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Merging and expanding existing ontologies to cover the Built Cultural Heritage domain

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Abstract

Purpose – The purpose of this paper is to present the development of an ontological model consisting of terms and relationships between these terms, creating a conceptual information model for the Built Cultural Heritage (BCH) domain, more specifically for preventive conservation.

Design/methodology/approach – The On-To-Knowledge methodology was applied in the ontology development process. Terms related to preventive conservation were identified by means of a taxonomy which was used later to identify related existing ontologies. Three ontologies were 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 were defined as to provide a complete semantic framework for management of BCH.

Findings – A BCH-ontology for preventive conservation was created. It consists of 143 classes from which 38 originate from the Mondis ontology, 38 from Geneva CityGML, 37 from CIDOC-CRM and 30 were newly created. The ontology was applied in a use case related to the New cathedral in the city of Cuenca, Ecuador. Advantages over other type of systems and for the BCH-domain were discussed based on this example.

Research limitations/implications – The proposed ontology is in a testing stage through which a number of its aspects are being verified.

Originality/value – This ontological model is the first one to focus on the preventive conservation of BCH.

Keywords CIDOC-CRM, BCH-ontology, CityGML, Mondis

Paper type Research paper

1. Introduction

1.1 Management of BCH

Management of information about Built Cultural Heritage (BCH) requires the involvement of multiple disciplines, actors, data sources and systems, creating a complex schema integration problem (Doerr, 2009). Several international charters, such as the Athens (ICOMOS, 1931), Venice (ICOMOS, 1964), and Burra (ICOMOS, 2003) charters, recommend applying a preventive conservation approach for BCH. Preventive conservation of BCH suggests conservation actions considering not only the assessment of state but also periodic assessments of risks and threats. It is meant to facilitate early damage detection by addressing the deterioration causes so that intervention can be kept to a minimum (Forster and Kayan, 2009).

Preventive conservation (Figure 1) is described in the ICOMOS Charter – principles for the analysis, conservation and structural restoration of architectural heritage (ICOMOS, 2013).

There is a plethora of information generated when preventive conservation approach is applied. This information is managed with the help of technology, such as Geographic

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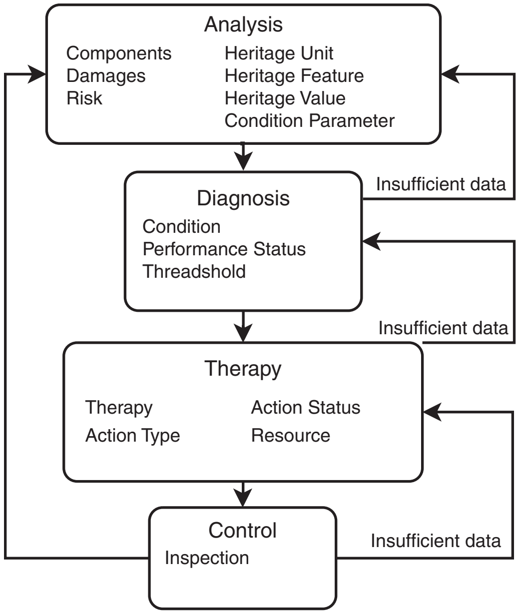


Sources: ICOMOS (2013) and Heras *et al*. (2013)

Figure 1. Preventive conservation approach and required information

Information System (GIS) (Bello, 2017). Three-dimensional modeling standards (Kolbe, 2009) are also widely used. Moreover, there is an increasing necessity to integrate and share all types of data (Hart, 2008). Ontologies are increasingly used to overcome barriers to data sharing and integration.

1.2 Ontological approach

According to Antoniou and Van Harmelen (2004), an ontology consists of a finite list of terms and the relationships between these terms, creating a conceptual model for a specific domain. Axioms are used to represent the relationships between the terms and to add a logic layer to the conceptual model.

We conducted a search for the identification of already developed ontologies aligned with the terms used in the preventive conservation approach. The search returned three ontologies: the CIDOC Conceptual Reference Model (CIDOC-CRM) (Doerr, 2009), the Geneva City Geographic Markup Language (Geneva CityGML) (Kolbe, 2009), and the Monument Damage ontology (Mondis) (Cacciotti *et al.*, 2013).

The CIDOC-CRM is a formal ontology developed by the International Council of Monuments through its International Committee for Documentation. It is intended to facilitate integration, and interchange of heterogeneous cultural heritage information. Although the scope of CIDOC-CRM is the description and maintenance of museums artifacts, several of its terms can be used to describe historical buildings. Geneva CityGML ontology is developed by the University of Geneva in Switzerland. It can be considered to be an ontological equivalent of the CityGML standard. The incorporation of this ontology allows to create 3D models of historical buildings. The Monument Damage ontology was developed in the framework of the Mondis research project that supports the documentation and analysis of monument damages.

These three ontologies complement each other, since each one covers a different aspect of BCH. Heritage values and heritage features are not represented by any of these listed ontologies but the applicable terms were implemented and merged resulting in the BCH-ontology.

The paper is structured as follows: Section 2 presents the information needs for preventive conservation of the management actors in the World Heritage city of Cuenca, Ecuador. Section 3 presents the methodology used to build the ontological model. Section 4 presents a selection of relevant classes and properties of the model. Section 5 presents a practical application of the ontology. Finally, section 6 summarizes the current findings of the research.

2. BCH-management in Cuenca – Ecuador: information needs for preventive conservation

The World Heritage City Preservation Management (VlirCPM) research project at the University of Cuenca operates under the UNESCO PRECOM3OS Chair. PRECOM3OS is a UNESCO chair on "preventive conservation, maintenance and monitoring of monuments and sites." It aims at providing the diverse audience's reflection on the framework of preventive conservation, so to support the activities of the establishing chair. Furthermore, its goal consists in establishing a forum for an active and updated exchange of the latest research results as well as on the needs and the feedback from the practice in fields related to preventive conservation (PRECOMOS, 2009).

The National Institute of Cultural Heritage (INPC) and the Municipality of Cuenca are governmental organizations that are in charge of preventive conservation. They work closely with the VlirCPM research project to execute maintenance campaigns and develop tools to manage the cultural heritage. After testing the tools in small areas, the municipality applies them at city level.

These organizations manage their information differently. The INPC has developed the "Sistema de Información del Patrimonio Cultural Ecuatoriano (SIPCE)" which is a personalized web application where general data and geographic location of heritage items can be consulted (INPC, 2014). The municipality of Cuenca has a Geoportal with maps from several administrative departments. The "historic and heritage areas" department has made available information related to construction permits and penalties for the historic buildings in the city (Cuenca GAD Municipal, 2016).

Having these organizations managing the BCH-assets of the city creates an integration problem, since there are no agreements on the standardization, the exchange or the sharing of the information each of them generates. Even GIS technology which is predominant in the field cannot be considered as a standard, since it is specialized in spatial information and BCH-data encompass a wide range of data types, such as audio, video, photography, relational databases, etc. The VlirCPM project researches solutions to improve preventive conservation through better information, i.e. by data sharing. The project manages its information internally through the use of relational databases, GIS, aerial images, etc.

A CityGML-ADE model was developed by the VlirCPM project through several interviews and workshops with representatives of the INPC, the Municipality of Cuenca, citizens, tourists and researchers. Basically, the CityGML-ADE model (Figure 2) merges the general purpose classes of the CityGML-Building module with specific purpose classes required for implementing a preventive conservation approach. The main classes in the CityGML-Building module enable a 3D representation of buildings and their components, such as walls, roofs, etc., whereas the preventive conservation classes allow the identification of building's heritage values, condition and risks.

The CityGML-ADE does not provide sufficient semantics for a proper BCH-management. A semantic approach can facilitate harmonization and data discovery through the use of inferences. The harmonization of the stakeholders' data sets and the data discovery will allow early analysis of the built heritage in Cuenca.

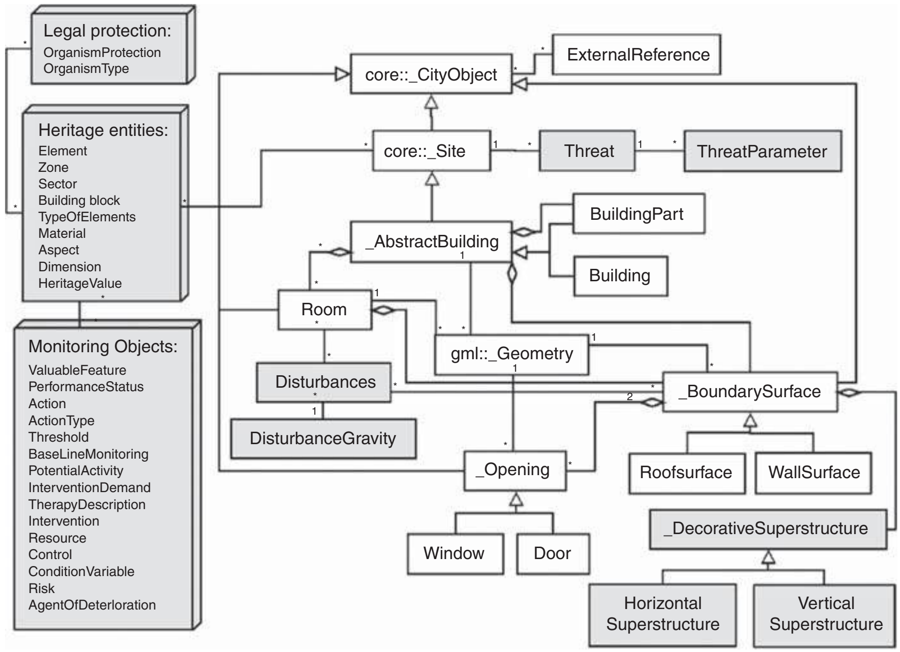


Figure 2.
Summary of the CityGML(white) + ADE (gray)

3. Methodology

3.1 Ontological engineering

The BCH-ontology was constructed according to the On-To-Knowledge Methodology which consists of two components: the Knowledge Meta process and the Knowledge process. The Knowledge Meta process leads to the construction of the ontology, while the Knowledge process specifies activities to populate and test the ontology.

In line with Staab and Studer (2009), the On-To-Knowledge methodology is chosen because of its clarity, well-elaborated definitions and its iterative and incremental characteristics. Its iterative and incremental features allow us to create several prototypes that are improved in any phase of the process which leads to an agile ontology development. For all these reasons, we have chosen this methodology. This paper is limited to the application of the Knowledge Meta process.

3.2 Application of the knowledge meta process to the study case

The Knowledge Meta process has been executed through two iterations. Figure 3 shows the steps taken in each iteration.

Feasibility study 0. This step identifies the problem, the opportunity areas and the potential solutions. Applying an ontological approach provides means to overcome the limitations of the CityGML-ADE model. This will bring some benefits to practitioners in the BCH-domain (Carlisle *et al.*, 2014), such as mitigating the lack of standardization in recording heritage information, accessing and sharing adequate information with stakeholders in time to mitigate risks and enriching original data sources with external data sets.

Kickoff 0-1. This step captures requirement specifications. A semi-formal description of the ontology was created by means of a taxonomy (Figure 4) derived from the CityGML-ADE model. The taxonomy was created using Protégé, a free open-source suite of tools to construct domain models and knowledge-based applications with ontologies (Stanford Center for Biomedical Informatics Research, 2015).

Initially, the source taxonomy included just the name of the classes from the CityGML-ADE model. In a second iteration, the attributes from the CityGML-ADE model were added to the taxonomy. The final taxonomy was extended from 52 classes to 143 classes.

A second activity in the kickoff step is to look for already developed ontologies. The search was performed using literature, catalogues and search engines recommended by the World Wide Web Consortium (W3C): Linked Open Vocabularies, Swoogle and Falcons (Davies *et al.*, 2006). The search was concluded with the selection of 22 knowledge-based representations.

Refinement 0-1. In this step, the semi-formal ontology description is refined by adding concepts and describing relations and a target ontology is formalized.

In this step, the knowledge-based representations were evaluated. The following criteria were used: availability (is the ontology downloadable?); completeness (number of matching terms between the source taxonomy and the ontology); creator provenance and reputation (is the creator trustful?); understandability (is the ontology clear?). Finally, additional criteria, such as the amount of data, the number of incoming and outgoing links, were added when

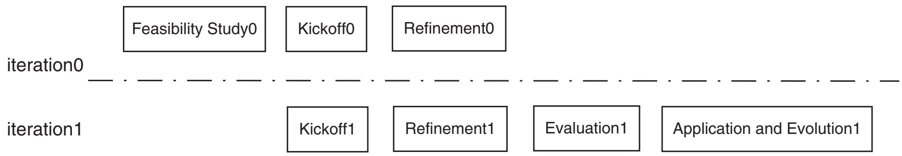


Figure 3.
Iterations performed for the Knowledge Meta process

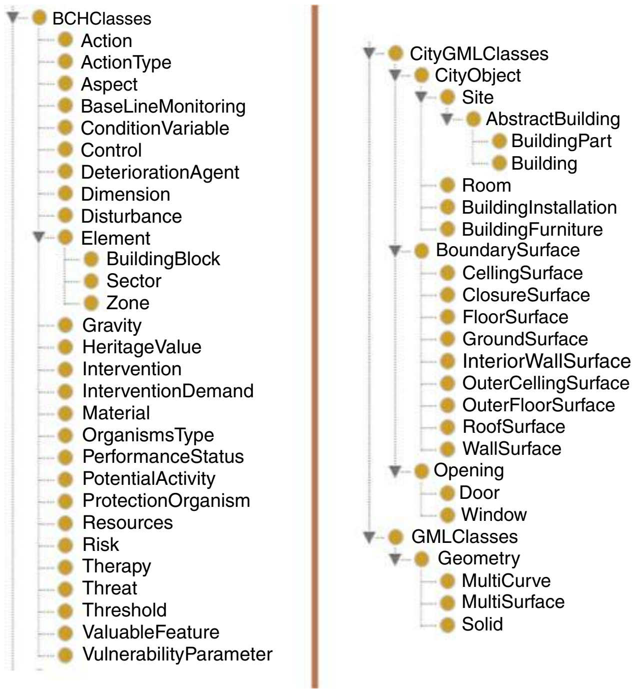


Figure 4.
Basic taxonomy for the BCH-domain

several ontologies were found to be equivalent. As a result of the evaluation activity, two major ontologies were identified in the first iteration: Geneva CityGML and Mondis. The second iteration allowed the identification of the CIDOC-CRM ontology.

Evaluation 1. In this step, the target ontology is evaluated to ensure that it will satisfy the requirement specifications. Figure 5 shows the formalized target BCH-ontology which covers all the source taxonomy classes. In this regard, the BCH-ontology is able to represent all the domain information. In addition, the ontology is capable to overcome the limitations of the initial CityGML-ADE model.

Application and Evolution 1. In this step, the ontology is built based on the conceptual model shown in Figure 4. The final model consists of an ontology with 143 classes, out of which 38 are from Mondis ontology, 38 from Geneva CityGML, 37 from CIDOC-CRM, and 30 new classes have been added.

The ontology was implemented using Protégé (Stanford Center for Biomedical Informatics Research, 2015) and is available at "https://github.com/BCHOntology/BCHOntology." In the following section, the main classes of the BCH-ontology are explained.

4. The BCH-ontology model

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

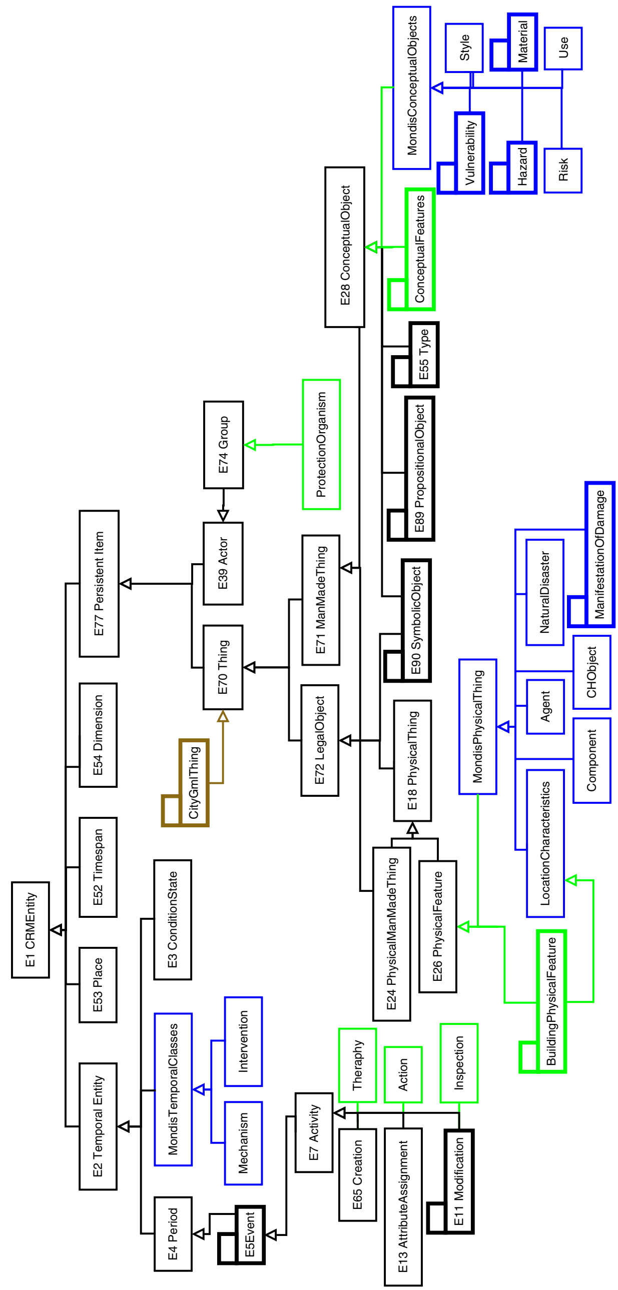
4.1 The BCH-ontology and the preventive conservation approach

In this section, the BCH-ontology classes are explained with reference to the preventive conservation approach steps (Figure 1). Table AI explains the terminology used in the following figures.

Analysis. In the analysis step, information regarding heritage units is collected. A heritage unit can be a single building, bigger geographic areas or the whole city. In Geneva CityGML, there are two classes to represent heritage units, namely "Building" and "_CityObjectGroup," while Mondis implements just the class "CHObject". We added the "E55 Type" subclass called "HeritageUnitType" in order to identify the type of heritage unit being referenced by "CHObject". The heritage unit information collected encompasses heritage values, condition variables, damages, and risks (Figure 6).

A subclass was added to "E89 PropositionalObject" for the representation of heritage values. The class "E89 PropositionalObject" comprises immaterial items that represent sets of propositions about real or imaginary things and that are documented as single units. The "HeritageValue" class refers to the "value" assigned to a heritage unit. The property "hasValue" is used to express the valorization. The general property "has note" can be used to add a description of the heritage value.

Heritage values are allocated because the heritage unit has features with a heritage impact. Heritage features can be represented by the classes "E26 Physical Features" or "ConceptualFeatures." "E26 Physical Features" comprise identifiable features that are physically attached in an integral way to particular physical objects. "ConceptualFeature" represents immaterial features related to a persistent item. The property "bearsFeature" assigns a physical feature to an instance of the "E19 PhysicalObject" class. The property



Notes: Blue: Mondis classes; black: CIDOC-CRM; brown: CityGML; green: newly developed BCH classes

Figure 5.
Target BCH-ontology model

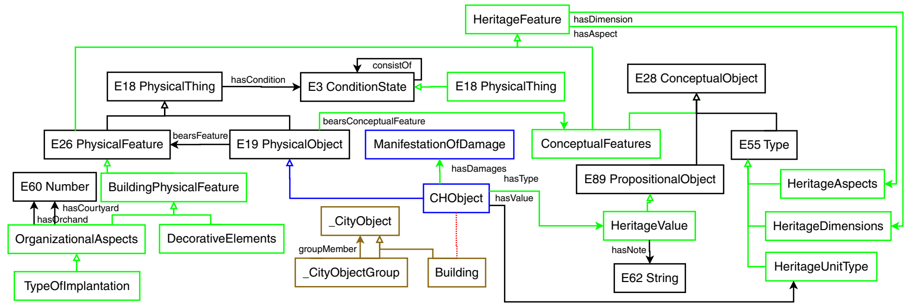


Figure 6.
Analysis step: heritage values and condition classes

Notes: Blue: Mondis classes; black: CIDOC-CRM; brown: CityGML; green: newly developed BCH classes

"bearsConceptualFeature" links the physical object with the conceptual features. The class "CHObject" inherits these properties because it is a subclass of "E19 PhysicalObject."

In the case that the heritage unit is a single building, there is a specification of physical features, such as "OrganizationalAspects" or the presence of "Decorative Elements." A subclass of "OrganizationalAspects" is "TypeOfImplantation." The Organizational Aspect class also has the properties "hasCourtyard" and "hasOrchand."

Heritage features are associated to one or many heritage aspects and dimensions. The properties "has Aspect" and "hasDimension" link the Aspect and Dimension to the feature.

For the case of the city of Cuenca, supplementary variables were identified which influence the condition of a heritage unit. For this reason, the class "ConditionVariable" was created. Condition variables are related to the general condition state with the property "consistOf." The property "hasDamages" links damages to the condition class, since the condition is derived from damages. During the analysis, condition variables are recorded, and in the following phase, the general condition is computed using these variables.

For the representation of damages, the class "ManifestationOfDamage" from the Mondis ontology is used. Mondis classifies damages present in a component or in the material covering the component, and then further classifies the type of damages that may exist, as shown in Figure 7. Damages are caused by a deterioration agent that can be specified

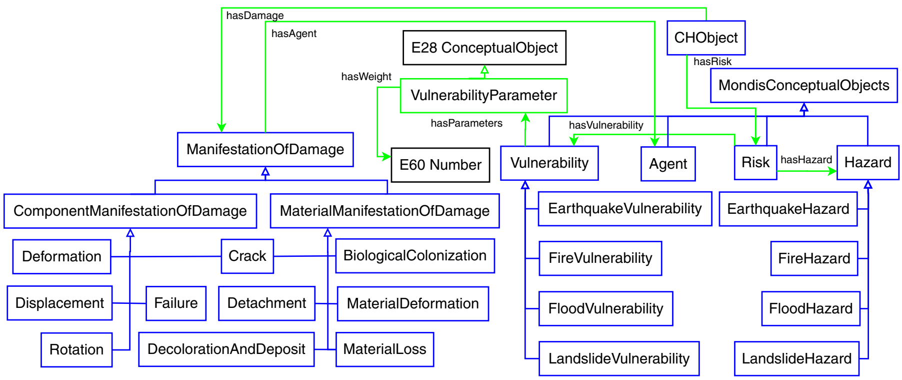


Figure 7.
Analysis step: damage and risk classes

Notes: Blue: Mondis classes; black: CIDOC-CRM; brown: CityGML; green: newly developed BCH classes through the class “Agent” and the property “has Agent.” The property “hasDamage” links the damage to the heritage unit.

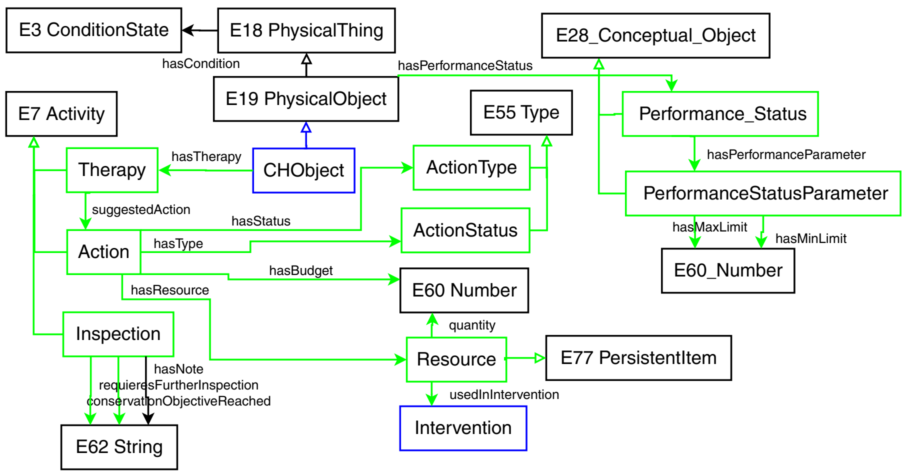
Risk assessment is a crucial activity for the preventive conservation management of historical buildings. There are several methodologies for risk assessment but basically the risk is computed by assessing Threats and Vulnerabilities (Jimenez, 2001; Meul, 2008). These elements are related to carrier objects. For example, a threat is linked to a possible affected area and the vulnerability is related to the heritage unit which is vulnerable against the threat. The Mondis ontology provides classes for “Risk” and “Vulnerability,” while threats are represented with the class “Hazard.” The properties “hasVulnerability” and “hasHazard” link these classes with the class “Risk.” Mondis also further classifies hazards and vulnerabilities with respect to earthquakes, fire, floods and landslides. To compute the vulnerability, the condition of the heritage unit and damages are also considered. The risk is related to the heritage unit through the property “hasRisk.”

For the particular case of Cuenca – Ecuador, a new class “VulnerabilityParameter” was created. These parameters are accompanied by a weight, since not all the parameters have the same importance, therefore the property “hasWeight” has also been added. The property “hasParameters” relates the parameters to the vulnerability class.

Diagnosis, therapy, and control. During the diagnosis step, the condition and the performance status are computed based on predefined parameters.

The condition of a heritage unit can be recorded through the class “E3 Condition State,” of which the instances are general statements about the physical condition of the heritage unit over a time-span. The condition state is related to the “E18 PhysicalThing” class through the property “has condition.”

The “Performance Status” and “Performances Status Parameters” classes have been added under “E28 Conceptual Object” class. The property “hasPerformanceStatus” links the heritage unit to the performance status and the property “hasPerformanceParameter” links the performance status with its parameters. The properties, namely “hasMaxLimit” and “hasMinLimit,” establish the limits or thresholds for the performance status parameters (Figure 8).



Notes: Blue: Mondis classes; black: CIDOC-CRM; brown: CityGML; green: newly developed BCH classes

Figure 8.
Diagnosis, therapy and control steps

After computing the performance status, a set of actions are selected. The class "Action" was created under the class "E7 Activity." Actions can be classified as Curative or Preventive. The preventive actions are subdivided into direct and indirect. These classifications are represented through a specialization of the class "E55 Type" called "ActionType." An action also has a budget associated to it. The property "hasBudget" is used for this matter. A second classification of actions is called "ActionStatus." This status changes from "demand of intervention," to "suggested action," and to "executedAction." After checking the feasibility of the suggested action, the status changes to "suggestedAction." The property "hasTherapy" links the therapy with the heritage unit.

The Mondis class "Intervention" is used to keep track of the suggested actions applied to the heritage object. The "ActionStatus" class instantiated as "executedAction" means that the suggested therapy actions were executed in the intervention. The property "hasResource" links the resources used during the execution of the action. The "Resource" class is a "E77 persistent item"; the property "usedInIntervention" specifies the intervention where the resource was used and the property "quantity" specifies the used amount.

The control stage ends with several inspections which verify whether the actions reached the conservation objective. The class "Inspection" was created under "E7 Activity" class. The property "requiresFurtherInspections" is established if more control activities are required. The property "conservationObjectiveReached" points out if the conservation objective has been reached. Additional notes can be added through the general property "hasNote." The property "hasInspection" links the inspection to a therapy.

4.2 Spatial classes

As mentioned before, CityGML is a standard for spatial representation. We used the ontological version of this standard developed by the University of Geneva (Métral and Cutting-Decelle, 2011). This standard provides means to represent different city elements, such as buildings, tunnels, bridges, water bodies, etc. Within the scope of this research, only the building module is used even if all the modules are available in ontological form. The city objects can be represented with more or less specifications depending of the level of detail (LOD) that is used. Figure 9 shows the classes used in this research.

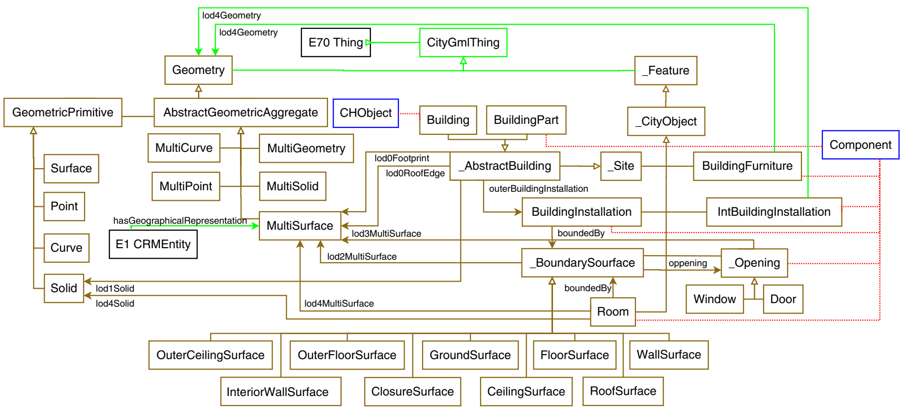


Figure 9.
Spatial classes

Notes: Blue: Mondis classes; black: CIDOC-CRM; brown: CityGML; green: newly developed BCH classes

LOD0 represents a building as a set of 2.5-dimensional surfaces: for example, one surface for the footprint of the building and other for the roof edge. The properties "lod0Footprint" and "lod0RoofEdge" are used for this purpose.

LOD1 represents the outer shell of the building as a block. The property "lod1Solid" associates a building with a gmlSolid.

LOD2 allows the representation of architectural details, like roof overhangs, columns, or antennas. The class used to represent these details is the "BuildingInstallationClass." Its geometry is represented by the class "BoundarySurfaces" which is a collection of "multiSurface" geometries. Architectural details are linked to the building through the property "outerBuildingInstallation," while the architectural detail is related to the boundary surface with the property "boundedBy" and the boundary surface is related to the multiSurface with the property "lod2MultiSurface."

LOD3 adds openings such as doors and windows using the multiSurface class with the property "lod3MultiSurface." A BoundarySurface shows the presence of an opening by using the property "opening."

LOD4 provides the highest LOD, incorporating the interior of the building. New elements as rooms, furniture, and interior building installations can be represented. A room can be represented as a solid or a set of multiSurfaces through the properties "lod4Solid" or "lod4MultiSurface." Also, a room can be related to a boundary surface through the property "boundedBy." The geometry of furniture and interior building installations are assigned using the property "lod4Geometry" which basically relates any set of geometries to the class.

In addition to the representation of buildings, the BCH-ontology also provides means to represent new spatial elements, such as areas related to several thematic classes. For example, flood hazard is identified to be higher on the border of rivers; location can be represented with surfaces of the geographical area; and cultural traditions are associated to some geographical areas more than to others. To represent this information, the property "hasGeographicalRepresentation" connects the "E1 CRMEntity" with the multiSurface class of the Geneva CityGML ontology.

The property "same as" was established between a number of classes in the ontology, e.g. between the "Building" class from Geneva CityGML and the "CHObject" class from Mondis. This means that the three-dimensional representation explained in this section for building also applies for "CHObjects." The same can be said about components and building parts, building installations, building interior installations, rooms and opening (Figure 10).

4.3 Temporal classes

For the representation of temporal entities, only Mondis classes are used. The class "E61 Time primitive" is an empty class that has not been further developed. Its purpose is to provide the means to integrate a time ontology such as the one developed by W3C and OGC (OGC and

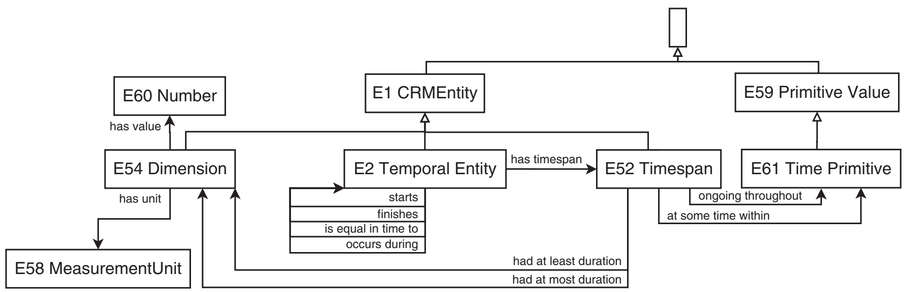


Figure 10.
Temporal classes

W3C, 2017). For the purpose of this paper, the classes and properties related with temporal entities are described assuming that the time primitive is defined by the time ontology.

The class "E52 Time-Spans" defines periods of time where some phenomenon was active. The property "ongoing throughout" establishes the precise period where the phenomenon happened. The property "at some time within" expresses a longer period of time than the actual period where the phenomenon happened. Other important properties are "had at least duration" and "had at most duration" which describe the duration of a phenomenon through the class "E54 Dimension" which can represent time primitives with a value and a measurement unit, e.g. value = 3, measurement unit = months.

The class "E2 TemporalEntity" comprises phenomena that happen over a limited period of time. The property "has time-span" relates a period of time with the temporal entity. The period of time where a phenomenon was active can be described by different relationships between temporal entities. For example, when two temporal entities have the same duration, the property "is equal in time to" can be used. If a temporal entity causes the beginning or end of another temporal entity, the properties "finishes" and "starts" are used. These properties are especially useful to describe cause and effect. Finally, the property "occurs during" is used to describe inclusion of temporal entities, which means that the temporal entity starts before and ends after another one.

In the BCH-domain, these temporal classes and properties are useful to describe sequences of activities and to keep track of the evolution of the cultural assets. For example, the changes in the condition state of a heritage unit during a period of time can be compared with the curative actions performed to help BCH managers to identify the actions causing better and faster effects.

5. BCHO-ontology example

Figure 11 shows the application of a subset of classes of the BCH-ontology for the New Cathedral of Cuenca. In this example, we documented the events: a heritage value, a heritage feature, and a damage.

The New Cathedral is a building with an "exceptional" heritage value. The "Form and design" of the cathedral show an important heritage feature: 3 domes with a high "artistic" dimension. Also, a crack was documented.

The CityGML-ADE model has some limitations that can be overcome by the use of ontologies. We will further illustrate how ontologies can overcome these limitations.

Ontologies store the information in triplets: subject-predicate-object. This means that all the information is stored in the same generic structure. Figure 12 (left) shows how to query all the information available about the heritageValue class; then the query is modified to get the information about heritageFeature (Figure 12, right).

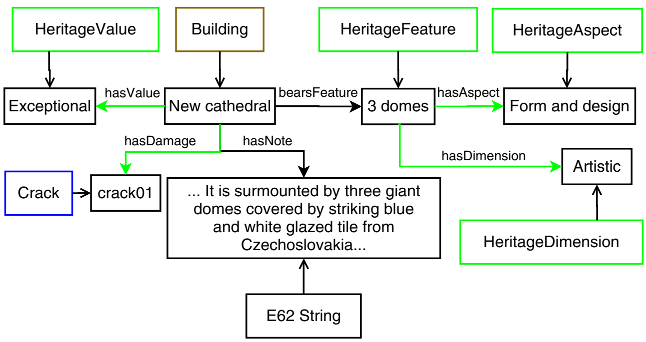


Figure 11.
BCH-ontology application

From this example, we can see that HeritageValue is a subclass of "E89 Propositional Object" and that HeritageFeature is subclass of "E55 Type." In this case, BCH stakeholders can publish their information online and other stakeholders can use this information without prior knowledge of the way the information is structured.

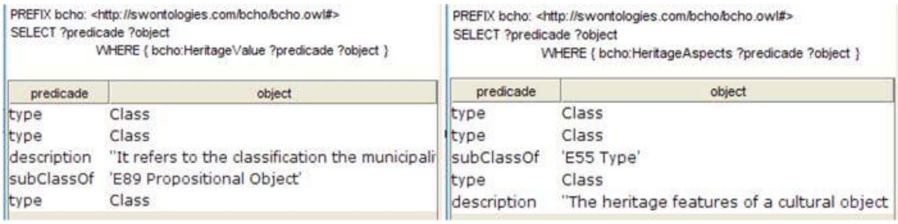
Data sets store information in predefine structures i.e. tables. To query this information, the user has to be well aware of the structure, e.g. the heritage value could be stored in the cathedral's general information table or in an independent table.

Modification of the models becomes easier because the storage structure never changes and modifications can be done by adding or removing triplets. Figure 13 shows the incorporation of open public spaces as heritage units. The classes and properties available for the other heritage units can be reused, such as condition, features, etc. Finally, new classes can be created to represent the specificities of public spaces, such as facilities, parking spaces, furniture, etc. The advantage compared with traditional systems is that the ontology can be used while the changes are made.

In an ontological approach, data from two heterogeneous data sets can be harmonized by adding triplets between the two data sets (Figure 14). The predicate "same as" aligns the record in both data sets. The logical rule allows the ontology to show the damages of the components when the damages in a building are queried.

The previous example shows damages in building inferred by the use of a logical rule. Also, in Figure 11, the cathedral is an instance of the "Building" class that is using the property "hasValue" which belongs to the class "CHObject." We infer that the use of the property is possible, since "Building" is a subclass of "CHObject."

These examples illustrate that the ontology provides a standard for data sharing that includes spatial data as well as the terms related to the BCH-domain. When the stakeholders implement their applications online, they can provide an ontological version of their information allowing use by other users.



```
PREFIX bcho: <http://swontologies.com/bcho/bcho.owl#>
SELECT ?predicade ?object
        WHERE { bcho:HeritageValue ?predicade ?object }
```

predicade	object
type	Class
type	Class
description	"It refers to the classification the municipali
subClassOf	'E89 Propositional Object'
type	Class

```
PREFIX bcho: <http://swontologies.com/bcho/bcho.owl#>
SELECT ?predicade ?object
        WHERE { bcho:HeritageAspects ?predicade ?object }
```

predicade	object
type	Class
type	Class
subClassOf	'E55 Type'
type	Class
description	"The heritage features of a cultural object

Figure 12. Querying information related to heritageValue and heritageFeature

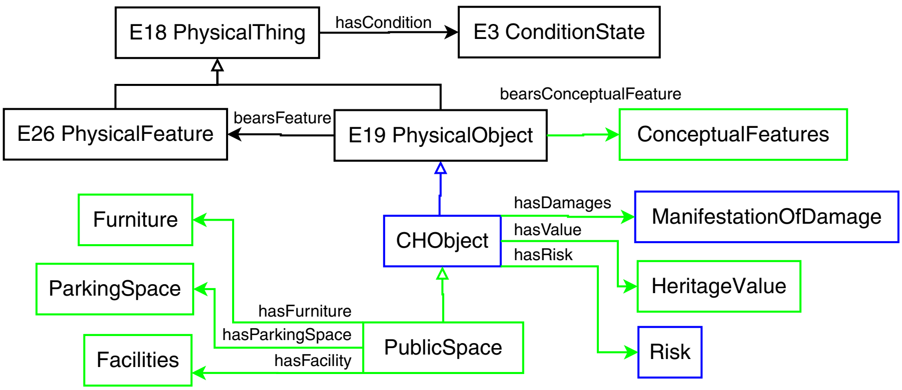


Figure 13. PublicSpace class added as a new heritage unit

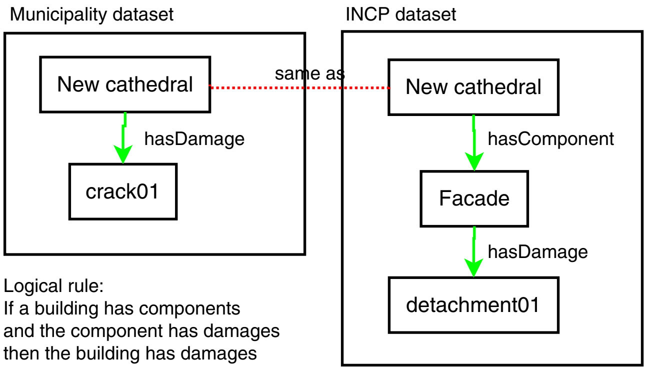


Figure 14.
Harmonization of heterogeneous data sets

The BCH-domain can also benefit from external semantic data sets, such as DBpedia and GeoNames. DBpedia is the ontological version of Wikipedia and GeoNames is a world geographic gazetteer.

The following triplets link the cathedral with the information contained in DBpedia and GeoNames:

- New cathedral – same as – http://dbpedia.org/page/New_Cathedral_of_Cuenca
- New cathedral – located – www.geonames.org/3658666/cuenca.html

The ontology can be used by any BCH-stakeholder, since it consists of general classes from the preventive conservation. Each city may make the modifications necessary to adapt to their reality.

Although the BCH-ontology entails clear benefits for the BCH-domain, it also has some limitations. First, the ontology is in a testing stage where some of its aspects are being verified. Once fully tested, it can further evolve toward a tool to support the decision making of BCH stakeholders. Second, a number of concepts have not been implemented in the ontology. A possible further elaboration is the inclusion of economic values and their effect in the destruction of cultural heritage (Ost, 2012). At this moment, the ontology is able to characterize economic values in the context of the Nara grid, i.e. the economic indicators can be modeled as heritage features belonging to a specific aspect and dimension. However, the impact of these economic values in the management of the Cuenca BCH-assets is being researched (Garcia *et al.*, 2017). Once that the economics values and impacts are characterized and understood, they can be added to the model.

6. Conclusions

The BCH-ontology presented in this paper is based on the integration and expansion of three mature ontologies widely recognized by the domain practitioners: CIDOC-CRM, as the backbone of the BCH-ontology, describes general classes as temporal or persistent elements that can be further classified as physical or conceptual objects. Mondis provides the classes to represent damages and risk assessment. Finally, Geneva CityGML provides the spatial representation for historical buildings and their components. The final model consists of an ontology with 143 classes, out of which 38 originate from the Mondis ontology, 38 from the Geneva CityGML ontology, 37 from the CIDOC-CRM ontology and 30 new classes have been added.

The BCH-ontology and ontologies in general present improvements when compared with traditional database systems: easy modification of models without affecting previous versions; Heterogeneous data sharing; and most importantly, the use of inferences for data discovery.

The BCH-ontology also brings advantages for the management of BCH-assets: It provides a standard for sharing several types of information about BCH. This will improve the management of heritage cities like Cuenca, since the stakeholders will be able to use data from multiple organizations for their analysis. More specialized systems can be built with more specialized information supporting the decision-making process.

The BCH-ontology can also be used in related domains. The tourism and education fields could benefit from using the ontology and building informative applications, virtual tours, educational games, etc.

Once the ontology will be fully tested and validated, it will be a promising tool for BCH stakeholders. Future extensions and improvements can already be envisaged such as generation of inferences by means of complex logical rules and the addition of new features like economic values and open public spaces.

Glossary

BCH	Built Cultural Heritage
GML	Geographic Markup Language
ADE	Application Domain Extension
GIS	Geographic Information System
CIDOC-CRM	CIDOC Conceptual Reference Model
MONDIS	Monument Damage Ontology
ICOM	International Council of Monuments
INPC	Cultural Heritage National Institute
VlirCPM	World Heritage City Preservation Management
PRECOM3OS	Preventive conservation, maintenance and monitoring of the monuments and sites
SIPCE	Sistema de Información del Patrimonio Cultural Ecuatoriano
W3C	World Wide Web Consortium

References

Antoniou, G. and Van Harmelen, F. (2004), "A Semantic Web Primer", Massachusetts Institute of Technology, Cambridge, MA.

Bello, L. (2017), "Documenting the impact of socioeconomic dynamics on heritage sites. The case of Vista Alegre district in Santiago de Cuba", *ISPRS Annals of the Photogrammetry, Remote Sensisng and Spatial Information Sciences, 26th International CIPA Symposium*, IV-2/W2, pp. 31-38, doi: 10.5194/isprs-annals-IV-2-W2-31-2017.

Cacciotti, R., Valach, J., Kunes, P., Cernansky, M., Blasko, M. and Kremen, P. (2013), "Monument damage information system (mondis): an ontological approach to cultural heritage documentation", ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Science, presented at the XXIV International CIPA Symposium, Strasbourg, pp. 55-60.

Carlisle, P.K., Avramides, I., Dalgity, A. and Myers, D. (2014), "The arches heritage inventory and management system: a standards-based approach to the management of cultural heritage information", paper presented at the CIDOC (International Committee for Documentation of the International Council of Museums) Conference: Access and Understanding – Networking in the Digital Era, Dresden, September 6-11.

Cuenca GAD Municipal (2016), "Geovisor Municipal", WWW Document, Geovisor Munic, available at: http://ide.cuenca.gob.ec/geovisor/home.seam (accessed December 12, 2017).

Davies, J., Studer, R. and Warren, P. (2006), *Semantic Web Technologies – Trends and Research in Ontology-based Systems*, John Wiley & Sons.

Doerr, M. (2009), "Ontologies for cultural heritage", in Staab, S. and Studer, R. (Eds), *Handbooks on Ontologies*, Springer, New York, NY, pp. 463-486.

Forster, A. and Kayan, B. (2009), "Maintenance for historic buildings: a current perspective", Structural Survey, Bingley, pp. 210-229.

Garcia, G., Amaya, J., Bello, L., Ost, C. and Van Balen, K. (2017), "Adjusting economic estimation of cultural values of historical cities. The case of Cuenca, Ecuador and Santiago, Cuba", presented at the IV Encuentro precomos Patrimonio y desarrollo freste a las transformaciones, Cuenca, October 2-3.

Hart, G. (2008), "Linking to the past, geographically speaking: the linked data web and historical GIS", presented at the Workshop: "The Cultural Heritage of Historic European Cities and Public Participatory GIS", York, September 17-18, 2009.

Heras, V., Steenberghen, T. and Zalamea, O. (2013), "A GIS based tool for a preventive conservation management approach", in Van Balen, K. and Vandesande, A. (Eds), *Reflections on Preventive Conservation, Maintenance and Monitoring of Monuments and Sites – PRECOM3OS UNESCO Chair*, ACCO, Leuven, pp. 86-93.

ICOMOS (1931), "The Athens Charter for the restoration of historic monuments", WWW Document, available at: www.icomos.org/en/charters-and-texts/179-articles-en-francais/ressources/charters-and-standards/167-the-athens-charter-for-the-restoration-of-historic-monuments (accessed December 12, 2017).

ICOMOS (1964), "International Charter for the conservation and restoration of monuments and sites", WWW Document, available at: www.icomos.org/charters/venice_e.pdf (accessed December 12, 2017).

ICOMOS (2003), "The Burra Charter", The Burra Charter was first adopted in 1979 at the historic South Australian mining town of Burra, Minor revisions were made in 1981, 1988, 1999, 2013.

ICOMOS (2013), "Charter – principles for the analysis, conservation and structural restoration of architectural heritage", Victoria Falls (Zimbabwe), 2003, WWW Document, available at: http://orcp.hustoj.com/2016/04/02/icomos-charter-principles-fora-the-analysis-conservation-and-structural-restoration-of-architectural-heritage-2003/ (accessed December 12, 2017).

INPC (2014), "Sistema de Información del Patrimonio Cultural Ecuatoriano (SIPCE)", WWW Document, available at: http://patrimoniocultural.gob.ec/sistema-de-informacion-del-patrimonio-cultural-ecuatoriano-sipce/

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, Quito.

Kolbe, T.H. (2009), "Representing and exchanging 3D city models with CityGML", Lee, J. and Zlatanova, S. (Eds), *3D Geo-Information Sciences*, Springer, Berlin and Heidelberg, pp. 15-31.

Métral, C. and Cutting-Decelle, A.-F. (2011), "Ontologies for interconnecting urban models", Falquet, G., Métral, C., Teller, J. and Tweed, C. (Eds), *Ontologies in Urban Development Projects*, Springer, London, pp. 105-122.

Meul, V. (2008), "Safeguarding the significance of ensembles: value assessment in risk management for cultural heritage", presented at the ICOM Committee for Conservation 15th Triennial Conference, ICOM, New Delhi, pp. 1051-1058.

OGC and W3C (2017), "Time ontology in OWL", WWW Document, available at: www.w3.org/TR/owl-time/ (accessed April 12, 2017).

Ost, C. (2012), "Mapping heritage economics for spatial analysis in historic city cores", Licciardi, G. and Amirtahmasebi, R. (Eds), *The Economics of Uniqueness : Investing in Historic City Cores and Cultural Heritage Assets for Sustainable Development*, The World Bank, Washington, DC, pp. 245-282.

PRECOMOS (2009), "Preventive conservation maintenance and monitoring of monuments and sites", WWW Document, available at: http://precomos.org/ (accessed May 30, 2017).

Staab, S. and Studer, R. (Eds) (2009), *Handbook on Ontologies*, 2nd ed., Springer-Verlag, New York, NY.

Stanford Center for Biomedical Informatics Research (2015), "Protege", WWW Document, available at: http://protege.stanford.edu/about.php (accessed November 26, 2015).

Appendix

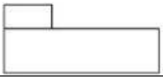
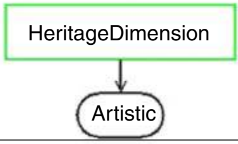
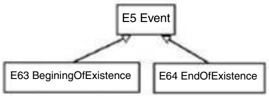
Term	Description
Class 	A class represents a category of items that share a number of common features. It is represented by a rectangle
Package 	A package represents a group of classes that shares some common characteristics
Instance 	A class or a property is instantiated when a value of the real world is assigned to it. For example "Artistic" is an instance of the class Heritage dimension. The value instantiated is represented by an ellipse. A single arrow points to the instantiated value
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 with head 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 instancesof 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
Knowledge-based representations	EncompassTaxonomies, Vocabularies and Ontologies
Taxonomy	A hierarchical structure of classes and subclasses representing terms of interest in a particular domain
Vocabulary	A taxonomy enriched with axioms representing relationships among the terms
Ontology	A vocabulary enriched with axioms representing additional restrictions that allow complex logical inferences

Table AI. Ontology related terms

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