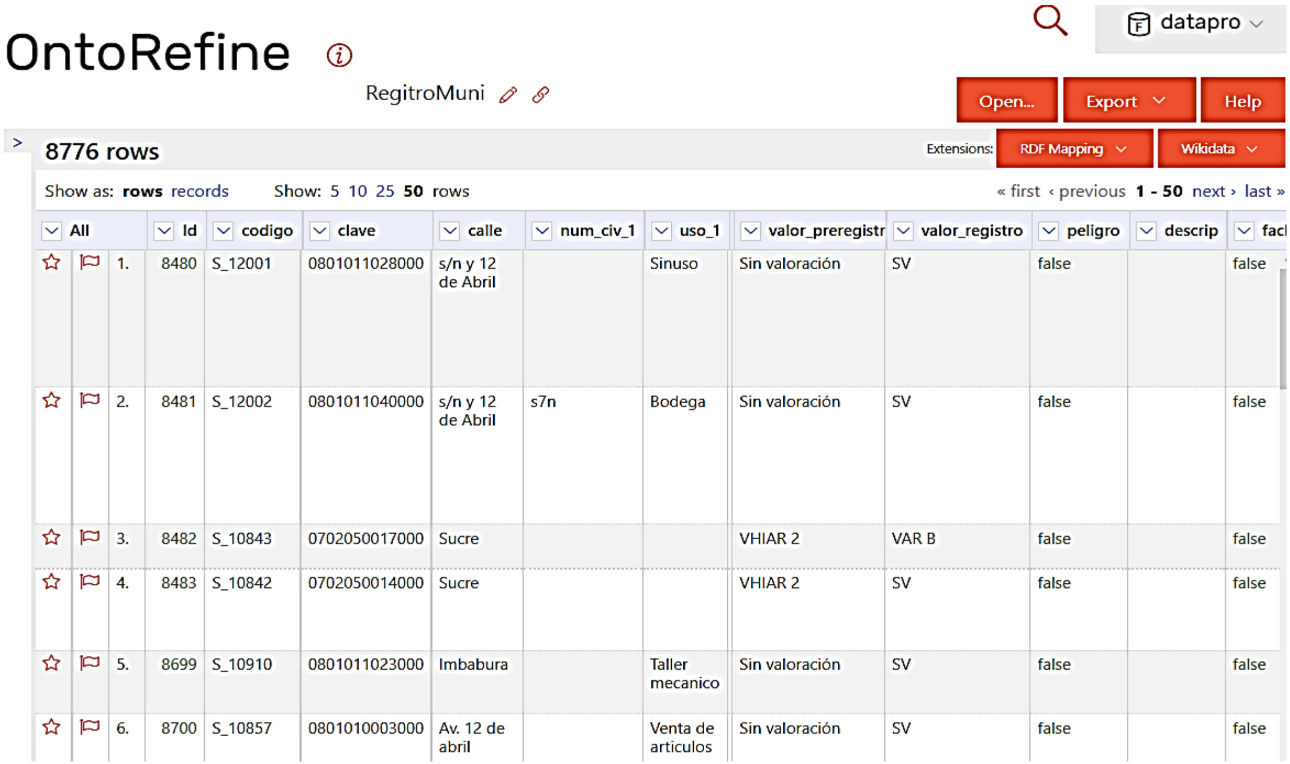


Figure 5.10 Inventory table in OntoRefine; where data can be transformed individually or in groups.

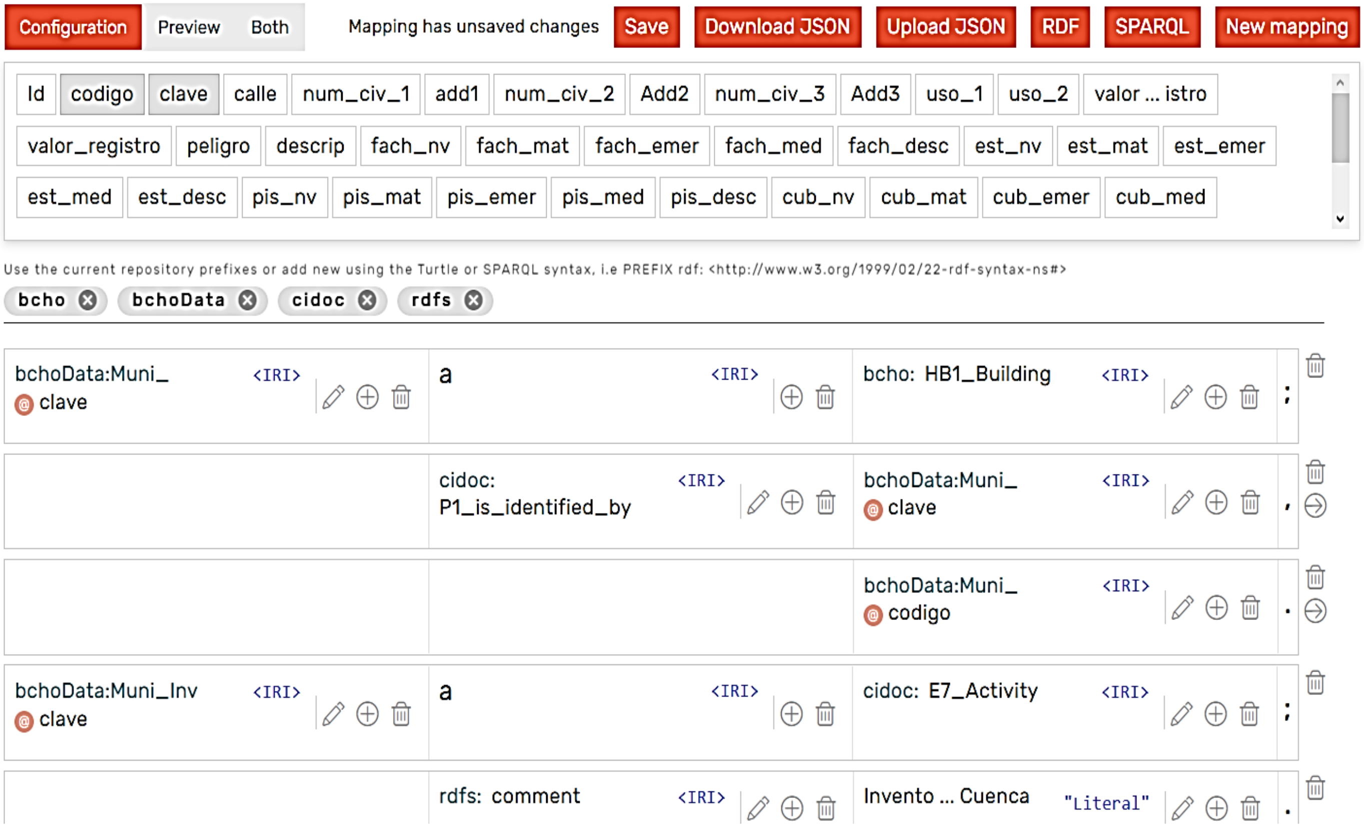


Figure 5.11 Graph DB triples of building, identifiers and activity.

In this case (Figure 5.11), 5 triples are created. The first one creates a 'building', the second and third ones assign identifiers (Table 5.2 lines 2,3), the fourth one creates an inventory activity (Table 5.2 line 21) and the fifth one describes this activity. The mapping can be stored in different formats, RDF is selected and a file is created (Figure 5.12) with the 5 triples described above for each row of the inventory table.

```
bchoData:Muni_0801011028000 a bcho:HB1_Building;
  cidoc:P1_is_identified_by bchoData:Muni_0801011028000, bchoData:Muni_S_12001 .

bchoData:Muni_Inv0801011028000 a cidoc:E7_Activity;
  rdfs:comment "Inventory 2010 by the Municipality of Cuenca" .

bchoData:Muni_0801011040000 a bcho:HB1_Building;
  cidoc:P1_is_identified_by bchoData:Muni_0801011040000, bchoData:Muni_S_12002 .

bchoData:Muni_Inv0801011040000 a cidoc:E7_Activity;
  rdfs:comment "Inventory 2010 by the Municipality of Cuenca" .

bchoData:Muni_0702050017000 a bcho:HB1_Building;
  cidoc:P1_is_identified_by bchoData:Muni_0702050017000, bchoData:Muni_S_10843 .

bchoData:Muni_Inv0702050017000 a cidoc:E7_Activity;
  rdfs:comment "Inventory 2010 by the Municipality of Cuenca" .
```

Figure 5.12 RDF file generated after using Graph DB's OntoRefine mapping tool.

Additionally new fields can be created to perform more complex transformations, e.g. the address which is a compound field. In this case (Figure 5.13), a new column is created to save the address and the same process is performed when it has more than one building number.

For some mappings it is also necessary to have a base list, such as for materials, heritage values, uses, registrants, coordinators, etc. Figure 5.14 shows different variants of use 'Housing' that have been registered (left column), which have been normalized using a base list made by the CPM project (middle column) and transformed to RDF (right column). Double uses such as 'housing - carpentry' are registered as two uses 'housing' and 'carpentry'. In this way, several RDF files are created that can later be processed to perform queries on the data.

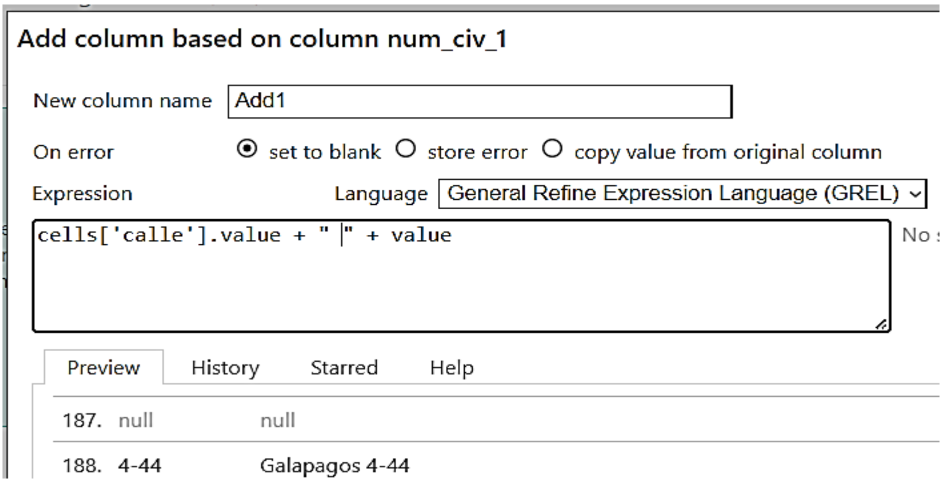


Figure 5.13 Column transformations of Figure 5.3 where the address is concatenated.

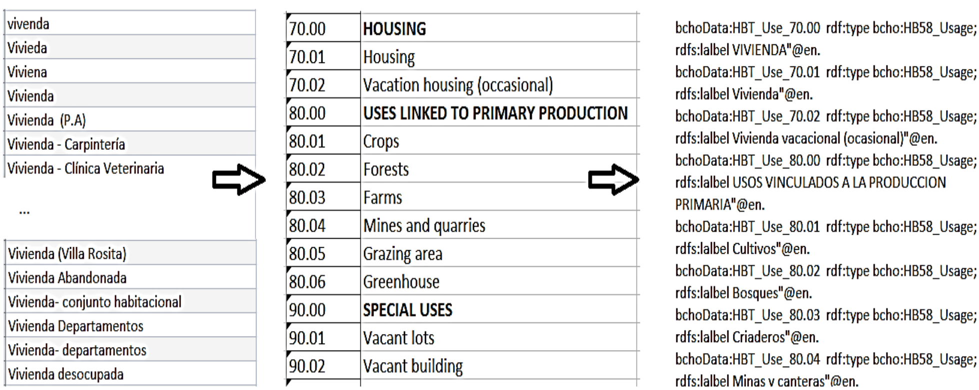


Figure 5.14 Variants of ‘housing’ use. The column in the left shows different variants of use 'Housing' that have been registered, which have been normalized using a base list made by the CPM research group(middle) and transformed to RDF (right).

5.3.2 Migration of geospatial data

In addition to the alphanumeric data, there is geospatial information. In this case polygons of properties and elements in each floor are already available from the Municipality of Cuenca (Table 5.1, row 4).

The INPC provided an excel document with information about the buildings (Table 5.1, row 5). Most columns are mapped like the examples in figures 5.9-5.11, thus the focus here is on the geospatial information stored in the 'coordinate' and 'coordinate_1' columns which represent the coordinates of the point where the building is located using UTM - 17S base on WGS84. The Municipality of Cuenca uses a polygon to represent the building parcel. In order to export the polygons to OntoRefine, the shapefile is exported as GeoJson file which uses geographic coordinates WGS84 and the units are degrees (Figure 5.15). For this reason the excel file is also opened in QGIS and exported to GeoJson, so that both spatial objects (points, polygons) employ the same units.

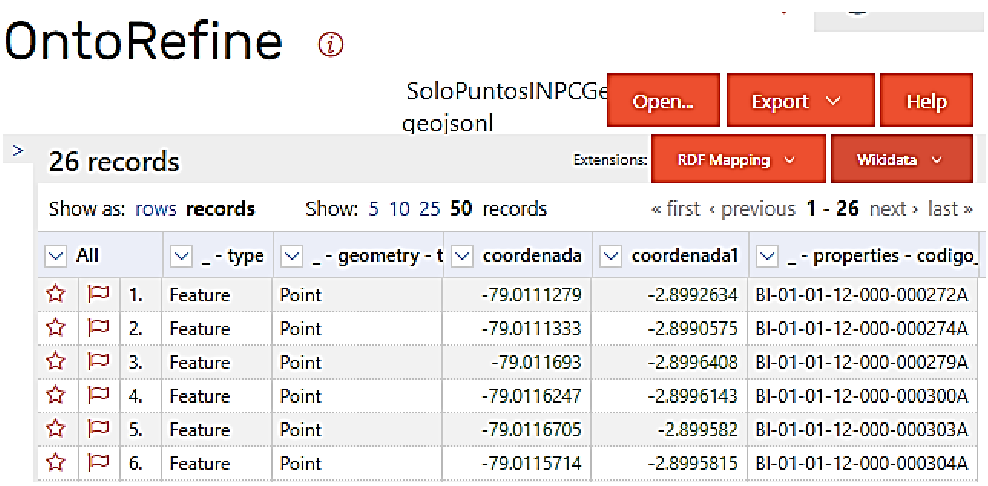


Figure 5.15 GeoJson file with the information of the INPC buildings' location is opened with OntoRefine.

Figure 5.15 shows the creation of a new column with the point representation in the required RDF format. Figure 5.16 shows the RDF file produced after the mapping of this information is linked to the INPC building.

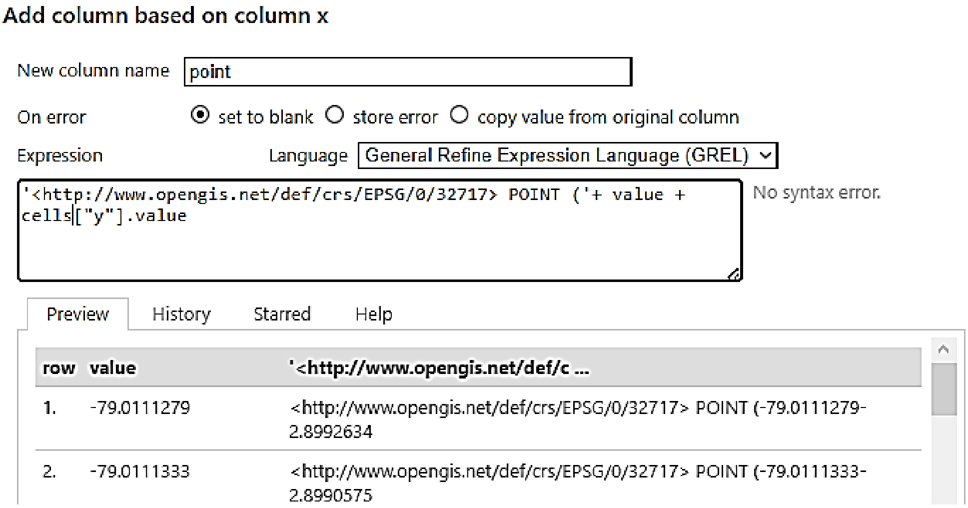


Figure 5.16 Creation of a new column with the point representation in RDF format.

```
bchoData:Inpc_BI-01-01-12-000-000272A a bcho:HB1_Building;
  geo:hasGeometry bchoData:GeomInpc_BI-01-01-12-000-000272A .

bchoData:GeomInpc_BI-01-01-12-000-000272A geo:asWKT
"<http://www.opengis.net/def/crs/EPSG/0/32717> POINT (-79.0111279, -
2.8992634)"^^geo:wktLiteral .

bchoData:Inpc_BI-01-01-12-000-000274A a bcho:HB1_Building;
  geo:hasGeometry bchoData:GeomInpc_BI-01-01-12-000-000274A .

bchoData:GeomInpc_BI-01-01-12-000-000274A geo:asWKT
"<http://www.opengis.net/def/crs/EPSG/0/32717> POINT (-79.0111333, -
2.8990575)"^^geo:wktLiteral .
```

Figure 5.17 RDF mapping of the mapping in Figure 5.9.

Although OntoRefine provides compatibility with Json files, the spatial attributes (coordinates) of polygons are stored as separate rows which are of variable size, since some polygons can have more vertexes than others. OntoRefine offers the 'Join multi-valued cells' function (Figure 5.18) which joins the coordinates with a specified character, in this case ',' which transforms the separate rows into one row where the coordinates look like "c1x, c1y, c2x, c2y, etc…". However since vertexes are represented with two coordinates, some additional transformations are required to remove the commas after each x-coordinate and include a space being the final result "c1x c1y, c2x c2y, etc." (Figure 5.19). Also the column was renamed to 'coordinates' to improve readability (Figure 5.20).

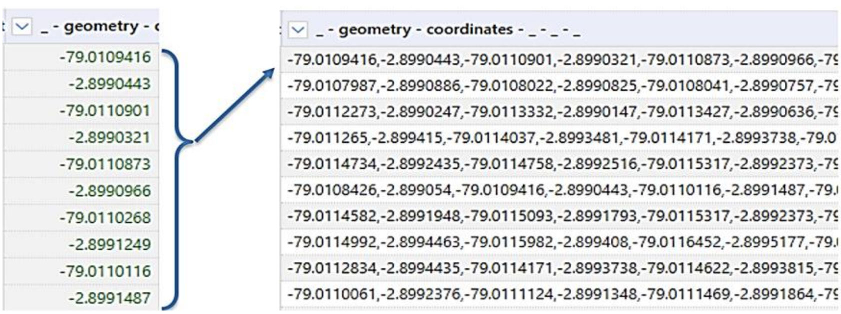


Figure 5.18 OntoRefine transformation of multiple values.

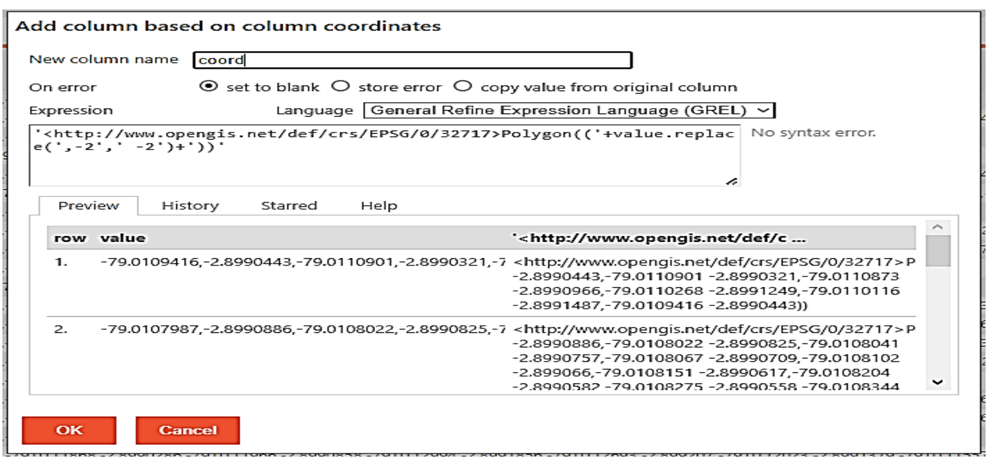


Figure 5.19 New column with the final transformation to represents polygons in RDF.

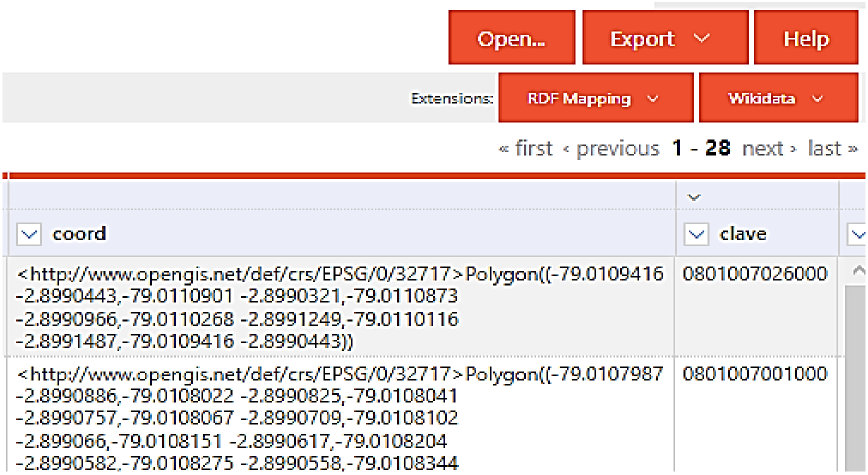


Figure 5.20 Final file with the transformations in OntoRefine.

The column 'clave' contains the cadastral key and column 'cood' the coordinates of the polygon. Figure 5.21 shows the mapping and the RDF file obtained in which the separate columns have been transformed into triples.

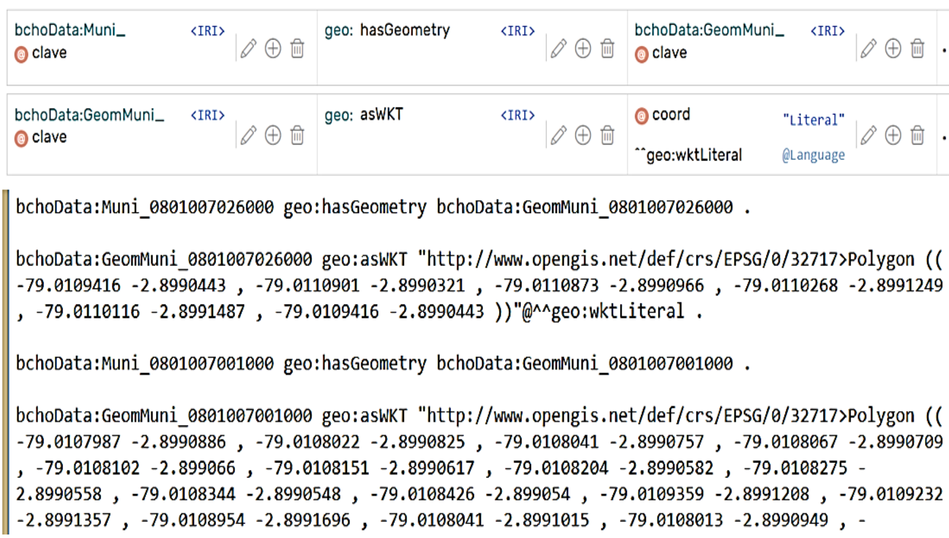


Figure 5.21 Mapping and the resulting RDF file of the Figure 5.13.

Finally, several RDF files have been created containing both alphanumeric and geospatial information of the stakeholders, which is imported by means of the Import/RDF file option to a previously created repository (Annex I).

5.4 Knowledge capture step

Once knowledge items are created, the next step is to capture their essential contents by linking the knowledge previously created. The data sets created above are not related to each other. From the Municipality there are 28 records, from the INPC 26 and from the CPM research group there are 28 more records, thus a query about the number of buildings will return 82 records. A visual query of the records information shows that they are not linked to each other (Figure 5.22).

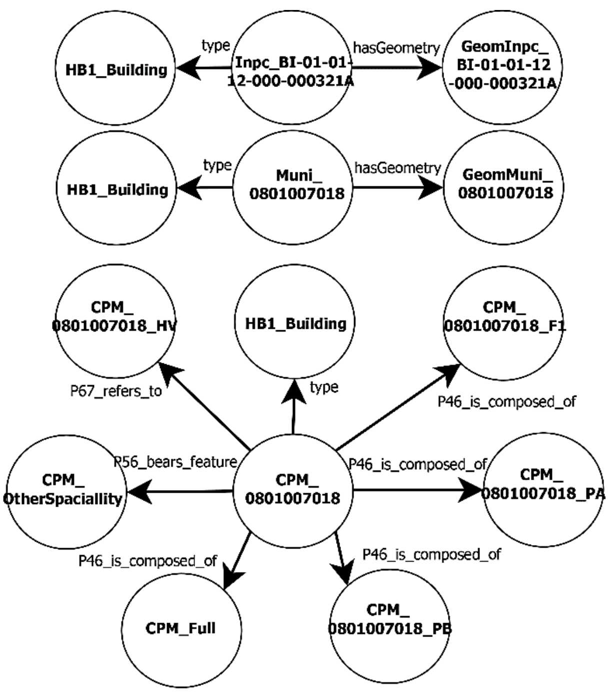


Figure 5.22 Shows the 3 records of the building with cadastral key 0801007018 unlinked.

If the stakeholders use the same identifier, the records can be linked. The owl:sameAs clause allows us to link two records. For this use case the name bchoData:Muni_0801011028000 is used to identify a property of the municipality and bchoData:CPM_0801011028000 to identify a property of the CPM research group. The triple "bchoData:CPM_080100707028000 owl:sameAs bchoData:Muni_080100707028000" indicates that it is the same building. This is easily assigned in an automatic manner by replacing the CPM letters by Muni through a function in any programming language. For example, Microsoft excel functions can be used.

However, there are not always known identifiers that can be automatically linked. The Municipality of Cuenca manages a cadastral code while the INPC manages its own codes. In this case the geospatial properties are used to determine which records should be linked. Figure 5.23 show the location of buildings of the INPC and the Municipality of Cuenca's parcels.

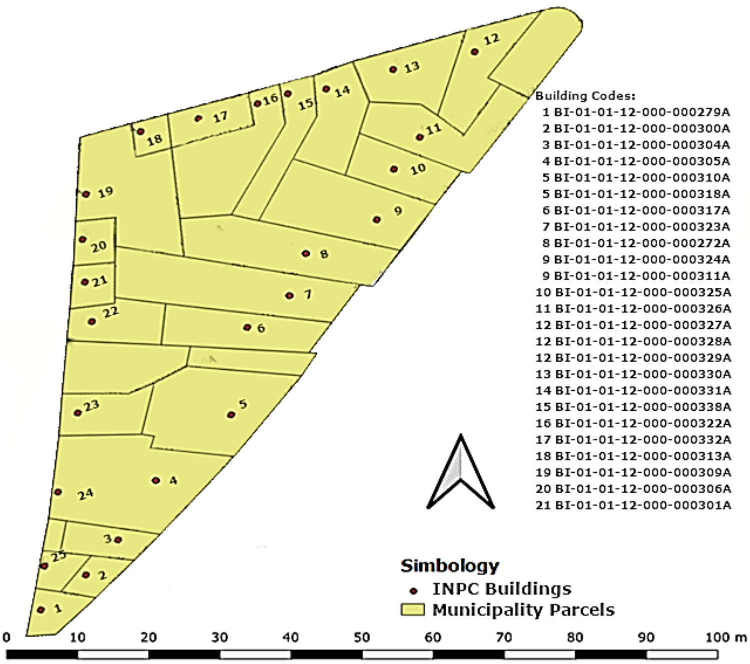


Figure 5.23 Location of buildings of the INPC and the Municipality of Cuenca.

```
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
INSERT { ?m owl:sameAs ?n }
WHERE {
?m geo:hasGeometry ?mgeo .
?mgeo geo:asWKT ?p.
?n geo:hasGeometry ?ngeo .
?ngeo geo:asWKT ?q.
FILTER (geo:sfContains( ?m, ?n) )
}
```

Figure 5.24 SPARQL query that integrates the records of the INPC and the Municipality of Cuenca.

Figure 5.24 shows a SPARQL query that identifies the point contained in the polygons and linked them with the predicade 'owl:sameAs'. After linking we can query the information of a particular building and we see that the information of the other stakeholders is also linked.

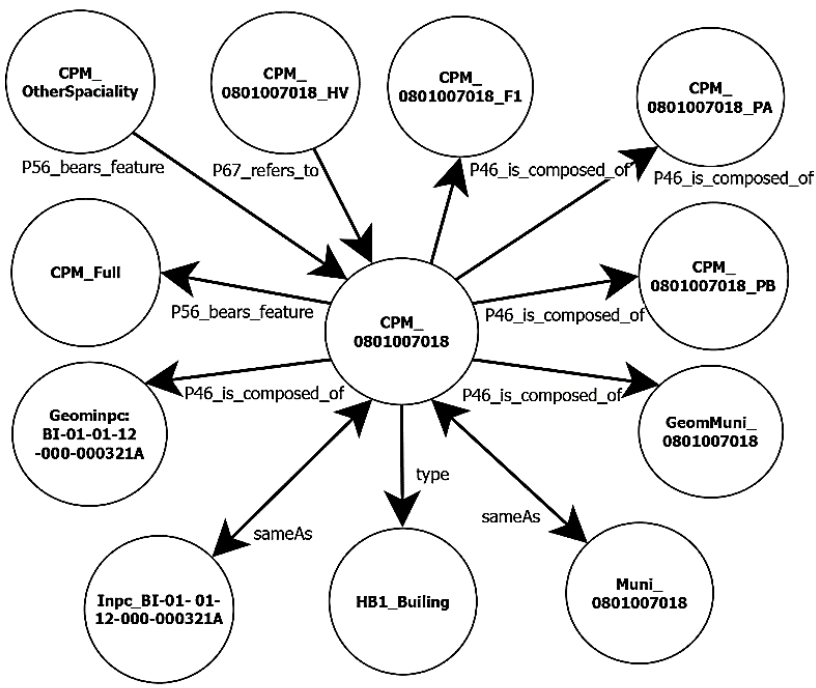


Figure 5.25 Linked records, at the top the information of the CPM research group. In the lower part the information of the INPC and the Municipality of Cuenca.

The integration made in Figure 5.25 allows connection with the complete datasets from the 3 stakeholders. On traditional systems as databases when a 'join' is performed just the information in the two tables that are being joined is available. However in this case all the information related to the building is available without restrictions of which data source comes from.

5.5 Knowledge retrieval and access step

Information stored in the ontology is accessed satisfying simple requests of the user requirements. A use case querying and searching general information regarding the location of damages an activities on BCH assets is developed. In accordance with the requirements listed in Table 4.1, the following competency questions are defined and have been applied in the study area.

CQ1: What are the most common damages in historical buildings?

To answer this question the information from the maintenance campaign carried out by the CPM research group in 2014 (Table 5.1, row 3) is used. A damage record was created by means of a Microsoft Access file (Figure 5.26).

Clave Pred	Nivel de edificació	Factor de	elemen	Código	Estado	Materia	Materia
0801007003	1ra P. Subsuelo	Estabilidad	Entrepiso	SO_03	Malo	27. Madera	
0801007003	P. Baja	Estabilidad	Muros portante	PB_09	Regular	1. Adobe	16. Empañ
0801007003	2da P. Alta	Estabilidad	Estructura	2PA_03	Regular	27. Mader	17. Enchar

Daño 1	Daño 2	Causa 1	cod_ca	Magnitu	Calas d	Descrip	Fotogra	Observa
2.1.5		F1		Alto (67 - 1	FALSE	V003_02	F003_02 / F003_03	
2.1.2.		M19		Medio (34	FALSE	V003_03		
2.2.3.		F1	O3	Medio (34	TRUE	V003_04	F003_05	

Figure 5.26 Damage record of the San Roque maintenance campaign.

The damage record identifies the building, the floor, the room, and the element in which a damage is found, as well as the magnitude and possible causes that led to the occurrence of the damage. The first competency question can easily be answered with a query that counts the number of times a damage has been recorded in the DB. However, since there is more specific information such as magnitude, which is classified as High, Medium or Low, high magnitude damages are query. The results are presented in Figure 5.27; at this point the ontology does not present any advantage in comparison with traditional systems since the same query can be performed in similar terms using SQL.

```
select ?DamLabel  (COUNT(*) AS ?count)
{
    ?s a mondisCore:ManifestationOfDamage.
    ?s cidoc:P46_is_composed_of ?DamType.
    ?x rdf:type cidoc:E13_Attribute_Assignment.
    ?x cidoc:p141_assigned bchoData:HBT_CPM_DamMagnitud1.
    ?x cidoc:P140_assigned_attribute_to ?s.
    ?DamType rdfs:label ?DamLabel.
}
group by ?DamLabel
order by desc (?count)
```

	DamLabel	count
1	"Exploration craks"@en	"5"^^xsd:integer
2	"Detachment (fragments)"@en	"4"^^xsd:integer
3	"Stains"@en	"4"^^xsd:integer

Figure 5.27 SPARQL query of damages of high magnitude recorded in the San Roque maintenance campaign.

CQ2: Where are the most common damages located (Diagnosis phase)?

The second competency question refers to the location of these data. This question could be answered in a similar way to the previous one, using only the textual fields of floor room and element. However, in the same maintenance campaign, drawings of the buildings were made by floor (Figure 5.29), which were not linked to the damage.

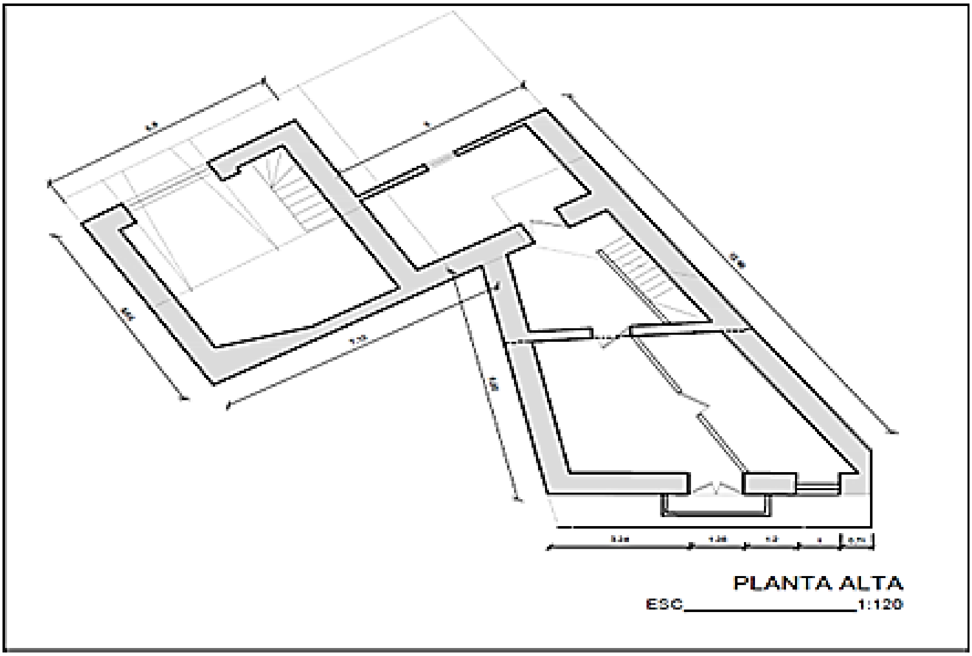


Figure 5.28 Drawings of floor by building.

For this question the integration of the different datasets is exploited to link the damage to the geospatial element. The greatest difficulty was to link the elements of the damage card with the polygon shapefile elements because they were at different levels. In some cases the element in which the damage was recorded was not present in the shapefile, for example the ceilings. In this case the damage is linked to the next container element higher in hierarchy, in this case the room in which the damage is located. Finally, the damage can also be located by building. For all these queries the building is handled as a single entity and its attributes are queried in a general way regardless of the dataset it comes from. Figure 5.29 shows the SPARQL query performed to locate the damages by building.

```
prefix cidoc: <http://www.cidoc-crm.org/cidoc-crm/#>
prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX mondisCore: <http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX bchoData: <http://www.ciudadpatrimoniomundial.com/ontologias/BCH/Data/>
PREFIX bcho: <http://www.ciudadpatrimoniomundial.c1om/ontologias/BCH#>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
select distinct ?BuildingRoom ?BuildingCompType ?DamageCode ?DamageName ?Geom  {
?BuildingDam a mondisCore:ManifestationOfDamage;
             cidoc:P46_is_composed_of ?DamageCode.
?DamageCode rdfs:label ?DamageName.
?x rdf:type cidoc:E13_Attribute_Assignment.
?x cidoc:p141_assigned bchoData:HBT_CPM_DamMagnitud1.
?x cidoc:P140_assigned_attribute_to ?BuildingDam.
?BuildingComp cidoc:P56_bears_feature ?BuildingDam.
?BuildingRoom cidoc:P46_is_composed_of ?BuildingComp.
?BuildingComp rdf:type mondisCore:Component; cidoc:P2_has_type ?BuildingCompType.
?BuildingFloor cidoc:P46_is_composed_of ?BuildingRoom.
?Building cidoc:P46_is_composed_of ?BuildingFloor.
?Building geo:hasGeometry ?GeomName.
?GeomName geo:asWKT ?Geom.
}
```

Figure 5.29 SPARQL query performed to locate the damages by building.

The results obtained can be stored as a GeoJason file and opened directly in Qgis where the results can be visually explored. This is very useful information for the control technicians and shows the direct collaboration between academic institutions and municipality. Figure 5.30 shows the results of damage location at different levels. Annexes V, VI and VII show the complete queries. Competency question 5 can be answered in a similar way and the complete query and results are shown in Annex (VIII).

Figure 5.30 Location of damages by element, room and building.

This use case is the one that shows the advantages of the BCH-ontology. After the integration of Figure 5.25 the information is treated indistinctly of where it comes from. Damages from the maintenance campaign (CPM-Microsoft Access) is shown in QGIS liked to the element, the room (CPM-shapefiles) or the building (Municipality of Cuenca, parcels shapefile).

5.6 Knowledge use step

After importing the datasets and making sure we can used them, we will now investigate how to retrieve knowledge to be further used in a specific context. Knowledge items are not just queried, but processed for further use. Sometimes implicit information stored in the ontology is more important than the explicit one.

In order to determine the future applications of the BCH-Ontology, local and international stakeholders are involved. We make a distinction between representatives of academic institutions and governmental institutions. Two workshops were held, and surveys were filled out. Three representatives from the municipal GAD, two from the INPC, and seven faculty members teaching subjects related to the maintenance of heritage buildings, along with five researchers from the CPM group were present. More details on the surveys are shown in Annex IIX.

The following sections show the general conclusions obtained after performing a thematic analysis of this group discussion. We discuss possible applications of the BCH-ontology, relevant stakeholders' information that can be represented and improvements to the BCH-ontology.

5.6.1 Identified applications for the BCH-ontology

Intra-institutional integration in the Municipality of Cuenca within the cadastre department. The cadastre department is in charge of managing the information about the parcels and buildings in the city of Cuenca, such as any change of owners, unification or fragmentation of properties, correction of areas or measurements. All these changes are made without the involvement of the DGAHP which only updates its information when a procedure of its competence is required; thus, there is a large amount of information that is not updated.

Since each department (DGAHP, cadastre) is autonomous with respect to the systems it employs to manage its data, the integration of its databases and information in general is not straightforward. The BCH-ontology could facilitate the integration of the overlapping information between these two departments. Similarly, the case of the information of the municipal mobility company can be considered, who manages their information at the city level, but the DGAHP also has its own mobility plans, programs and projects with special treatment for historic areas.

Inter-institutional integration to improve building intervention plans. Before intervening in a heritage building it is necessary to investigate its background to make a better analysis and previous diagnosis. Therefore, it is important to be able to share a summary of the interventions. It is also important to share information about the heritage values of the buildings, such as the unique, historical and intangible heritage elements related to the property, so the proper therapy can be chosen.

"When one is going to intervene or investigate a certain sector of a city, it is necessary to know if there are interventions in its history (what were they) and what actors or type of actors are involved". (INPC Technician).

In addition to the interventions, there are also several initiatives for the study and analysis of historic buildings in which the different stakeholders carry out visits or inspections that could support the monitoring and control activities carried out by the Municipality of Cuenca.

Inter-institutional integration with other governmental institutions. Although the workshops were attended by government institutions that work with heritage management, the need to integrate information from other government institutions such as the Internal Revenue Service, the Ministry of Economic and Social Inclusion and the Civil Registry was recognized. These institutions handle information about taxes, vulnerable groups and citizens in general. Citizens tend to keep updated information on their address and marital status, as well as their economic activities, which is reflected in changes in the use of the buildings.

Integration with other areas of interest. In general terms, the significant bidirectional contribution that other areas can make and receive to and from heritage management is mentioned. In the area of tourism and culture there is a direct relationship with the intangible heritage. In the educational area it offers a great opportunity for citizen's awareness and the collection of data mentioned in the inter-institutional integration. The organic law of culture currently in force (Asamblea Nacional, 2016) is based on several principles, one of which is about integrality and complementarity. It implies the interrelation with education, communication, environment, health, social inclusion, science, technology, tourism, agriculture communication, environment, health, social inclusion, science, technology, tourism, agriculture, economics and production, among other areas and systems.

5.6.2 Identification of valuable Stakeholders' information

Governmental and academic institutions have a plethora of information that is of great importance for heritage management. Some specific and general types of information have been identified.

Specific stakeholder information

The municipality of Cuenca by law is the institution in charge of the BCH of the city, thus is the one that should have updated information about the state of the buildings and the interventions performed, which is not always the case. This information is public, with exception of those aspects that are confidential due to privacy and legal issues. The process to access the information is very bureaucratic and depends on the knowledge of the user regarding what information exists. Workshop participants agreed that there should be more efficient ways of knowing what information exists, its level of accessibility (public, confidential) and how to request it.

The Academia has undergraduate and master's degree works and theses that are not available to governmental institutions. Most of them are purely informative and the collected information remains in the hands of the students and is not delivered to the educational institution, much less to third parties. It is important to take into account that what the student delivers is a document but the data collected during this work is rarely distributed. For the municipality of Cuenca and the INPC these contributions would be of great importance as it is a good way to keep the information updated, especially since many of these works are carried out jointly with the support of the municipality and the INPC.

"The input/outputs of the workshop groups (conservation subject) as academic and innovative intervention experiences should be reused because this information is currently unused and relevant." (CPM Researcher).

The INPC has records about buildings of interest and with heritage value, using their own valorization and risk assessment methodologies. It also developed several projects oriented to the preservation of BCH. Municipal personnel requesting access to SIPCE information are granted a technical module access account. However, when requesting information on the other projects executed by the INPC, they suffer from the same bureaucratic issues as with the municipality.

General stakeholder information identification

The institutions handle a large amount of multimedia material, such as photographs, videos, audios, etc., providing documentation of the buildings. Sometimes they are reviewed in detail to be applied in a particular project, such as analysis of elements in heritage facades or reports of types of pathologies. This generates files with a lot of information which could be automatically identified and liked with the thematic information in the databases. The need to document the buildings, elements, materials, construction techniques, pathologies, etc. that are visible in the multimedia material, is also mentioned.

Something that was not discussed in depth in the workshop yet was concluded by the participants, is the importance of active participation of citizens, who are undoubtedly the actors who can provide first-hand information on the current state of conservation and the presence of pathologies in the building. However, for most citizens the possession of a heritage building is associated with restrictions and fines, thus rewarding processes should be implemented to encourage citizen collaboration.

In the workshop it was also mentioned that many projects are carried out with the purpose of sharing their results through maps or information reports online. However after a short discussion it was clear that this information as such cannot be easily reused since it is displayed but not downloadable. Therefore, it is necessary to create awareness of what is reusable and what is not, since there is a misconception in this respect.

5.6.3 Improvements and operational concerns to the BCH-ontology

The possible improvements to the BCH-ontology are organized in three sub-themes:

Main focus on the 5 categories of cultural heritage. At the national level, Ecuador defines 5 heritage categories: immovable, movable, intangible, documentary and archaeological. The BCH-ontology is designed for the management of historic buildings and defines the rest of the heritage categories as physical or conceptual features (HB28 Heritage Feature) associated with the building that give it a heritage value. Generally, this prioritization of the built heritage has always happened. However it emphasizes the need to manage each category in depth and then find the relationships between them, rather than defining them as simple attributes of the built heritage. Other ontologies or an extension of the BCH-ontology would be necessary to manage the other categories of cultural heritage. Linked data is very suited for such extensions since it allows easy integration of complete datasets and the BCH-ontology already provides a framework where the PCA can be used.

"For many years only historical buildings have been considered heritage, however we must not forget that movable, intangible, documentary and archaeological heritage are equally important and have been neglected for a long time, so they are most at risk". (Ex-Director of DGAHP).

Larger management scales such as PITs and UAUs should be characterized. From its conception, the BCH-ontology describes the built heritage in relation to its context, so different types of 'M1 CH Objects' are defined as the components of the building, building blocks, sectors, zones, and city. For each of them a PCC can be generated based on the analysis of their values and heritage attributes, making a diagnosis, defining a therapy, and monitoring and controlling the effects of a particular intervention. However, the attributes of the different cultural objects are not defined. A closer look at the class 'E26 physical feature' (Figure 5.31) shows that these attributes are defined for the building but not for the building blocks or the other levels.

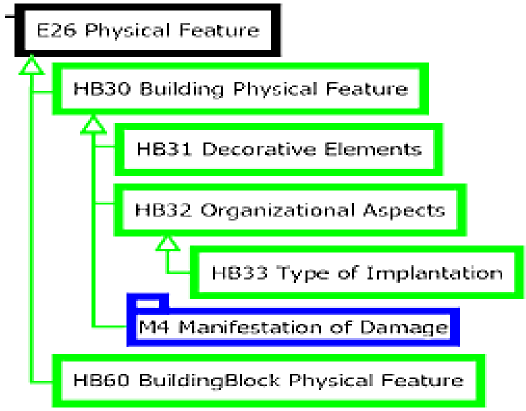


Figure 5.31 Physical Features sub-classes.

Although the section of the building and the building block are the levels of approximation that have been most characterized in the management of built heritage in Cuenca, it has always been a matter of discussion whether these should be the heritage management units. In fact, the new land use and land management plans for the Canton of Cuenca (PDOT-PUGS) (Consejo Cantonal, 2022) define Polígonos de Intervension Territorial'/territorial intervention polygons (PIT) and the Unidades de Acción Urbanas / Urban Action Units (UAU). They are pointed out as a new line of research since, being recently defined, there is little information on them.

> *"Even though it is interesting having information about the building components, the larger scales on which management decisions are made are more important. Specifically, the characterization of PITs and UAUs". (Faculty member).*

This opinion from this interviewee is of great significance as it demonstrates that the relationship between the building and its context is crucial. The use of 3D models can been highly beneficial in this regard, even though they are not specifically mentioned by the interviewees.

Operational concerns related to the implementation of the BCH-ontology. The institutions involved in the workshop recognize the importance of sharing their data. However, they also have some concerns regarding the following issues: quality of information, protection of personal data, security and ethics of information management.

Regarding the quality of the information, it is recognized that information that has not been properly validated might (undesirably) be integrated. The first issue that was discussed is that the information must be documented correctly. In most cases there is no associated metadata that provides relevant information on when and how the information has been collected. Therefore, guaranteeing the quality of the information begins with each institution. However, the same data integration can allow for the discovery of inconsistencies between the different data sources so they can be updated and corrected.

With respect to the management of personal data, security and ethics of information management, it is recognized that there are stakeholders among whom different types of information can be shared. Government institutions may have higher and more open levels of access, while for academic institutions there is a lot of information that must be anonymized to guarantee the protection of personal data and critical information. On the other hand, the need for legal advice for the signing of agreements and terms of use of the information to be integrated was also discussed.

Finally, a path was visualized in which inter-institutional collaboration could be defined. In this case one of the objectives will be to test semantic models for the integration of provided inputs and collected data, always taking into account the ethical and legal considerations mentioned above. In addition, the need to institutionalize research was mentioned, since governmental institutions are oriented to citizen service and there are not many resources for research and joint work with academic institutions. Although collaborative projects have always been carried out, the participation of governmental institutions should be more active or not limited to being an information provider.

In summary, the first step towards the implementation of the BCH-Ontology at local level is the incorporation of linked data principles and the use of ontologies in the technological plan for the management of the historic centre of Cuenca, so it does not depend on the goodwill of the stakeholders but is imposed by law. The assignment of a BCH-Ontology manager should be discussed among government stakeholders. It is essential to sign the necessary agreements so that the ontological model is always kept as an open product and easily accessible to other stakeholders, as this is the very essence of the creation of ontologies. Then, the BCH-Ontology should be extended with the new official management levels PITs and UAUs that are currently in force followed by an integrated exercise where main institutions are involved. The updating of the SICPE with the information of the historic centre of Cuenca and the updating of the TIPVP with the information of the SICPE could be a very useful example. After this, the stakeholders have several paths to follow, such as the integration of their internal information, the definition of more inter-institutional integration exercises and the creation of new ontologies for the independent management of other types of heritage such as movable, intangible, archaeological and documentary.

5.7 Discussion

In section 3.4 specific advantages that ontological models provide with respect to current gaps in BCH were described. In this section, the advantages provided by ontologies in a general way applied to different domains are shown by means of some examples in the heritage domain.

5.7.1 Ontologies flexible structure.

Ontological models follow a triple structure which makes it easy to explore the data. When using ontologies it is good practice to properly document the ontology in order to be able to reuse it. In this thesis, sections 4.3, 4.4, 5.1-5.6 fulfill that function in a general way. However, a triple store may contain more or less information depending on each stakeholder so stakeholders should provide the corresponding documentation for each triplestore. However, if such information is not available, it is easy to consult a triplestore and find all the available information since everything is stored with a triple pattern. In other words it is possible to use the same type of queries that are used for data retrieval to understand the structures of the underlying ontologies.

a)

```
select * where {
    ?s ?p ?o .
}
```

b)

```
select distinct * where {
    ?s rdf:type ?o .
}
```

c)

```
select distinct * where {
    ?s rdf:type rdfs:Class
}
```

d)

```
select distinct * where {
    ?s rdf:type rdf:Property
}
```

e)

```
select * where {
 {bcho:HB1_Building ?p ?o.}
    union
 {?s ?p bcho:HB1_Building.}
}
```

Figure 5.32 Basic queries to explore an unknown triple store.

In Figure 5.31a the query returns the complete triple store, Figure 5. 31b provides a list of all the classes defined in the data. Figure 5. 31c focuses on the classes and Figure 5.26d on the properties. Figure 5. 31e shows all the triples where the HB1_Building is the subject or the object. This last query is of great importance because this is not possible in a traditional database where it is necessary to know the name of the tables where the information of a building is stored and where the building is a foreign key. Therefore, in traditional systems a previous knowledge of the database design is necessary, while in an ontological model it is easy to explore the data and find all the information related to a specific subject.

Empty data gathering systems cannot answer any query. In traditional systems such as databases, the information is stored after creating a model. The model is just an empty container with no real use. An empty ontological model can offer plenty of important information. Figure 5.33, for example, shows the classification of “M4 ManifestatioOfDamage”, where it is shown that there are damages in components and materials and how are they are sub-classified as well.

Figure 5.34 shows the “HB48 Therapy” class and all properties related to it. All of this information can be extracted without requiring any actual instances of data within the ontology.This shows that 'empty' ontologies contain a wealth of semantics that can be queried.

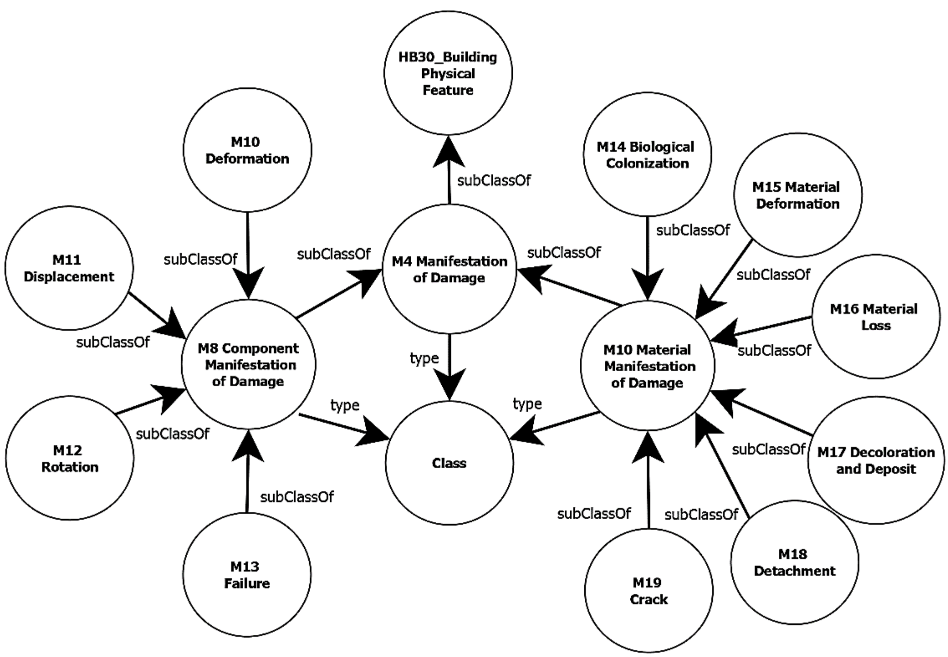


Figure 5.32 Classification of “M4 ManifestatioOfDamage.”

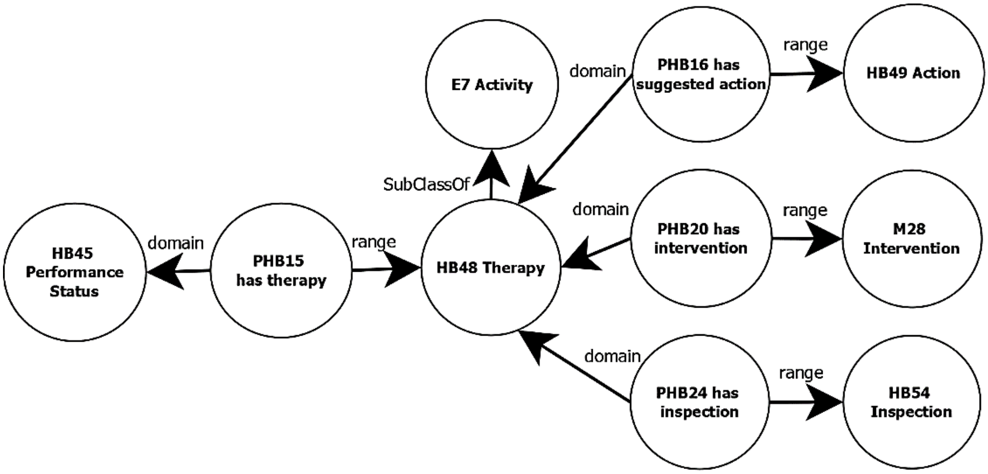


Figure 5.33'HB48 Therapy' class and properties.

5.7.2 Knowledge is embedded in URIs

One of the best practices for publishing data (Table 2.1) is that subjects, predicates and objects are represented through URIs which allow exploring all related information. It is important to take into account that all the elements that are stored in a triple store are represented by URIs, which means that it is not only a text that we visualize. Through a process of dereferencing, the link can be followed displaying the information related to that element. Figure 5.34 shows the dereferencing of the element 'bcho:HB1Building' when the ontology has not been populated with data. Thus the employment of URIs also allows us to explore the underlying ontology.

HB1 Building

Source: http://www.ciudadpatrimoniomundial.com/ontologias/BCH/HB1_Building

subject predicate object context all   Explicit and Implicit   Show Blank Nodes   Download as

	subject	predicate	object	context
1	bcho:HB1_Building	rdf:type	owl:Class	http://www.ontotext.com/explicit
2	bcho:HB1_Building	rdfs:label	"HB1 Building"@en	http://www.ontotext.com/explicit
3	bcho:HB1_Building	rdfs:subClassOf	mondis:CHObject	http://www.ontotext.com/explicit
4	bcho:HB1_Building	rdf:type	rdfs:Class	http://www.ontotext.com/implicit
5	bcho:HB1_Building	rdfs:subClassOf	cidoc:E18_Physical_Thing	http://www.ontotext.com/implicit
6	bcho:HB1_Building	rdfs:subClassOf	cidoc:E19_Physical_Object	http://www.ontotext.com/implicit
7	bcho:HB1_Building	rdfs:subClassOf	cidoc:E1_CRM_Entity	http://www.ontotext.com/implicit

Figure 5.34 shows the dereferencing of the element 'bcho:HB1Building' when the ontology has not been populated with data.

5.7.3 Multilevel inheritance

Ontological approaches implement the concept of inheritance in an efficient and practical manner. Superclasses properties can be used by the subclasses of any level without giving further specification. For example, 'P1 is identified by' is a property of the 'E1 CRM Entity' class which is the root class of the BCH-ontology; this property can be used by the remaining 147 classes of the ontology without having to define anything else. Figure 5.34 shows explicit and implicit triples. The implicit ones give account of the hierarchical structure (Figure 5.35) to which the class belongs and therefore it can automatically use all the properties defined for the parent classes. This is important since simplifies the way inheritance is implemented, on traditional systems query the inherit properties implies querying every single table whit a high hierarchy.

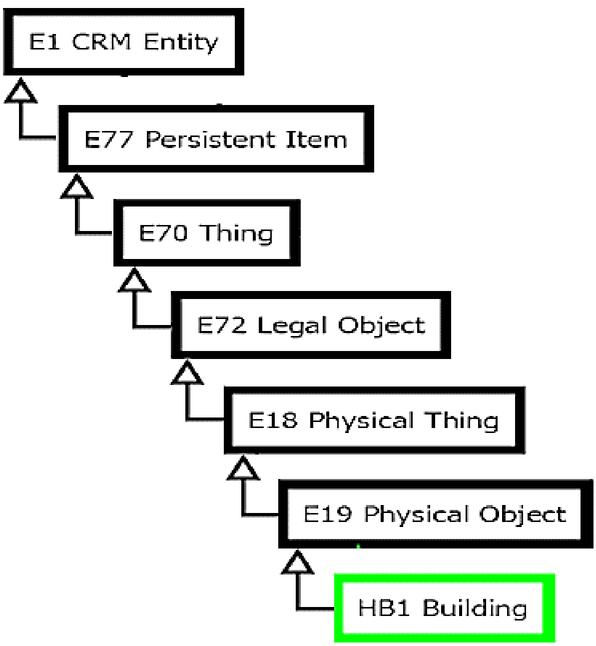
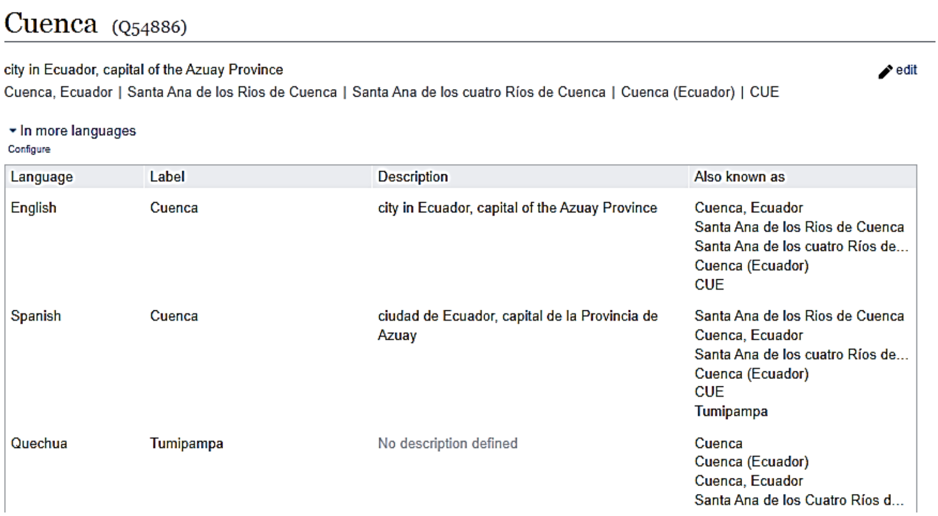


Figure 5.35 Hierarchical structure of the HB1 Building class.

5.7.4 Data enrichment.

Ontologies are tools that allow integration of information and enrichment of datasets with external sources at all levels. Internationally, there are high quality triple stores such as Wikidata and Geonames.

Linking the information of the municipality of Cuenca with the property owl:sameAs to the URI of Cuenca in Wikidata and enables it to cross-reference information with other triple stores where Cuenca is referenced with the Wikipedia URI or any of the names defined in the "Also known as" column (Figure 5.36).



Cuenca (Q54886)

city in Ecuador, capital of the Azuay Province edit

Cuenca, Ecuador | Santa Ana de los Rios de Cuenca | Santa Ana de los cuatro Ríos de Cuenca | Cuenca (Ecuador) | CUE

In more languages

Configure

Language	Label	Description	Also known as
English	Cuenca	city in Ecuador, capital of the Azuay Province	Cuenca, Ecuador Santa Ana de los Rios de Cuenca Santa Ana de los cuatro Ríos de... Cuenca (Ecuador) CUE
Spanish	Cuenca	ciudad de Ecuador, capital de la Provincia de Azuay	Santa Ana de los Rios de Cuenca Cuenca, Ecuador Santa Ana de los cuatro Ríos de... Cuenca (Ecuador) CUE Tumipampa
Quechua	Tumipampa	No description defined	Cuenca Cuenca (Ecuador) Cuenca, Ecuador Santa Ana de los Cuatro Ríos d...

Figure 5.36 shows the Wikidata web page on Cuenca - Ecuador.

Geonames provides geographic information worldwide. In this case, there is the location and administrative division of Cuenca by country, province and canton (Figure 5.37). This information is available for countries, cities, mountains, lakes, etc. This information undoubtedly enriches data in the sense that it standardizes them worldwide and opens up the possibilities of extracting information from more sources.

Figure 5.37shows the Geonames web page on Cuenca - Ecuador.

5.8 Conclusions: Lessons learned from the validation of the BCH-ontology

In this chapter the BCH-ontology has been put into practice. In sections 5.1 the limitations working with 3D models were presented. However, this is an isolated example with particular software (Virtuosos triple store), thus more testing is required to make more precise conclusions. Unfortunately, stakeholders in most cases don't use 3D information.

In section 5.2 the competency questions established in the ontology requirements specification document (Table 4.1) are replied. Each step of the knowledge process shows how to use the developed ontology, while the last section 5.6 shows possible future applications. Section 5.7 presents in a general way the advantages of using ontology models. However, our reflection is oriented to the concerns expressed by the stakeholders. First of all, integration processes cannot be based on wills; this must start from a government policy.

The integration shown in between the information from the municipality and the INPC was done automatically, since in one case the location of the property was stored as a point and in the other the parcel where the buildings are located, thus with the query in Figure 5.24 the records were automatically linked. The integration between the information of the CPM and the municipality was done manually since there were few records; however, this process can also be automated since both the CPM and the municipality handle the cadastral keys. If there are no common fields, more complex attributes such as addresses, names of owners, etc. can always be used.

In July 2022, the Open Data Policy for Ecuador was published which aims to legislate the implementation of open data in government institutions to strengthen citizen participation, government transparency, improve efficiency in public management, promote research, entrepreneurship and innovation in society. This, together with the PDOT-PUGS, provide an enormous opportunity to regulate the use of ontological models. However, at the same time the concepts of the semantic web, ontologies, etc. are a dark field difficult to understand conceptually so more exercises of small integrations are necessary to clarify the usefulness of these models. Specific inter-institutional projects should be sought where the objective is not the collection of new information but the integration of the existing one.

Chapter 6: Conclusions

This chapter presents the conclusions of this thesis summarized in the deliverables [Section 6.1], the answer to the research questions posed in Chapter 1 [Section 6.2]. Followed by the contributions in the cultural [Section 6.3] and spatial [Section 6.3] domains; as well as for the improvement of the local situation in Ecuador [Section 6.4]. Finally, a perspective for future work is shown [Section 6.5].

6.1 Thesis deliverables

The research, performed in this PhD and described in this thesis, results in a flexible model that is an attempt that can help reduce the problems of institutional integration of BCH information. The main deliverables are listed below.

For the dissemination of the BCH -ontology a repository has been created and made available on Github. It can be publicly accessed at https://github.com/BCHOntology and consists of the folders BCHO, DOCUMENTATION, SOURCEONTOLOGIES. The BCH-ontology is the main contribution of this thesis and can be found in the BCHO folder under a Common Creative Attribution license. The ontology is presented in TURTLE format and consists of the following files:

- bchoClassesProperties.ttl: contains the declaration of all classes and properties of the bchontology.
- bchoCommentsEN.ttl: contains labels and comments in English.
- bchoCommentsES.ttl: contains labels and comments in Spanish.

The independent comment files allow for the ontology to be used in different languages or in both languages if necessary.

The BCH-ontology documentation consists of the following files:

- BchoDoc.html: web page describing the ontology, created by Widoloco. This is a tool that allows to automatically generate the documentation of an ontology based on the available comments and generates a web page.
- BchoModel.pdf: This document presents the description of the BCH-ontology model from section 4.3.
- BchoUseCase.pdf: Presents the use cases of sections 5.1-5.5, as an example of the use of the BCH-ontology.

In addition to the BCH-ontology documentation, the folder SOURCEONTOLOGIES includes the versions of the used CIDOC-CRM, CityGML-Geneva and MONDIS ontologies.

6.2 Answers to the Research questions

At the beginning of the research some questions were formulated. Based on the research described in this work we provide the following responses.

RQ1: What are the BCH data issues of preventive conservation that cannot be resolved with traditional systems?

The response addresses three data issues of traditional systems:

Issue 1: Challenging modification of traditional structured models.

PCA is a cyclical approach that allows for fast corrections and readaptation of the information or methodologies used, basically because heritage as such depends on what each generation considers a valuable legacy of past generations. Therefore, the passage of time can lead to changes in asset valuation indicators or risk analysis methodologies. However, when this information is stored in traditional structured models, its modification is time consuming and complicated.

For example, in a database there are primary and secondary tables; information can be deleted from secondary tables independently. However if one wants to delete information from a primary table one must first verify that there is no information from that record in secondary tables. Dealing with primary and foreign keys also complicates modifications. Section 3.4.1 shows a conceptual example of the modification of a risk assessment methodology in which this problem is solved.

Issue 2: Inadequacy of traditional structured models for handling heterogeneous and overlapping Data

Usually, BCH data is stored in several traditional systems, such as isolated GIS and relational databases. However, the management of BCH requires that these datasets of different stakeholders are integrated. In the Ecuadorian context, the case of the integration of the Cuenca's information in the SIPCE is a clear example of this problem.

The example used in section 5.5 demonstrates how the BCH-ontology can be used for this purpose. Although the damage information was stored by the CPM at element level, here it is displayed at room level and even at parcel level which is an input managed by the DGAHP.

Issue 3: Limitations of traditional structured models in retrieving data inferences

Traditional systems explicitly display the information that is stored in the system. However, ontologies allow the presentation of information that is acquired on the basis of logical inferences. In the example in section 5.5, the ontology as such 'knows' that the parcels contain buildings with elements in which damages may be present. Another example of inferences is presented in Figure 5.24 where with the simple use of the 'same as' there is access to all the information on a particular building collected by the three stakeholders regardless of the identifier used to enquire about the building. Information like this is of great importance for decision making related to the management of heritage buildings as it allows for more value criteria. This type of inference is difficult to implement in traditional systems and the possible solutions are very time consuming.

RQ2: What are the advantages and shortcomings of currently existing tools and methodologies for the construction, evaluation and use of ontologies for the integration of heterogeneous BCH information?

Several tools and methodologies were studied in chapter 2. There is a wide variety of ontology development methodologies.

The On-To-Knowledge Methodology is the one that best fits the requirements of this research because of its clarity, consistency and its distinction between the phases of construction and use of ontologies. With respect to ontologies editors there is much less variety but Protege and Web Protege provide sufficient functionalities for the creation of ontologies. A critical issue is the absence of tools for finding already developed ontologies. Basically, only the LOV catalogue is available to this end, since all search engines, such as Swoogle, Watson and Falcons, are no longer available. This complicates the search as we have to resort to time consuming literature reviews to complement this task. Likewise, the technical validation process of the ontology suffers from the same issue, given that OOPS is presently the only tool under active maintenance.

In contrast to the construction phase, the ontology use phase has been mostly exploited as there is a variety of complete frameworks such as the triple store shown in Annex I. Although there is a lot of functionality, there are still some limitations, especially when working with 3D spatial information, since although it can be represented, there is not much else that can be done with it, as shown in section 5.1.

RQ3: Which ontology requirements can be derived from a use case for resolving the BCH data issues?

The description of the stakeholders in chapter 3 has allowed the definition of the BCH-ontology requirements specification document (Table 4.1). These requirements were defined based on the information that was available from the stakeholders. Among these requirements, the use of the CityGML-ADE model, previously developed for the case of Cuenca-ecuador, is mentioned, because it is an input worked on by the stakeholders in a first attempt to homogenise the heritage information of Cuenca. The implementation of a bilingual ontology has been selected because Spanish is the official language of Ecuador, which will facilitate its local use. However, as the BCH-ontology is also applicable in an international context, English has been selected as well.

The competency questions have been defined as examples taking into account the datasets provided by the stakeholders. However, the applications proposed by the same stakeholders in later workshops (Section 5.6) serve to define new requirements and competency questions.

RQ4: Which new components can be developed and verified in a multidisciplinary, multiscale and multiresolution ontology for the BCH preventive conservation?

The CityGML-ADE model was used to define the concepts that should be used in the BCH-ontology. After finding and thoroughly evaluating several candidate ontologies, several concepts were still missing and were therefore proposed in this research. In addition, stakeholders also reviewed the BCH-ontology and proposed new terms. Figure 4.13-4.16 show these concepts in green. Generally these terms were related to the valuation of heritage assets and to the risk assessment.

RQ5: How can the BCH preventive conservation ontology be validated through use cases?

A use case was selected for the validation of the BCH-ontology, which aims to integrate stakeholder information about the San Roque neighborhood. Specifically, information from the maintenance campaigns of the CPM research group and the location of parcels where buildings are located from the municipality GAD's 2D plans were used.

The use case employed the classes defined in the BCH-ontology to demonstrate that information can be stored, integrated and queried to answer the competency questions defined in chapter 4; which are common questions in management of BCH.

Stakeholders were also an important key for the BCH.ontology validation. Stakeholders already compiled a list of important terms for PC in Cuenca in 2001 (3.4 Stakeholders collaboration). So a taxonomy (Figure 4.2) derived from this model is use as reference terms. The stakeholders checked the the BCH-ontology terms again (4.2.2 Expert opinion questionnaire) and during the identification of applications for the BCH-ontology (Section 5.6), there was also a discussion about how to represent some specific information.

An attempt was also made to work with 3D information. However the limitations described in section 5.1 caused this exercise to be performed only in a rudimentary way. This emphasizes the need to give more support to the handling of 3D information, as there is currently a law in Cuenca (Section 3.2.4) which is not being regulated in which GIS technology and 3D models must be used for height and volumetric analyses.

The input given by the stakeholder have Stakeholders already compiled a list of important terms for PC in Cuenca in 2001 (3.4 Stakeholders collaboration). So a taxonomy (Figure 4.2) derived from this model is use as reference terms. The the stakeholders checked the the bch-ontology terms again (4.2.2 Expert opinion questionnaire) and during the identification of applications for the BCH-ontology, they also check the terms and asked how to represent some specific information.

6.2 Contribution to the BCH domain

In the field of heritage management the ontology provides a tool that fits the PCA and it is flexible enough to accommodate information that does not strictly adhere to this approach.

All phases of preventive conservation can be enriched with information from other stakeholders; this leads to better diagnosis and thus therapy. Control and monitoring can be distributed between academic, governmental and citizen institutions, practices that are already in place but whose information is not integrated between them. BCH-ontology can turn this weakness into a great opportunity.

The valorization of all heritage categories: movable, intangible, archaeological and documentary can benefit from the same process of integration of information that already exists, which can identify a baseline to characterize the other heritage categories that have so far been neglected.

6.3 Contribution to the Spatial domain

The BCH-ontology is a tool developed to improve the integration of information on heritage assets. Specifically, it allows to represent both thematic and spatial information. In this research we have worked at the building level as well as at the building block level, which means a contribution to the integration of information at different geographic scales.

The integration of thematic information and special 2D information has been relatively straightforward. The main difficulties were encountered in having information stored with different units of measurement (meters, degrees) which represented a series of transformations of file formats in different software applications but ultimately only required successive transformations. The excel files were passed to CSV, then exported to GeoJason and finally transformed using OntoRefine functions. While none of the processes is overly complicated, the final transformation chain can be somewhat confusing and ultimately always constitutes manual processes that should be automated. This is another line of research that deserves future studies.

The CityGML standard, which is part of BCHO, allows to enrich this information with 3D representations of various resolutions. The integration of spatial information in 3D really remains an open question that needs to be further investigated. Despite the unknowns that remain open, it is also important to emphasize that the integration exercises presented in Section 5.3 show that the integration of thematic and spatial information is already possible in a simpler and more fluid way. By setting the owl:sameAs property, the data can be handled immediately without further requirements. Finally, "a picture is worth a thousand words" and moving from statistical reports to a visual representation allows the identification of events, materiality, damage, etc. in a clearer and more user-friendly way which is undoubtedly already a support for decision making. Moreover, section 4.2.3 shows the height and volume analyses required when submitting projects for the modification or construction of buildings. However, one limitation is the lack of specialized technical personnel to put these issues into practice, which is why, despite being a law in force in the canton of Cuenca, it has not yet been implemented.

6.4 Contribution to the local situation of Ecuador

The work done with the stakeholders in chapter 5 shows the current needs for integration in the BCH domain, and the possible applications of BCH-ontology. However, it should not be forgotten that as long as the concerns raised by the stakeholders in section 5.6.3 are not resolved, there will always be a hesitation to participate freely in these processes.

The BCH-ontology has been tested with the use case of Cuenca-Ecuador, so for local stakeholders the examples seen in chapter 5 are very familiar and have increased the curiosity about other types of integrations. The BCH-ontology helps to understand the principles and advantages of the semantic web and linked data. These are unknown in Ecuador, because although there is an open data policy, in practice the dissemination of information is far from complying with the guidelines of the aforementioned policy.

In particular, there is direct work with the DGAHP of the municipality of Cuenca to include the notions of the use of ontologies in the technological plan for the management of the historic centre. Although this plan has to be approved in two sessions, the fact that the results of this research are being taken into account for this plan is already an important achievement that had not been considered at the start. The current open data regulations also give it a strong legal basis.

The potential presented by 3D models is very useful. At the building level, the actual location of damages in a virtual model would be of great importance, not only to present a current state of the building but also to be able to work with future projection models where, based on constant monitoring, it would be possible to understand the evolution of the damages.

The proposed new PITs define specific policies for each of them, such as permitted uses, maximum height of buildings, etc. A study of how the new building heights affect the visual impact or the landscape would also be useful. Geosparql allows a level of basic functionality that is certainly already important. But the aforementioned analyses are much more advanced with the use of other tools such as City Engine. In this sense, it is important to understand that ontologies are information integration tools that facilitate decision making; they are not daily management tools. Therefore, ontologies would be a means to facilitate the dissemination of these 3D models for further analysis in external software and whose results in turn can be fed back into the ontology for dissemination to different stakeholders.

6.5 Future Work

Future work can be organized in two aspects: according to the needs of the stakeholders and according to the technical improvements of the methods and tools used during the development of this thesis.

6.5.1 Stakeholder needs.

The present work provides input from an academic and research perspective but it is essential that BCH-ontology starts to be used in local institutions with real data. Section 5.6 provides possible applications that can be worked on. The work done with the Municipality of Cuenca to include these topics in the technological plan for the management of the cultural heritage of the city is a first step. Locally, the work carried out for the validation of the BCH-ontology must also continue in order to concretely identify the integration exercise with real data that can be carried out.

The stakeholder workshop described in section 5.6 has raised a lot of expectations about the type of integrations that can be made. By the time of writing, recent events in the country have demonstrated the need to integrate information from governmental institutions for better decision making. On March 18, 2023 an earthquake of Magnitud local calculada en la componente vertical / Calculated local magnitude in the vertical component (MLv) of 6.5 left 15 dead, including 1 in the city of Cuenca due to the collapse of the facade of a heritage building. Currently the Emergency Operations Committee of the city of Cuenca is preparing different reports on the state of services, buildings, roads and other resources of the city.

Cuenca's Centro de operaciones de emergencia / Emergency Operations Centre (COE) is made up of representatives from different institutions, including: the Cuenca Mayor's Office, the National Police, the Fire Department, the Risk Management Secretariat, the Red Cross, the National Risk and Emergency Management Service. These institutions work in a coordinated manner to ensure a timely and effective response to emergency situations such as earthquakes, floods, landslides, among other events. However, the work of integrating their information is done manually because each institution manages its own information management systems. The usefulness of semantic schemas in these institutions whose purpose is based on working in conjunction is undeniable, since instead of creating reports that must then be manually integrated and analyzed, they could provide cross-referenced information in a more timely manner.

Adicionalmente la BCH-onotolgy permite la integracion de BCH pero todavía no existen muchos recursos para representar otras heritage categories such as movable, intangible, documentary and archaeological.

6.5.1 Stakeholder needs.

In this section, recommendations about the gap between methodologies and tools, the automation of ontology discovery, enhanced support for 3D geoSPARQL, and the imperative for linking triple stores with application programs such as GIS and CityEngine are presented.

There is a clear gap between development methodologies and existing tools. Most of the methodologies address the ontology life cycle both in its creation and its use. But in practice the existing tools are isolated, they do not integrate with each other. For example Protégé which is very popular for ontology creation does not have a direct link with GraphDB which allows to store ontology information. It would be desirable to find a more fluid link between these types of tools.

The search of already developed ontologies is fundamental since one of the purposes of ontologies is their reuse, so a correct identification is needed. However, in practice there is a lack of tools that help to fulfill this function. For several years tools are created and disappear, such is the case of Soogle, Watson and Falcons. LOV, however, has remained constant over the years. LOV provides a variety of searches either by term, vocabulary or agent that are basically performed individually when this same search could be automated since we are dealing with structured information such as the taxonomy presented in Fig. 4.2 that serves to identify our terms of reference. A tool that compares two ontologies automatically is required. Also a synonym management system can be implemented in it, allowing more accurate results.

The issue of spatial information representation and management is a topic that also requires attention. Tools implement geoSPQARQL and perform well with two dimensions but fail to incorporate the third dimension. This limitation is presented in the exercise in section 5.1 where several intermediate steps have to be taken to simulate the necessary operations in 3D. This issue is really necessary because the perspective of height opens the door for new analysis. Elevation analyses allow the identification of flood zones. The use of ontology inferences would also allow the identification of buildings that are inaccessible but which, due to proximity to existing damage to another building, could be at risk. 3d models also help to identify heritage elements such as arches, balustrades or columns whose presence can denote a higher heritage value in buildings. The presence of deformations, detachments and other pathologies may suggest the risk of loss of such value in the future.

It is also important to recognize that there are other tools specialized in spatial information visualization and management such as GIS or CityEngine. These tools lack the integration of semantic information. In other words, in order to visualize data from the triple stores, a series of transformations are again necessary to be able to move from OWL or RDF to a format compatible with these applications. At some point an experimental plug in in QGIS called Unicorn was tested but this also did not give good results and it was immediately discarded. Basically the plug in imported small spatial data samples but failed to work with larger triple stores.

References:

Aien, A., Rajabifard, A., Kalantari, M., & Shojaei, D. (2015). Integrating Legal and Physical Dimensions of Urban Environments. *ISPRS International Journal of Geo-Information*, *4*(3). https://doi.org/10.3390/ijgi4031442

Alani, H., Brewster, C., & Shadbolt, N. (2006). *Ranking Ontologies with AKTiveRank*. https://doi.org/10.1007/11926078_1

Alatrish, E. (2012). *Comparison of Ontology Editors* (Vol. 4).

Arenas, M., Bertails, A., Prud'hommeaux, E., & Sequeda, J. (n.d.). *A Direct Mapping of Relational Data to RDF*. Retrieved March 19, 2019, from https://www.w3.org/TR/rdb-direct-mapping/

Asamblea Nacional. (2016). *Ley Orgánica de Cultura el Ecuador*. Registro Oficial. https://www.presidencia.gob.ec/wp-content/uploads/2017/08/a2_LEY_ORGANICA_DE_CULTURA_julio_2017.pdf

Asunción Gómez-Pérez. (2003). Ontology evaluation. In *Handbook on ontologies* (S. Staab and R. Studer, editors, 2st Ed., pp. 251–273). Springer Berlin Heidelberg.

Ath, S., Wielinga, B., & Jansweijer, W. (1995). *The KACTUS view on the 'O'word*. Technical Report, ESPRIT Project 8145 KACTUS, University of Amsterdam, The Netherlands.

Australia ICOMOS. (2000). *The Burra Charter: The Australia ICOMOS charter for places of cultural significance 1999*. https://australia.icomos.org/wp-content/uploads/BURRA_CHARTER.pdf

Autodesk. (2010). *Revit Architecture 2011 User guide*. Graphisoft; 2018-05-10. http://images.autodesk.com/adsk/files/revit_architecture_2011_user_guide_en.pdf

Barbato, D., & Morena, S. (2017, November 27). *BIM and Low-Cost Survey Techniques for Building Heritage Conservation*. International and Interdisciplinary Conference IMMAGINI? Image and Imagination between Representation, Communication, Education and Psychology, Brixen, Italy. https://doi.org/10.3390/proceedings1090930

Berners-Lee, T. (2001). The Semantic Web. *Scientific American*, *284*, 34–43.

Berners-Lee, T. (1998, September). *Relational Databases and the Semantic Web (in Design Issues)*. https://www.w3.org/DesignIssues/RDB-RDF.html

Berners-Lee, T. (2006, July 27). *Linked Data—Design Issues*. http://www.w3.org/DesignIssues/LinkedData.html

Berrueta, D., Fernández, S., & Frade, I. (2008). Cooking HTTP content negotiation with Vapour. *Proceedings of 4th Workshop on Scripting for the Semantic Web 2008 (SFSW2008). Co-Located with ESWC2008*. 4th workshop on Scripting for the Semantic Web 2008.

Bizer, C., & Cyganiak, R. (2006). D2R Server—Publishing Relational Databases on the Semantic Web. *International Semantic Web Conference (ISWC 2006)*.

Bizer, C., & Cyganiak, R. (2007, September 8). *D2RQ — Lessons Learned*. https://www.w3.org/2007/03/RdfRDB/papers/d2rq-positionpaper/

Bizer, C., Heath, T., & Berners-Lee, T. (2009). Linked Data—The Story So Far. *International Journal on Semantic Web and Information Systems*, *5*(3), 1–22.

Boyatzis, R. E. (1998). *Transforming qualitative information: Thematic analysis and code development.* (pp. xvi, 184). Sage Publications, Inc.

Brank, J., Grobelnik, M., & Mladenić, D. (2009). *A survey of ontology evaluation techniques*.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Cardoso, F., Achig-Balarezo, M. C., & Barsallo, G. (2018). Preventive conservation tools in southern Ecuador. *Journal of Cultural Heritage Management and Sustainable Development*, *8*(2). https://doi.org/10.1108/JCHMSD-06-2017-0033

Casellas, N. (2011). Methodologies, Tools and Languages for Ontology Design. In *Legal Ontology Engineering: Methodologies, Modelling Trends, and the Ontology of Professional Judicial Knowledge* (pp. 57–107). Springer Netherlands. https://doi.org/10.1007/978-94-007-1497-7_3

Centofanti, M., Continenza, R., Brusaporci, S., & Trizio, I. (2012). *The architectural information system SIARCH3D-UNIVAQ for analysis and preservation of architectural heritage: Vol. XXXVIII-5/W16*. https://doi.org/10.5194/isprsarchives-XXXVIII-5-W16-9-2011

Cheng, G., Ge, W., & Qu, Y. (2008). Falcons: Searching and browsing entities on the semantic web. *Proceedings of the 17th International*

Conference on World Wide Web, 1101–1102. http://wwwconference.org/www2008/papers/pdf/p1101-cheng.pdf

Chung, Y. S. S. (2007). Heritage Planning. *The SAA Archaeological Record -The Magazine of the Society for American Archaeology, 7*(4), 42–46.

Ciribini, A., Mastrolembo Ventura, S., & Paneroni, M. (2015). *BIM methodology as an integrated approach to heritage conservation management*. https://doi.org/10.2495/BIM150231

Conrad, O., Bechtel, B., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., & Böhner, J. (2015). *System for Automated Geoscientific Analyses (SAGA) v. 2.1.4* (Vol. 8). https://doi.org/10.5194/gmd-8-1991-2015

Consejo Cantonal. (2022). *Plan de Desarrollo y Ordenamiento Territorial y el Plan de Uso y Gestión de Suelo (PDOT-PUGS)*. Municipality of Cuenca. https://www.cuenca.gob.ec/content/pdot-pugs-2022

Corcho, O., Fernández-López, M., Gómez-Pérez, A., & López-Cima, A. (2005). Building Legal Ontologies with METHONTOLOGY and WebODE. In V. R. Benjamins, P. Casanovas, J. Breuker, & A. Gangemi (Eds.), *Law and the Semantic Web: Legal Ontologies, Methodologies, Legal Information Retrieval, and Applications* (pp. 142–157). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-32253-5_9

Corcho, O., Gomez-Perez, A., González-Cabero, R., & del Carmen Suárez-Figueroa, M. (2004). *ODEVAL: A Tool for Evaluating RDF(S), DAML+OIL and OWL Concept Taxonomies*. 369–382.

Crlisle, P. K., Avramides, I., Dalgity, A., & Myers, D. (2014). *The Arches Heritage Inventory and Management System: A standards—Based approach to the management of cultural heritage information*. English Heritage, World Monuments Fund and t he J. Paul Getty Trust. http://archesproject.org/wp-content/uploads/2014/10/I-1_Carlisle_Dalgity_et-al_paper.pdf

Cuenca GAD Municipal. (2016). *Cuenca Geovisor*. Cuenca GAD Municipal. http://ide.cuenca.gob.ec/geovisor/home.seam

Cyganiak, R., & Bizer, C. (2006). *D2R Server: A Semantic Web Front-end to Existing Relational Databases*.

D'Aquin, M., Baldassarre, C., Gridinoc, L., Angeletou, S., Sabou, M., & Motta, E. (2007, 9/10). *Watson: Supporting next generation Semantic Web Application*. WWW/Internet 2007, Villareal, Spain. http://oro.open.ac.uk/23560/1/WWWInternet07.pdf

Das, S., Sundara, S., & Cyganiak, R. (2012). *R2RML: RDB to RDF Mapping Language*. https://www.w3.org/TR/r2rml/
Dassault Systèmes, Spatial Corp. (2021). *Glossary—IFC*. https://www.spatial.com/resources/glossary/what-is-ifc
Davies, J., Studer, R., & Warren, P. (2006). *Semantic Web Technologies – Trends and Research in Ontology-based Systems.* John Wiley & Sons.
De Nicola, A., & Missikoff, M. (2016). *A Lightweight Methodology for Rapid Ontology Engineering* (Vol. 59). https://doi.org/10.1145/2818359
De Nicola, A., Missikoff, M., & Navigli, R. (2009). A Software Engineering Approach to Ontology Building. *Information Systems*, *34*(2), 258–275. https://doi.org/10.1016/j.is.2008.07.002
Degbelo, A. (2017, September 11). A Snapshot of Ontology Evaluation Criteria and Strategies. *Proceedings of Semantics2017*. Semantics2017, Amsterdam, Netherlands. https://doi.org/10.1145/3132218.3132219
Della Torre, S. (2010, 24/02). *Critical reflection document on the draft European Standard CEN/TC 346 WI 346013 Conservation of cultural property—Condition survey of immovable heritage*. Seminar on condition reporting systems f or the built cultural heritage, Monumentenwacht Vlaanderen.
Deng, Y., Cheng, J. C. P., & Anumba, C. (2016). Mapping between BIM and 3D GIS in Different Levels of Detail Using Schema Mediation and Instance Comparison. *Automation in Construction*, *67*, 1–21. https://doi.org/10.1016/j.autcon.2016.03.006
Ding, L., Finin, T., Joshi, A., Pan, R., Cost, R. S., Peng, Y., Reddivari, P., Doshi, V., & Sachs, J. (2004). Swoogle: A Search and Metadata Engine for the Semantic Web. *Proceedings of the Thirteenth ACM International Conference on Information and Knowledge Management*, 652–659. https://doi.org/10.1145/1031171.1031289
Dividino, R., Romanelli, M., & Sonntag, D. (2008). *Semiotic-based Ontology Evaluation Tool (S-OntoEval).*
Dolbear, C., & Goodwin, J. (2007). *Position paper on Expressing Relational Data as RDF*.
Domingue, J., Fensel, D., & Hendler, J. A. (n.d.). Introduction to the Semantic Web Technologies. In *Handbook of Semantic Web Technologies*. Springer Heidelberg Dordrecht London.
Du, H., Alechina, N., Mike, J., & Glen, H. (2013). Matching Formal and Informal Geospatial Ontologies. In *Geographic Information Science*

at the Heart of Europe (pp. 155–171). Springer International Publishing. http://www.cs.nott.ac.uk/~hxd/paper/315253_1_En_9_Chapter_OnlinePDF.pdf

Elkan, C., & Greiner, R. (1993). *Building large knowledge-based systems: Representation and inference in the cyc project: D.B. Lenat and R.V. Guha* (Vol. 61). https://doi.org/10.1016/0004-3702(93)90092-P

ESRI. (2001). *What is ArcGIS? ArcGIS9*. http://downloads.esri.com/support/documentation/ao_/698What_is_ArcGis.pdf

Fernández, M., Overbeeke, C., Sabou, M., & Motta, E. (2009). *What Makes a Good Ontology? A Case-Study in Fine-Grained Knowledge Reuse*. *5926*. https://doi.org/10.1007/978-3-642-10871-6_5

Fernández-López, M., Gómez-Pérez, A., & Juristo, N. (1997). METHONTOLOGY: From Ontological Art Towards Ontological Engineering. *Ontological Engineering on Spring Symposium Series*.

Filip Biljecki, Jantien Stoter, Hugo Ledoux, Sisi Zlatanova, & Arzu Çöltekin. (2015). *Applications of 3D City Models: State of the Art Review*. *4*(4), 435–443. https://doi.org/10.3390/ijgi4042842

Forster, A., & Kayan, B. (2009). *Maintenance for historic buildings: A current perspective*. 210–229.

Gangemi, A., Catenacci, C., Ciaramita, M., & Lehmann, J. (2005). *Ontology evaluation and validation: An integrated formal model for the quality diagnostic task.* Technical report, Laboratory of Applied Ontologies – CNR,. http://www.loa-cnr.it/Files/ OntoEval4OntoDevFinal.pdf.

Gangemi, A., Catenacci, C., Ciaramita, M., & Lehmann, J. (2006). *Modelling Ontology Evaluation and Validation*. 140–154. https://doi.org/10.1007/11762256_13

Garijo, D., & Poveda-Villalón, M. (2020). *Best Practices for Implementing FAIR Vocabularies and Ontologies on the Web*.

Geiger, A., Benner, J., & Haefele, K. H. (2015). Generalization of 3D IFC Building Models. In M. Breunig, M. Al-Doori, E. Butwilowski, P. V. Kuper, J. Benner, & K. H. Haefele (Eds.), *3D Geoinformation Science: The Selected Papers of the 3D GeoInfo 2014* (pp. 19–35). Springer International Publishing. https://doi.org/10.1007/978-3-319-12181-9_2

Gennari, J. H., Musen, M. A., Fergerson, R. W., Grosso, W. E., Crubézy, M., Eriksson, H., Noy, N. F., & Tu, S. W. (2003). The evolution of Protégé: An environment for knowledge-based systems development. *International Journal of Human-Computer Studies*, *58*(1), 89–123. https://doi.org/10.1016/S1071-5819(02)00127-1

Glimm, B., Horrocks, I., Motik, B., Stoilos, G., & Wang, Z. (2014). HermiT: An OWL 2 Reasoner. *Journal of Automated Reasoning*, *53*(3), 245–269. https://doi.org/10.1007/s10817-014-9305-1

Gómez-Pérez, A., & Fernández, M. (2007). *Towards a Method to Conceptualize Domain Ontologies*.

Gómez-Pérez, A., Fernández-López, M., & Corcho, O. (2004). *Ontological Engineering: With Examples from the Areas of Knowledge Management, E-Commerce and the Semantic Web*.

Gómez-Pérez, A., Juristo, N., & Pazos, J. (1995). Evaluation and assessment of the knowledge sharing technology. In *Towards very large knowledge bases* (N.J.I. Mars, pp. 289–296). IOS Press.

Gröger, G., Kolbe, T. H., Czerwinski, A., & Nagel, C. (2008). *OpenGIS City Geography Markup Language (CityGML) Encoding Standard, Version 1.0.0, OGC Doc. No. 08-007r1*. Open Geospatial Consortium.

Gruber, T. R. (1993). A translation approach to portable ontology specifications. *Knowledge Acquisition*, *5*, 199–220. http://dx.doi.org/10.1006/knac.1993.1008

Gruber, T. R. (1995). *Towards principles for the design of ontologies used for knowledge sharing. 43*(5/6), 907–928.

Gruninger, M., & Fox, M. S. (1995). *Methodology for the design and evaluation of ontologies.* IJCAI95 Workshop on Basic Ontological Issues in Knowledge Sharing, Montreal.

Grüninger, M., & Fox, M. S. (1995). *Methodology for the Design and Evaluation of Ontologies*.

Guarino, N., Oberle, D., & Staab, S. (2009). What is an ontology? In *Handbook on ontologies*. Springer–Verlag.

Guarino, N., & Welty, C. (2009). *An Overview of OntoClean* (pp. 201–220). https://doi.org/10.1007/978-3-540-92673-3_9

Gutteridge, C. (n.d.). *RDF Triple-Checker*. Retrieved March 19, 2019, from http://graphite.ecs.soton.ac.uk/checker/

Haase, P., & Sure-Vetter, Y. (2005). *D3.2.1 Usage Tracking for Ontology Evolution*. Institute AIFB, University of Karlsruhe.

Heras, V. (2014). *Towards a 3D GIS based monitoring tool for a Preventive Conservation Management of the World Heritage City of Cuenca* [PhD]. KULeuven.

Heras, V., Wijffels, A., Cardoso, F., Vandesande, A., Santana, M., Van Orshoven, J., Steenberghen, T., & Van Balen, K. (2011). A value-based monitoring system to support heritage conservation planning. *Journal of Cultural Heritage Management and Sustainable Development*, *3*(2), 130–147. https://doi.org/DOI 10.1108/JCHMSD-10-2012-0051

Hlomani, H., & Stacey, D. A. (2013). Contributing Evidence to Data-driven Ontology Evaluation: Workflow Ontologies Perspective. *IC3K 2013; KEOD 2013 - 5th International Conference on Knowledge Engineering and Ontology Development, Proceedings*. https://doi.org/10.5220/0004543602070213

Horridge, M. (2022). *WebProtégé 4.0.0 release notes*. https://github.com/protegeproject/webprotege/releases

ICOM. (2015). *CIDOC CRM Conceptual Reference Model*. Version 6.2.1. http://www.cidoc-crm.org/Version/version-6.2.1

ICOMOS. (1987). *Charter for the Conservation of Historic Towns and Urban Areas, The Washington Charter. Adoped at Adopted by ICOMOS General Assembly in October* (Washington, DC).

ICOMOS. (2011). *The Valletta Principles for the Safeguarding and Management of Historic Cities, Towns and Urban Areas. Adopted by the 17th ICOMOS General Assembly, November 28* (Paris, France).

ICOMOS. (2013). *Charter—Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage, Victoria Falls (Zimbabwe), 2003*. http://www.icomos.org/charters/structures_e.pdf

INPC. (2014). *Sistema de Información del Patrimonio Cultural Ecuatoriano (SIPCE)*. http://patrimoniocultural.gob.ec/sistema-de-informacion-del-patrimonio-cultural-ecuatoriano-sipce/

Jarrar, M., & Meersman, R. (2009). Ontology Engineering – The DOGMA Approach. In T. S. Dillon, E. Chang, R. Meersman, & K. Sycara (Eds.), *Advances in Web Semantics I: Ontologies, Web Services and Applied Semantic Web* (pp. 7–34). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-89784-2_2

Jimenez, J. C. (2001). *Vulnerabilidad Sismica de las Edificaciones de la Ciudad de Cuenca mediante técnicas de simulación* [Master en Ingenieria Estructural]. Escuela Politecnica Nacional.

Kapoor, B., & Sharma, S. (2010, July). A Comparative Study Ontology Building Tools for Semantic Web Applications. *International Journal of Web & Semantic Technology (IJWesT)*, *1*(3). https://www.researchgate.net/publication/45825700_A_Comparative_Study_Ontology_Building_Tools_for_Semantic_Web_Applications

Karsli, F. (2003). *Building 3d Photo-texture Model Integrated with Gis for Architectural Heritage Conservation*.

Kehagias, D., Papadimitriou, I., Hois, J., Tzovaras, D., & Bateman, J. (2008). *A methodological approach for ontology evaluation and refinement.* The 2nd International Conference of ASK-IT., Nuremberg, Germany.

Leo Obrst, Werner Ceusters, Inderjeet Mani, Steve Ray, & Barry Smith. (2007). The evaluation of ontologies. In *Revolutionizing Knowledge Discovery in the Life Sciences* (Christopher J.O. Baker and Kei-Hoi Cheung, editors, pp. 139–158).

Liebich, T. (2014). *IFC4 Coordination view*. buildingSMART International. http://iug.buildingsmart.org/resources/itm-and-iug-meetings-2014-stockholm/plenary-meetings/ifc4-coordination-view

Liu, J., Willkens, D. S., & Foreman, G. (2022). *An introduction to technological tools and process of Heritage Building Information Modeling (HBIM)*. *16*, 50–65.

Liu, X., Wang, X., Wright, G., Cheng, J., Li, X., & Liu, R. (2017). *A State-of-the-Art Review on the Integration of Building Information Modeling (BIM) and Geographic Information System (GIS)* (Vol. 6). https://doi.org/10.3390/ijgi6020053

Lohmann, S., Negru, S., Haag, F., & Ertl, T. (2016). Visualizing Ontologies with VOWL. *Semantic Web*, *7*(4), 399–419. https://doi.org/10.3233/SW-150200

Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (1999). *Geographic Information Science and Systems: Vol. Vol 1* (2nd edition). JOHN WILEY & SONS, INC.

Löwner, M.-O., Benner, J., Gröger, G., Gruber, U., Häfele, K.-H., & Schlüter, S. (2012). *CityGML 2.0 – Ein internationaler Standard für 3D-Stadtmodelle. Teil 1: Datenmodell*. *137*(6), 340–349.

Löwner, M.-O., Benner, J., Gröger, G., & Häfele, K.-H. (2013). New Concepts for Structuring 3D City Models – An Extended Level of Detail Concept for CityGML Buildings. In B. Murgante, S. Misra, M. Carlini, C. M. Torre, H.-Q. Nguyen, D. Taniar, B. O. Apduhan, & O. Gervasi (Eds.), *Computational Science and Its Applications – ICCSA 2013* (pp. 466–480). Springer Berlin Heidelberg.

Maedche, A., & Staab, S. (2002). Measuring Similarity between Ontologies. *Knowledge Engineering and Knowledge Management: Ontologies and the Semantic Web*, *2473*, 15–21. https://doi.org/10.1007/3-540-45810-7_24

Manosalvas, F. (2022, December 15). *Personal communication.* [Personal communication].

Matthys, M., De Cock, L., Vermaut, J., Van de Weghe, N., & De Maeyer, P. (2021). An “Animated Spatial Time Machine” in Co-Creation: Reconstructing History Using Gamification Integrated into 3D City Modelling, 4D Web and Transmedia Storytelling. *ISPRS International Journal of Geo-Information, 10*(7). https://doi.org/10.3390/ijgi10070460

Menzel, C. (2003, September 16). *Reference ontologies—Application ontologies: Either/or or both/and?* Proceedings of the Workshop on Reference Ontologies and Application Ontologies , KI 2003, Hamburg - Germany.

Métral, C., & Cutting-Decelle, A.-F. (2011). Ontologies for Interconnecting Urban Models. In *Ontologies in Urban Development Projects* (Claudine Métral Anne-Françoise Cutting-Decelle, pp. 105–122). Springer London.

Michel, F., Montagnat, J., & Faron Zucker, C. (2013). *A survey of RDB to RDF translation approaches and tools*. https://hal.archives-ouvertes.fr/hal-00903568

Murphy, M., McGovern, E., & Pavía, S. (2007). *Parametric Vector Modelling of Laser and Image Surveys of 17th Century Classical Architecture in Dublin*.

Musen, M. A. (2015). The protégé project: A look back and a look forward. *AI Matters, 1 4*, 4–12.

National BIM Standard. (2018). *Frequently Asked Questions About the National BIM Standard-United States™ | National BIM Standard—United States*. https://www.nationalbimstandard.org/faqs#faq1

Nonaka, I., & Toyama, R. (2005). The Theory of the Knowledge-Creating Firm: Subjectivity, Objectivity and Synthesis. *Industrial and Corporate Change*, *14*, 419–436. https://doi.org/10.1093/icc/dth058

Noy, N. F., & Hafner, C. D. (1997). *The state of the art in ontology design: A survey and comparative review. 18*(3), 53.

Noy, N. F., & Mcguinness, D. L. (2001). *Ontology Development 101: A Guide to Creating Your First Ontology*.

OGC & W3C. (2017). *Time Ontology in OWL*. https://www.w3.org/TR/owl-time/

Ontology Engineering Group - UPM. (n.d.). *Linked Open Vocabularies (LOV)*. Retrieved March 19, 2019, from https://lov.linkeddata.es/dataset/lov/vocabs

Ouyang, L., Zou, B., Qu, M., & Zhang, C. (2011). A method of ontology evaluation based on coverage, cohesion and coupling. *Proceedings - 2011 8th International Conference on Fuzzy Systems and Knowledge Discovery, FSKD 2011*, *4*, 2451–2455. https://doi.org/10.1109/FSKD.2011.6020046

Paolini, A., Vafadari, A., Cesaro, G., Quintero, M. S., Van Balen, K., & Pinilla, O. V. (2012). *Risk Management at Heritage Sites: A Case Study of the Petra World Heritage Site*. UNESCO.

Perry, M., & Herring, J. (2012). *OGC GeoSPARQL - A Geographic Query Language for RDF Data*. Open Geospatial Consortium. http://www.opengis.net/doc/IS/geosparql/1.0

Pinto, H. S., & Martins, J. P. (2004). Ontologies: How can They be Built? *Knowledge and Information Systems*, *6*(4), 441–464. https://doi.org/10.1007/s10115-003-0138-1

Pinto, H. S., Staab, S., & Tempich, C. (2004). DILIGENT: Towards a fine-grained methodology for DIstributed, Loosely-controlled and evolvInG Engineering of oNTologies. *Proceedings of the 16th European Conference on Artificial Intelligence (ECAI*, 393–397.

Porzel, R., & Malaka, R. (2004). A Task-based Approach for Ontology Evaluation. *ECAI Workshop on Ontology Learning and Population, Valencia, Spain*.

Poveda-Villalón, M., Gomez-Perez, A., & Suárez-Figueroa, M. C. (2014). OOPS! (OntOlogy Pitfall Scanner!): An on-line tool for ontology evaluation. *International Journal on Semantic Web and Information Systems*, *10*, 7–34. https://doi.org/10.4018/ijswis.2014040102

Poveda-Villalón, M., Suárez-Figueroa, M. C., & Gomez-Perez, A. (2012). *Validating ontologies with OOPS!* 267–281. https://doi.org/10.1007/978-3-642-33876-2_24

PRECOM3OS. (2009, March 29). *About the UNESCO PRECOM^{3}OS Chair*. Unesco Precomos Chair. https://set.kuleuven.be/rlicc/research/precomos

QGIS project. (2018). *QGIS User Guide Release 2.18*. https://docs.qgis.org/2.18/pdf/en/QGIS-2.18-UserGuide-en.pdf

Raad, J., & Cruz, C. (2015). *A Survey on Ontology Evaluation Methods*. https://doi.org/10.5220/0005591001790186

Rodas Espinoza, P. F. (2016). *Modelo de Gestión para la Conservación del Patrimonio Edificado de la ciudad de Cuenca* [Magíster en Conservación y Gestión del Patrimonio Cultural Edificado, University of Cuenca]. http://dspace.ucuenca.edu.ec/handle/123456789/25809

S. Staab, R. Studer, H. P. Schnurr, & Y. Sure. (2001). Knowledge processes and ontologies. *IEEE Intelligent Systems*, *16*(1), 26–34. https://doi.org/10.1109/5254.912382

Saygi, G., & Remondino, F. (2013). *Management of Architectural Heritage Information in BIM and GIS: State-of-the-art and Future Perspectives* (Vol. 2). https://doi.org/10.1260/2047-4970.2.4.695

Shah, V., Shah, A., & Deulkar, K. (2015). *Comparative Study Of Semantic Search Engines*. *4*(11). 14969-14972. http://www.ijecs.in/index.php/ijecs/article/view/2879

Simmons, T. M. (1998). *ArchiCAD - Step by Step Tutorial version 7.0*. Graphisoft.

Sirin, E., Parsia, B., Grau, B. C., Kalyanpur, A., & Katz, Y. (2007). Pellet: A practical OWL-DL reasoner. *Journal of Web Semantics*, *5*(2), 51–53. https://doi.org/10.1016/j.websem.2007.03.004

Stanford Center for Biomedical Informatics Research. (2007, October 3). *ProtegeDesktopUserDocs—Protege Wiki*. https://protegewiki.stanford.edu/wiki/Protege4UserDocs

Stanford Center for Biomedical Informatics Research. (2008, July 14). *WebProtege—Protege Wiki*. https://protegewiki.stanford.edu/wiki/WebProtege

Stanford Center for Biomedical Informatics Research. (2016). *Protégé*. https://protege.stanford.edu/products.php

Studer, R., Benjamins, V. R., & Fensel, D. (1998). Knowledge engineering: Principles and methods. *Data & Knowledge Engineering*, *25*(1–2), 161–197. http://dx.doi.org/10.1016/S0169-023X(97)00056-6

Studer, R., Grimm, S., & Abecker, A. (2007). *Semantic Web Services Concepts, Technologies, and Applications*. Springer-Verlag Berlin Heidelberg.

Suárez-Figueroa, M. C., Gómez-Pérez, A., & Fernández-López, M. (2012). The NeOn Methodology for Ontology Engineering. In *Ontology Engineering in a Networked World* (pp. 9–34). Springer Berlin Heidelberg. http://oa.upm.es/21469/

Suárez-Figueroa, M. C., Gomez-Perez, A., & Fernández-López, M. (2015). *The NeOn Methodology framework: Ascenario-based methodology for ontologydevelopment* (Vol. 10). https://doi.org/10.3233/AO-150145

Suárez-Figueroa, M. C., Gomez-Perez, A., & Motta, E. (2012). *Ontology Engineering in a Networked World*. Springer-Verlag Berlin Heidelberg.

Sure, Y., Staab, S., & Studer, R. (2009). Ontology Engineering Methodology. In *Handbooks on Ontologies.* Springer-Verlag Berlin Heidelberg.

Sure, Y., & Studer, R. (1999). *On-To-Knowledge Methodology*.

Swartout, B., Patil, R., Knight, K., & Russ, T. (1997). Towards distributed use of large-scale ontologies. *AAAI Spring Symposium on Ontological Engineering*.

Swick, R., Schreiber, G., & Wood, D. (2006, April 10). *W3C Semantic Web Best Practices and Deployment Working Group*. W3C - Semantic Web Activity. https://www.w3.org/2001/sw/BestPractices/

Tejo-Alonso, C., Berrueta, D., Paredes, L., & Fernández, S. (2012). Metadata for Web Ontologies and Rules: Current Practices and Perspectives. *International Journal of Metadata, Semantics and Ontologies*, *7*, 93–100. https://doi.org/10.1504/IJMSO.2012.050016

Tobler, W. (1988). Resolution, Resampling, and all that. In *Building Database for Global Science* (H. Mounsey and R. Tomlinson, pp. 129–137). Taylor & Francis.

TopQuadrant Inc. (2016). *TopBraid Composer Getting Started Guide—Version 5.2*. https://www.topquadrant.com/docs/TBC-Getting-Started-Guide52.pdf

TopQuadrant Inc. (2001). TopBraid Products | TopQuadrant, Inc. *TopQuadrant, Inc*. https://www.topquadrant.com/products/

UNESCO. (1972). *Convention concerning the protection of the World Cultural and Natural Heritage*. http://www.icomos.org/publications/93touris12.pdf

UNESCO. (2017, July 26). *UNITWIN/UNESCO Chairs Programme*. UNESCO. https://en.unesco.org/unitwin-unesco-chairs-programme

Uschold, M., & King, M. (1995). Towards a Methodology for Building Ontologies. *Workshop on Basic Ontological Issues in Knowledge Sharing, Held in Conjunction with IJCAI-95*.

Van Balen, K. (2008). The Nara Grid: An Evaluation Scheme based on the Nara Document on Authenticity. *APT Bulletin: Journal of Preservation Technology*, *49*(2), 39–45.

Van Balen, K. (2015). *Preventive Conservation of Historic Buildings*. *21*(2–3), 99–104.

Vrandečić., D. (2009). Ontology evaluation. In *Handbook on ontologies* (S. Staab and R. Studer, editors, 2nd Ed., pp. 293–313). Springer Berlin Heidelberg. DOI 10.1007/978-3-540-92673-3

W3C. (2001, September 21). *URIs, URLs, and URNs: Clarifications and Recommendations 1.0*. https://www.w3.org/TR/uri-clarification/

W3C. (2011). *W3C Semantic Web Activity*. http://www.w3.org/2001/sw/
W3C. (2013a, February 5). *OWL 2 RL in RIF (Second Edition)*. https://www.w3.org/TR/rif-owl-rl/
W3C. (2013b, March 21). *SPARQL 1.1 Overview*. https://www.w3.org/TR/sparql11-overview/
W3C. (2013c, March 21). *SPARQL 1.1 Query Language*. https://www.w3.org/TR/sparql11-query/
W3C. (2014a, February 25). *RDF 1.1 XML Syntax*. https://www.w3.org/TR/2014/REC-rdf-syntax-grammar-20140225/
W3C. (2014b, February 25). *RDF Schema 1.1*. https://www.w3.org/TR/rdf-schema/
W3C Interest Group. (2008, December 3). *Cool URIs for the Semantic Web*. https://www.w3.org/TR/cooluris/
Wang, J.-J. (2015). Flood risk maps to cultural heritage: Measures and process. *Journal of Cultural Heritage*, *16*(2), 210–220. http://dx.doi.org/10.1016/j.culher.2014.03.002
Wolstencroft, K., Mcentire, R., Stevens, R., Tabernero, L., & Brass, A. (2005). Constructing ontology-driven protein family databases. *Bioinformatics (Oxford, England)*, *21*, 1685–1692. https://doi.org/10.1093/bioinformatics/bti158
World heritage centre. (2017). *Operational Guidelines for the Implementation of the World Heritage Convention* (Granada - Spain). http://whc.unesco.org/en/guidelines
Wu, J., & Li, H. (2006). Concepts of Scale and Scaling. In *Scaling and Uncertainty Analysis in Ecology* (JIANGUO WU, K. BRUCE JONES , HARBIN LI , ORIE L. LOUCKS, pp. 3–15).
Yulia Gromova. (2019, August 13). *BIM FOR HERITAGE: HOW TO DEVELOP A HISTORIC BUILDING INFORMATION MODEL*. https://strelkamag.com/en/article/bim-to-the-rescue-of-heritage-sites
Yusuf Arayici. (2008). Towards building information modelling for existing structures. *Structural Survey*, *26*(3), 210–222. https://doi.org/10.1108/02630800810887108

Annexes

Annex I: GraphDB visual tools

GraphDB proved to be a very powerful tool for data analysis. Some of the most useful features are presented in this annex. First of all, the OntoRefine tool presents a visual tool for data mapping. The power of this tool lies in the different types of transformations and filters that can easily modify the data in the desired format. There are also programmed functions for common transformations such as uppercase, lowercase, conversion between data types, column fragmentation, etc. Then the mapping of triples also provides many possibilities since constants, column-based values and logical expressions can be used. Along with the mappings, a preview of how the data looks like once mapped is also available. Finally, the mapping can be exported in various formats such as JSON, RDF and SPARQL.

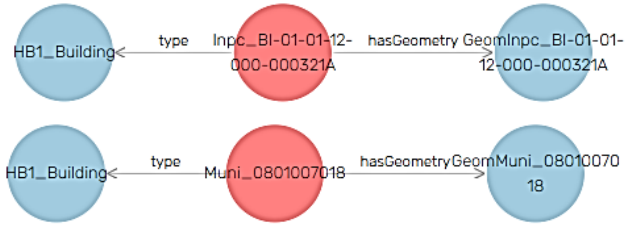


Figure A.1 GrapDB graophical view

GraphDB has two forms of data visualization: tabular (Figure 5.26) and graphical (Figure A.1). In the tabular view, the use of inferences can be enabled and disabled which allows implicit data of a class such as inherited predicates through the use of the "owl:sameAs" property. Data can be stored in different formats: RDF-XML, JSON, NTriples, NQuads, Trutle, TriX, TriG and binary RDF. In the graphical view, double-clicking on each node of the graph displays the relationships of that node, allowing easy and fast exploration of the data.

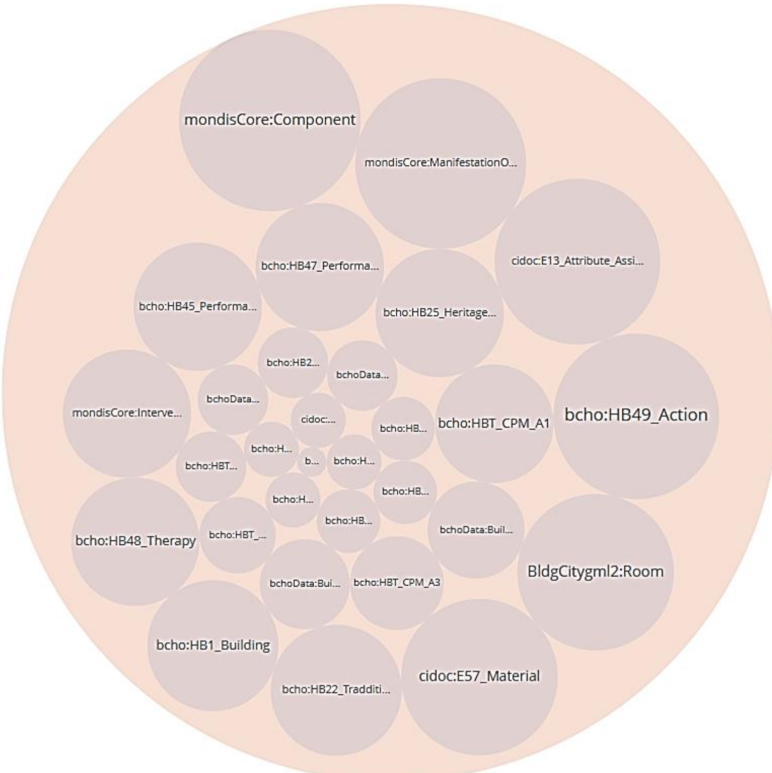


Figure A.2 Class hierarchy view of Graph DB. Classes with more instances are bigger than others.

Additionally, there are two graphical views for statistical information: the class hierarchy (Figure A.2) shows the classes that have more instances. Clicking on the class name displays all instances of the class. The view of relationships between classes (Figure A.3) shows the outgoing relationships from the components to material and damages, as well as the incoming ones from the rooms ad buildings. The width of each branch demonstrates which relations are more numerous. In this case, for example, the number of relations between component and material are more than those of building to component.

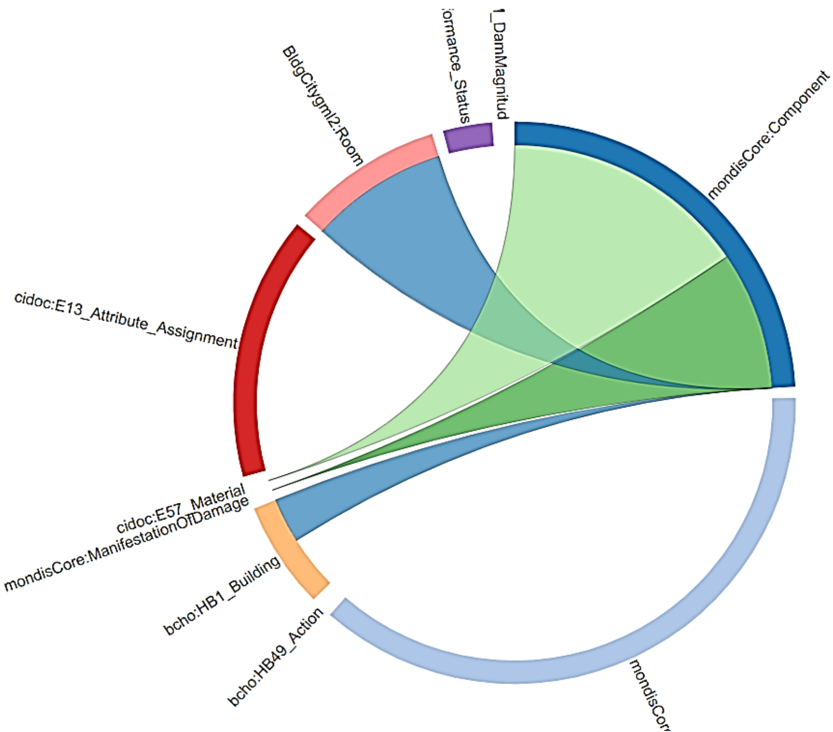


Figure A.3 Class relationships view of Graph DB. Classes with more relations are wider than others.

The area for creating SPARQL queries also provides some functionalities such as opening, saving or generating URIs for queries, enabling and disabling inferences and sameAs statements. The results are displayed by default in the tabular view but can also be opened in the graphical view or exported to the formats mentioned above.

The Monitor section (Figure A.4) allows us to see if there are any queries being executed or to view them as a computer resource usage report.

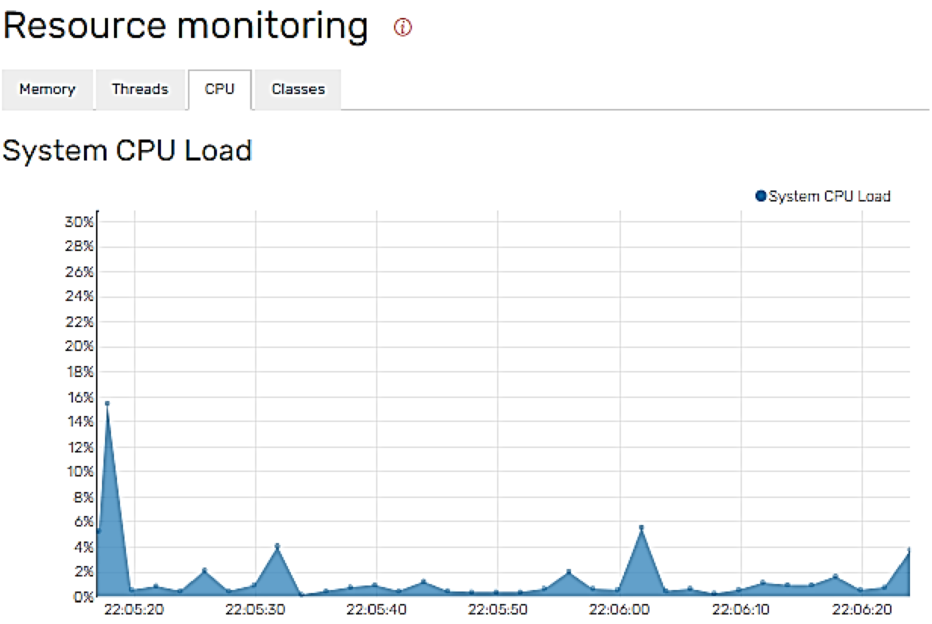


Figure A.4 Report of CPU use, section de Monitor/Recursos.

The configuration section allows the creation of repositories, users, connections, and namespaces. The user control is very important as it grants different users and roles access for reading and writing, using inferences, accessing the data schema, etc. This feature discussed in chapter 5 is one of the biggest concerns of stakeholders.

Annex II: BCH-ontology Properties

Table A.1 BCH-Ontology properties.

PROPERTY	DOMAIN	RANGE	INVERSE
P1 is identified by	E1 CRM Entity	E41 Appellation	P1i identifies
P2 has type	E1 CRM Entity	E55 Type	P2i is type of
P4 has time-span	E2 Temporal Entity	E52 Time-Span	P4i is time-span of
P5 consists of	E3 Condition State	E3 Condition State	P5i forms part of
P28 custody surrendered by	E10 Transfer of Custody	E39 Actor	P28i surrendered custody through
P29 custody received by	E10 Transfer of Custody	E39 Actor	P29i received custody through
P30 transferred custody of	E10 Transfer of Custody	E18 Physical Thing	P30i custody transferred through
P43 has dimension	E70 Thing	E54 Dimension	P43i is dimension of
P45 consists of	E18 Physical Thing	E57 Material	P45i is incorporated in
P46 consists of	E18 Physical Thing	E18 Physical Thing	P46i forms part of
P56 bears feature	E19 Physical Object	E26 Physical Feature	P56i is found on
P67 refers to	E89 Propositional Object	E1 CRM Entity	P67i is referred by
P68 foresees use of	E29 Design or Procedure	E57 Material	P68i use foreseen by
P83 had at least duration	E52 Time-Span	E54 Dimension	P83i was minimum duration of
P84 had at most duration	E52 Time-Span	E54 Dimension	P84i was maximum duration of

P91 has unit	E54 Dimension	E58 Measurement Unit	P91i is unit of
P108 has produced	E12 Production	E24 Physical Man-Made Thing	P108i was produced by
P110 augmented	E79 Part Addition	E24 Physical Man-Made Thing	P110i was augmented by
P111 added	E79 Part Addition	E18 Physical Thing	P111i was added by
P112 diminished	E80 Part Removal	E24 Physical Man-Made Thing	P112i was diminished by
P113 removed	E80 Part Removal	E18 Physical Thing	P113i was removed by
P115 finishes	E2 Temporal Entity	E2 Temporal Entity	P115 finishes (is finished by)
P116 starts	E2 Temporal Entity	E2 Temporal Entity	P116 starts (is started by)
P127 has broader term	E55 Type	E55 Type	P127i has narrower term
P140 assigned attribute to	E13 Attribute Assignment	E1 CRM Entity	P140i was attributed by
P141 assigned	E13 Attribute Assignment	E1 CRM Entity	P141i was assigned by
P148 has component	E89 Propositional Object	E89 Propositional Object	P148i is component of
PG1 lod0FootPrint	G16 Abstract Building	G11 MultiSurface	*PG1 lod0FootPrint of
PG2 lod0RoofEdge	G16 Abstract Building	G11 MultiSurface	*PG2 lod0RoofEdge of
PG3 lod1Solid	G16 Abstract Building	G7 Solid	*PG3 lod1Solid of
PG4 outerBuildingInstallation	G16 Abstract Building	G19 Building Installation	*PG4 outerBuildingInstallation of
*PG5 boundedBy	G14 CityObject	G20 Boundary Sourface	*PG5 bounded
PG6 lod2MultiSurface	G20 Boundary Sourface	G11 MultiSurface	*PG6 lod2MultiSurface of
PG7 lod3MultiSurface	G29 Opening	G11 MultiSurface	*PG7 lod3MultiSurface of
PG8 opening	G20 Boundary Sourface	G29 Opening	*PG8 opening of

PG9 lod4Solid	G32 Room	G7 Solid	*PG9 lod4Solid of
PG10 lod4MultiSurface	G32 Room	G11 MultiSurface	*PG10 lod4MultiSurface of
*PG11 lod4Geometry	G14 CityObject	G1 Geometry	*PG11 lod4Geometry of
PHB1 has scope	E40 Legal Body	HB23 Scope	PHB1 is scope of
PHB4 has agent	M4 Manifestation of Damage	M5 Agent	PHB4 is agent of
PHB5 has damage	HB34 Gravity	M4 Manifestation of Damage	PHB5 is damage of
PHB7 has vulnerability parameter	M6 Vulnerability	HB42 Vulnerability Parameter	PHB7 is vulnerability parameter of
PHB10 has condition variable	HB44 Condition Variable Assignment	HB43 Condition Variable	PHB10 is condition variable of
PHB11 has condition	HB25 Heritage Value	E3 Condition State	PHB11 refers to value
PHB12 has parameter	HB45 Performance Status	HB46 Performance Status Parameter	PHB12 is parameter of
PHB15 has therapy	HB45 Performance Status	HB48 Therapy	PHB15 is therapy of
PHB16 has suggested action	HB48 Therapy	HB49 Action	PHB16 is suggested action of
PHB17 has status	HB49 Action	HB45 Action Status	PHB17 is status of
PHB19 has resource	HB49 Action	HB52 Resource	PHB19 is resource of
PHB20 has intervention	HB45 Therapy	M28 Intervention	PHB20 is interventio of
PHB21 has intervention action	M28 Intervention	HB46 Action	PHB21 is intervention action of
PHB24 has inspection	HB48 Therapy	HB53 Inspection	PHB24 is inspection of
PHB25 has geographical representation	E77 Persistent Item	HB54 Spatial Representation	PHB25 is representation of
PM1 refers to hazard	M3 Risk	M7 Hazard	*PM1 is subject to risk
PM2 is subject to	M6 Vulnerability	M7 Hazard	*PM2 refers to

PM3 is eliminated by intervention	M5 Agent	M28 Intervention	*PM3 eliminates
PM4 is repair of damage	M28 Intervention	M4 Manifestation of Damage	*PM4 is repaired on

* Properties created in this research to complement MONDIS and Geneva-CityGML ontologies.

Annex III: Creation of a repository for the heritage information of Cuenca

*A repository is selected in OWL language to be able to use the owl:sameAs property and link separate datasets.

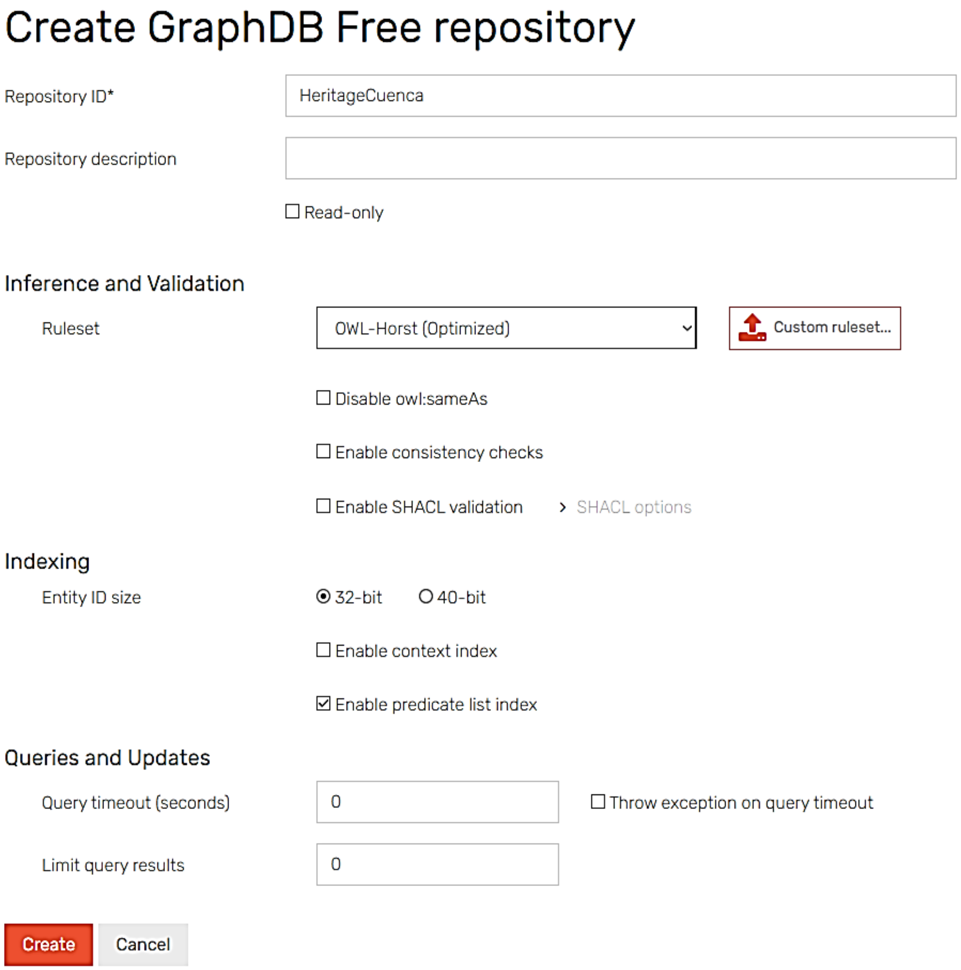


Figure A.5 Creation of a repository for the heritage information of Cuenca.

Annex IV: SPARQL query of components with damages

```
prefix cidoc: <http://www.cidoc-crm.org/cidoc-crm/#>
prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>
prefix mondisCore:
<http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX bchoData:
<http://www.ciudadpatrimoniomundial.com/ontologias/BCH/Data/>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
select distinct ?BuildingRoom ?BuildingCompType ?DamageCode
?DamageName ?Geom {
   ?BuildingDam a mondisCore:ManifestationOfDamage.
   ?BuildingDam cidoc:P46_is_composed_of ?DamageCode.
   ?DamageCode rdfs:label ?DamageName.
   ?x rdf:type cidoc:E13_Attribute_Assignment.
   ?x cidoc:p141_assigned bchoData:HBT_CPM_DamMagnitud1.
   ?x cidoc:P140_assigned_attribute_to ?BuildingDam.
   ?BuildingComp cidoc:P56_bears_feature ?BuildingDam.
   ?BuildingRoom cidoc:P46_is_composed_of ?BuildingComp.
   ?BuildingComp  rdf:type mondisCore:Component;
                          cidoc:P2_has_type    ?BuildingCompType.
   ?BuildingFloor cidoc:P46_is_composed_of ?BuildingRoom.
   ?Building cidoc:P46_is_composed_of ?BuildingFloor.
   ?BuildingFloor geo:hasGeometry ?GeomName.
   ?GeomName geo:asWKT ?Geom; cidoc:P2_has_type
?BuildingCompType. }
```

Figure A.6 Components with damages displayed in QGIS

Annex V: SPARQL query of rooms with damages

```
prefix cidoc: <http://www.cidoc-crm.org/cidoc-crm/#>
prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>
prefix mondisCore:
<http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-
core.owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX bchoData:
<http://www.ciudadpatrimoniomundial.com/ontologias/BCH/Data/>
PREFIX bcho:
<http://www.ciudadpatrimoniomundial.com/ontologias/BCH#>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
select distinct ?BuildingRoom ?BuildingCompType ?DamageCode
?DamageName ?Geom {
   ?BuildingDam a mondisCore:ManifestationOfDamage.
   ?BuildingDam cidoc:P46_is_composed_of ?DamageCode.
   ?DamageCode rdfs:label ?DamageName.
   ?x rdf:type cidoc:E13_Attribute_Assignment.
   ?x cidoc:p141_assigned bchoData:HBT_CPM_DamMagnitud1.
   ?x cidoc:P140_assigned_attribute_to ?BuildingDam.
   ?BuildingComp cidoc:P56_bears_feature ?BuildingDam.
   ?BuildingRoom cidoc:P46_is_composed_of ?BuildingComp.
   ?BuildingComp      rdf:type mondisCore:Component;
cidoc:P2_has_type ?BuildingCompType.
   ?BuildingFloor cidoc:P46_is_composed_of ?BuildingRoom.
   ?Building cidoc:P46_is_composed_of ?BuildingFloor.
   ?BuildingRoom geo:hasGeometry ?GeomName.
   ?GeomName geo:asWKT ?Geom; cidoc:P2_has_type
bcho:HBT_CPM23_Floor. }
```

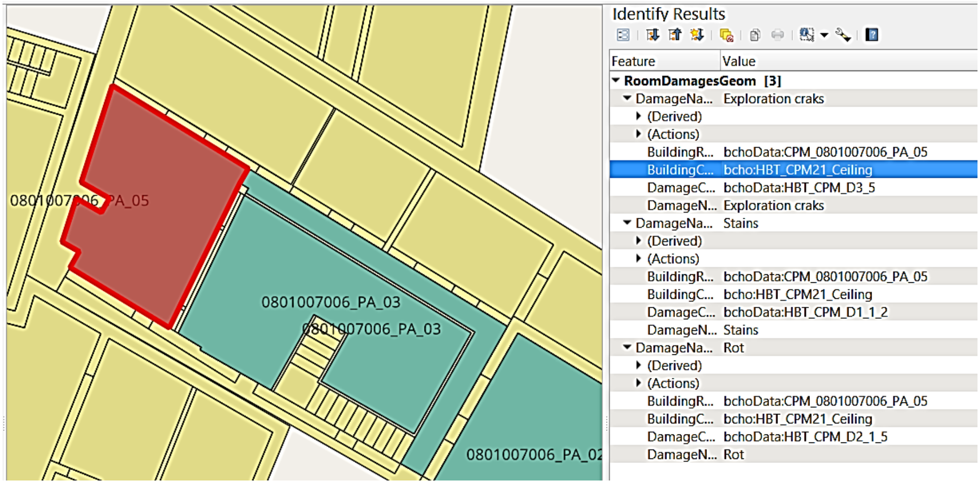


Figure A.7 Rooms with damages displayed in QGIS

Annex VI: SPARQL query of buildings with damages

```
prefix cidoc: <http://www.cidoc-crm.org/cidoc-crm/#>
prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>
prefix mondisCore:
<http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-core.owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX bchoData:
<http://www.ciudadpatrimoniomundial.com/ontologias/BCH/Data/>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX bcho:
<http://www.ciudadpatrimoniomundial.com/ontologias/BCH#>
select distinct ?BuildingRoom    ?BuildingCompType ?DamageCode
      ?DamageName      ?Geom {
  ?BuildingDam a mondisCore:ManifestationOfDamage.
  ?BuildingDam cidoc:P46_is_composed_of ?DamageCode.
  ?DamageCode rdfs:label ?DamageName.
  ?x rdf:type cidoc:E13_Attribute_Assignment.
  ?x cidoc:p141_assigned bchoData:HBT_CPM_DamMagnitud1.
  ?x cidoc:P140_assigned_attribute_to ?BuildingDam.
  ?BuildingComp cidoc:P56_bears_feature ?BuildingDam.
  ?BuildingRoom cidoc:P46_is_composed_of ?BuildingComp.
  ?BuildingComp rdf:type mondisCore:Component;
cidoc:P2_has_type   ?BuildingCompType.
  ?BuildingFloor cidoc:P46_is_composed_of ?BuildingRoom.
  ?Building cidoc:P46_is_composed_of ?BuildingFloor.
  ?Building geo:hasGeometry ?GeomName.
  ?GeomName geo:asWKT ?Geom. }
```

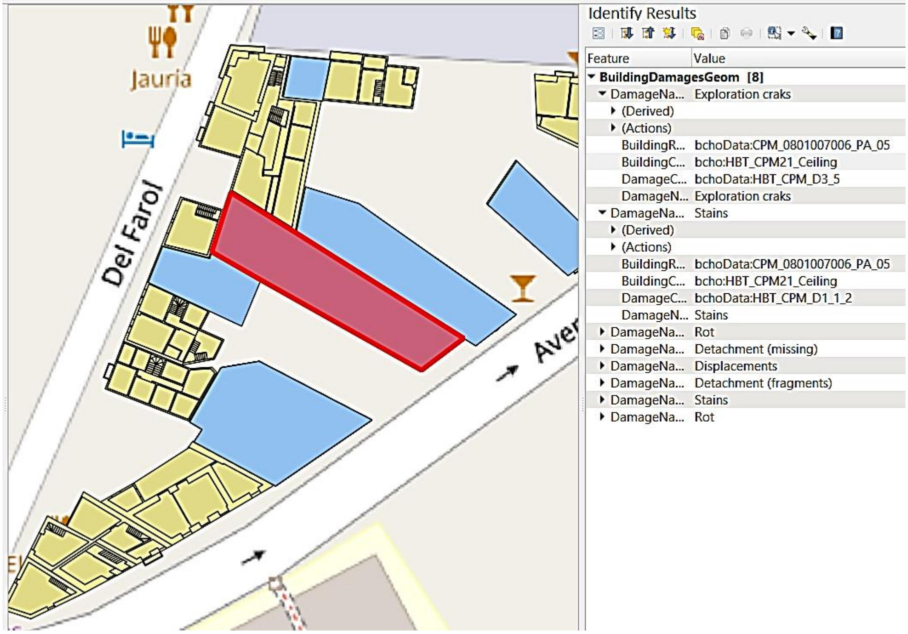


Figure A.8 Buildings with damages displayed in QGIS.

Annex VII: SPARQL query of actions performed on buildings with damages

```
prefix cidoc: <http://www.cidoc-crm.org/cidoc-crm/#>
prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>
prefix mondisCore:
<http://kbss.felk.cvut.cz/ontologies/2011/monument-damage-
core.owl#>
prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
prefix bchoData:
<http://www.ciudadpatrimoniomundial.com/ontologias/BCH/Data/>
prefix geo: <http://www.opengis.net/ont/geosparql#>
prefix bcho:
<http://www.ciudadpatrimoniomundial.com/ontologias/BCH#>
select distinct ?Building ?INTActionName ?Geom {
   ?BuildingDam rdf:type mondisCore:ManifestationOfDamage.
   ?BuildingDam cidoc:P46_is_composed_of ?DamageCode.
   ?DamageCode rdfs:label ?DamageName.
   ?DamageAssig rdf:type cidoc:E13_Attribute_Assignment.
?DamageAssig cidoc:p141_assigned
bchoData:HBT_CPM_DamMagnitud1.
   ?DamageAssig cidoc:P140_assigned_attribute_to ?BuildingDam.
   ?BuildingComp cidoc:P56_bears_feature ?BuildingDam.
   ?BuildingRoom cidoc:P46_is_composed_of ?BuildingComp.
   ?BuildingComp      rdf:type mondisCore:Component;
cidoc:P2_has_type ?BuildingCompType.
   ?BuildingFloor cidoc:P46_is_composed_of ?BuildingRoom.
   ?Building cidoc:P46_is_composed_of ?BuildingFloor.
   ?Building geo:hasGeometry ?GeomName.
   ?GeomName geo:asWKT ?Geom.
   ?BuildingHV cidoc:P67_refers_to ?Building.
   ?PSA cidoc:P140_assigned_attibute_to ?BuildingHV.
   ?PSA cidoc:P141_assigned ?BuildingPS.
   ?BuildingPS bcho:PHB20_has_intervention ?BuildingINT.
   ?BuildingINT bcho:PHB21_has_intervention_action ?INTAction.
   ?INTAction rdfs:label ?INTActionName. }
```

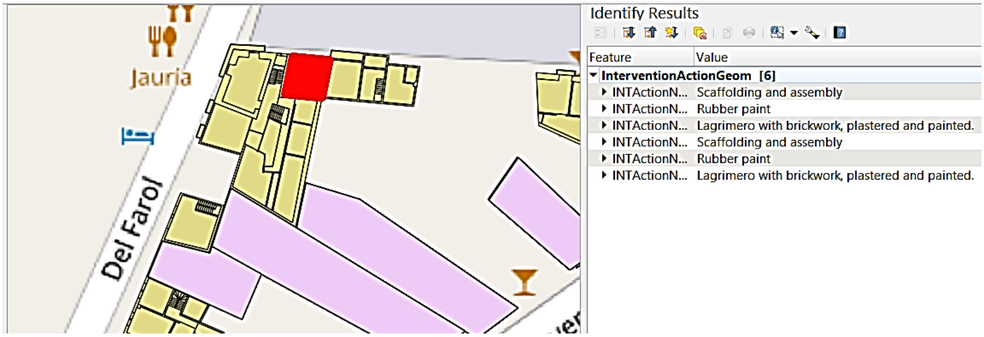


Figure A.9 Actions performed on buildings with damages displayed in QGIS.

Annex IIX: Stakeholder surveys and workshops

In this research, a thematic analysis is applied to identify possible applications to the BCH-ontology. Thematic analysis is a method for identifying, analyzing, and reporting patterns in data. During thematic analysis the data are not only organized and described, but also interpreted (Boyatzis, 1998).

Data collection

Two workshops are held with the presence of the Cuenca's BCH management main stakeholders. The use cases defined in sections 5.1.1 to 5.1.3 are shown, after which the stakeholders are asked to fill out a survey with the following open questions.

1. Which applications come to mind in which the BCH-ontology can be used?
2. What is still missing?
3. What useful information could you provide, so that others can reuse it?
4. What information would you like to access from others?
5. What is needed for you to make 3 and 4 operational?

Based on the answers, a discussion is held to define the type of institutional integration that would enable the use of ontology models and 13 surveys are filled out. Table A.2 shows the statistics of the surveys.

Table A.2 Workshop participants.

Nro	Institution	Role	Category
1	Municipality of Cuenca	Director of Historic and Heritage Areas	Governmental
1	Municipality of Cuenca	Council man representative of the Historic Areas Commission	Governmental
1	Municipality of Cuenca	Technician	Governmental

2	INPC	Technician	Governmental
1	Universidad del Azuay	Faculty member teaching subjects related to the maintenance of heritage buildings	Academic-Local
3	Universidad de Cuenca	Faculty member teaching subjects related to the maintenance of heritage buildings	Academic-Local
3	KU-Leuven	Faculty member teaching subjects related to the maintenance of heritage buildings. Ex-Director of the Raymond Lemaire International Centre for Conservation	Academic-International
5	Universidad de Cuenca	CPM researchers	Academic-Local
2	INPC	Technicians	Governmental

Data analysis

For the thematic analysis of the surveys the process suggested by Braun and Clarke (2006) was followed which is described in the following sections.

Familiarization with the data and generation of initial codes. Of the 13 surveys, 2 random ones are taken as examples. After codifying them, a list of codes is established and the rest of the surveys are coded. The final list of codes is shown in Table A.3.

Table A.3 List of codes for the thematic analysis

Nro.	Code
C1	BCHO+
C2	BCHO-
C3	Intra-institution
C4	Inter-institution
C5	External-Integration
C6	Public data
C7	Confidential data
C8	Academy

C9	Governmental
C10	INPC
C11	Municipality
C12	Citizenship
C13	Data provided
C14	Data required

Search for themes. Relationships between codes are established and it was observed that the opinions focused on the following themes:

Table A.4 List of initial themes.

Nro.	**Theme**
T1	BCH-Ontology applications
T2	Intra-institution collaboration
T3	Inter-institution collaboration
T4	External collaboration
T5	BCH-Ontology Improvements
T6	PITs and UAUs
T7	5 Heritage categories
T8	Stakeholders data identification
T9	Municipality bureaucratic processes
T10	Academic works
T11	Multimedia information
T12	INPC projects

Review of themes, definition and name of themes. After an in-depth analysis, themes and subthemes are specified in greater detail according to the following table.

Table A.5 List of final themes.

Nro.	**Theme**
T1	Identified applications for the BCH-Ontology
T1.1	Intra-institutional integration in the Municipality of Cuenca within the cadastre department
T1.2	Inter-institutional integration to improve building intervention plans
T1.3	Inter-institutional integration with other governmental institutions

T1.4	Integration with other areas of interest.
T2	Identification of valuable stakeholders information
T2.1	Specific stakeholder information
T2.1	General stakeholder information
T3	Improvements and operational issues to the BCH-ontology
T3.1	Main focus to the 5 categories of cultural heritage
T3.2	Larger managements scales such as PITs and UAUs should be characterized
T3.3	Operational concerns related to the implementation of the BCH-ontology

Report production

Section 5.5 shows the produced final report as part of the knowledge use step during the validation of the BCH-ontology.

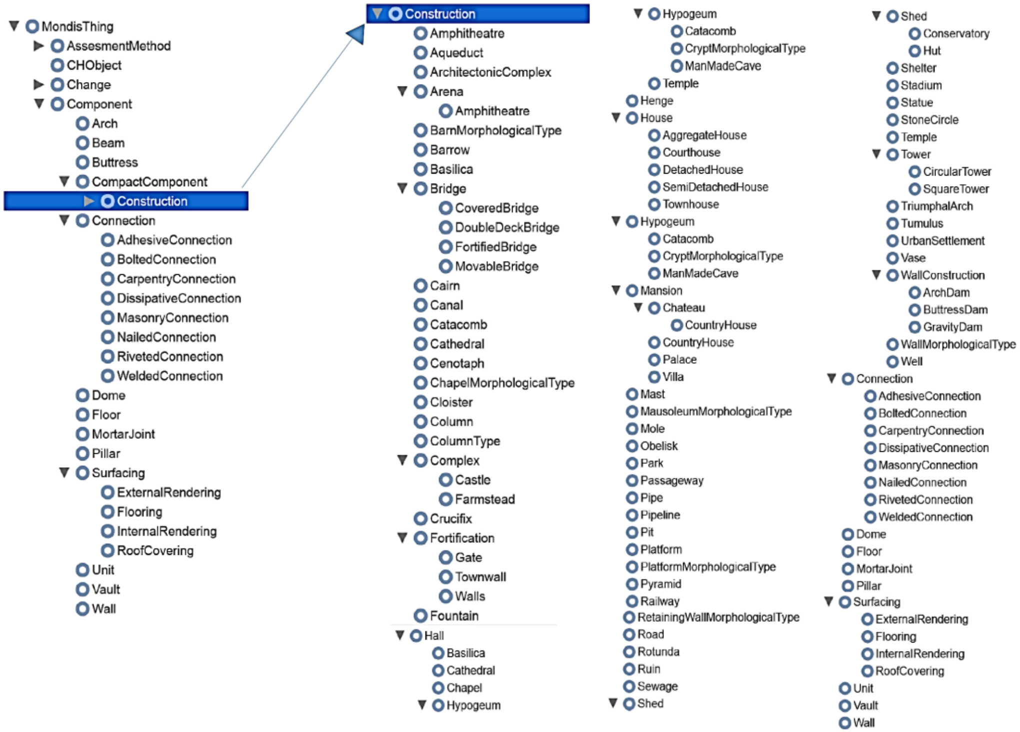


Figure A. 10 MONDIS taxonomy for components.

Curriculum

Olga Zalamea Patiño is an ecuadorian systems engineer, graduated from the University of Cuenca in 2008. She obtained her Master of Science degree in Computer Science from Shippensburg University, Pennsylvania, USA in 2011. Since 2014 she is a doctoral researcher at the Spatial Applications Division Leuven (SADL), Belgium. Her research focuses on the application of semantic technology in the management of cultural heritage at the urban level through a case study in Cuenca-Ecuador, where the construction of an ontology for heritage management is proposed. Since 2012, she has worked in the CPM research group at Univiersity of Cuenca. Her work focuses on the organization of the 14th World Congress on Earthen Architecture: Terra2025.

Personal information

Name:	Olga Piedad Zalamea Patiño
Nationality:	Ecuadorian
Date and place of birth:	July 21st, 1982. Cuenca, Ecuador
Home address:	Leopoldo Dávila 2-87. Cuenca, Ecuador. P.O. box 010207
Office address:	Facultad de Arquitectura, Universidad de Cuenca, Av. 12 de Abril, Cuenca, Ecuador. P.O. box 010101
Telephone:	+593 (0) 98-011-9156
Email address:	olga.zalamea@gmail.com

First author publications

1. Zalamea, O., Barsallo, G., Achig-Balarezo, M.C. (2021). Impacts from “Las Herrerias” maintenance campaign on the community. In García, G., Vandesande, A., Cardoso, F., & Van Balen, K. (Eds.). The Future of the Past: Paths towards Participatory Governance for Cultural Heritage (1st ed.). CRC Press.

2. Zalamea Patiño, O., Van Orshoven, J., Steenberghen, T. (2018). Knowledge-based representations applied to built cultural heritage. In: K. Van Balen, A. Vandesande (Eds.), Innovative Built Heritage Models: vol. 3, (93-100). Presented at the International conference on innovative built heritage models and preventive conservation, Leuven, 06 Feb 2017-08 Feb 2017. London. ISBN: 9781138498617.

3. Zalamea Patiño, O., Van Orshoven, J., Steenberghen, T. (2017). Merging and expanding existing ontologies to cover the Built Cultural Heritage domain. Journal of Cultural Heritage Management and Sustainable Development, 8 (2), 162-178. doi: 10.1108/JCHMSD-05-2017-0028.

4. Zalamea Patiño, O., Van Orshoven, J., Steenberghen, T. (2016). From a CityGML to an ontology-based approach to support preventive conservation of built cultural heritage. In: Proceedings of the 19th AGILE International Conference on Geographic Information Science, (Paper No. 165). Presented at the AGILE International Conference on Geographic Information Science, Helsinki, 14 Jun 2016-17 Jun 2016. Belgium. ISBN: 978-3-319-33782-1.

5. Zalamea Patiño, O., Heras, V., Tirry, D., Steenberghen, T. (2014). Ontologies as an integration tool for preventive heritage conservation. Presented at the Preventive and planned conservation conference, Monza and Mantua, Italy, 05 May 2014-09 May 2014.

Co-Author publications

6. Sinchi, E.; Jara, A.; Caldas, V.; Zalamea, O. (2022) Conceptual development of an information systemfor the management of the documentation generated in the preventive conservation process. Case study: Cuenca-Ecuador. Presented at the REHABEND 2020 Conference. ISSN: 23868198

7. Steenberghen, T., Dangol, A., Dewaelheyns, V., Zalamea Patiño, O., Van Orshoven, J. (2015). Linked OpenData for spatial monitoring. Presented at the IGU Regional Conference 2015, Moscow, Russia, 17 Aug 2015-21 Aug 2015.

8. Heras, V., Steenberghen, T., Zalamea Patiño, O. (2014). A GIS based tool for a Preventive Conservation Management Approach. In: K. Van Balen, A. Vandesande (Eds.), Reflections on preventive conservation, maintenance and monitoring by the PRECOM^{3}OS UNESCO chair, (86-93). Presented at the Reflections on Preventive Conservation, Maintenance and Monitoring of Monuments and Sites - PRECOM3OS UNESCO Chair, Leuven, 23 Jan 2013-25 Jan 2013. Leuven. ISBN: 9789033493423.

Professional experience

Researcher, July 2023 - present
CPM World Heritage City research group, University of Cuenca, Cuenca - Ecuador

- International coordination and organization of the Terra 2022 World Congress on Earthen Architecture

System technician, December 2022 – May 2023
Municipality of Cuenca, Ecuador

- Geographic information management.
- Design and development of heritage information management software.
- Creation of a technological plan for the management of heritage assets for the city of Cuenca.

Researcher, March 2019 - Dec 2022
CPM World Heritage City, University of Cuenca, Cuenca - Ecuador

- Specialized consultancy in information systems and scientific media.
- Design of the digital dissemination platform for the events.
- Advice and training in the use of scientific platforms.

PhD Student, Jul 2014 -present
KULeuven, Louvain - Belgium

- Research topic: Merging and expanding existing ontologies to cover the built cultural heritage domain; Case study Cuenca, Ecuador

Researcher, October 2012 - Jun 2014
VLIR-CPM World Heritage City, Cuenca - Ecuador

- Development of a web module for the visualization of heritage information collected at the Catalog level.
- Support in the validation of data models.
- Generation and processing of thematic and geospatial data.

Full time professor, September 2012 - Jun 2014
University of Cuenca, Cuenca - Ecuador

- Teaching the subjects: Database I, Database II, Computer Organization, Discrete Mathematics, and Algebra.

Part-time professor, September 2011 - August 2012.
University of Cuenca, Cuenca - Ecuador

- Teaching the subjects: Database I, Database II, Discrete Mathematics, Algebra and Introduction to databases.

Instructor, October 2010 - April 2011
McCann, School of Business and Technology, Shippensburg – PA.

- Teaching subjects: Introduction to Computing, Operating Systems, Hardware and Networking.
- Preparing students for A+ certification.

Applications Programmer, July 2010 - May 2011
GDC (Global Data Consultants), Shippensburg - PA

- Gathering client information.
- Researching best development practices.
- System analysis and design.
- Coding, debugging, test control and documentation of systems with Rational and Websphere MQ.

FACULTY OF SCIENCE
DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCE
GEOGRAPHY AND TOURISM DIVISION
Street 00 box 0000
Celestijnenlaan 200E
B-3001 HEVERLEE, BELGIUM
Olga.Zalamea@kuleuven.be
https://ees.kuleuven.be