An Ontology for Cultural Heritage Protection against Climate Change

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***Abstract*—Environmental factors, worsened by the increasing climate change impact, represent significant threats to European Cultural Heritage (CH) assets. In Europe, the huge number and diversity of CH assets, together with the different climatological sub-regions aspects, as well as the different adaptation policies to climate change adopted (or to be adopted) by the different nations, generate a very complex scenario. This paper will present a multidisciplinary methodology that will bridge the gap between two different worlds: the CH stakeholders and the scientific/technological experts. Since protecting cultural heritage assets and increasing their resilience against effects caused by the climate change is a multidisciplinary task, experts from many domains need to work together to meet their conservation goals. This paper discusses a method for facilitating the work for the different experts. A new ontology has been designed integrating all necessary aspects for improving the resilience of cultural heritages on site. This ontology combines the following topics: Cultural Heritage Assets, Stakeholders and Roles, Climate and Weather Effects, Risk Management, Conservation Actions, Materials, Sensors, Models and Observations, Standard Operation Procedures/Workflows and Damages.**

Keywords - Ontology; Knowledge Base; Ontology Visualization; Cultural Heritage.

I. INTRODUCTION

Europe has a significant cultural diversity together with exceptional historic architectures and artefact collections that attract millions of tourists every year. These incalculable values and global assets have to be preserved for future generations. Environmental factors, worsened by the increasing climate change impact, represent significant threats to CH assets such as monuments, historic structures and settlements, places of worship, cemeteries and archaeological sites. There are almost 400 UNESCO sites in Europe, located in different climatic European regions [1][2].

Therefore, eco-compatible solutions and materials for the long-term sustainable maintenance and preservation of CH in response to the events induced by climate changes are a necessity. The research and development of these solutions will benefit from an Information and Communication platform able to provide a timely up-to-date situational awareness about the site, thus supporting decision makers to plan the actions necessary for long term and short-term maintenance, intervention and risk management against the threats of the climate change. Life cycle assessment of the interventions on CH will be performed as comparative methodology supporting the decision making process.

Section 2, "Related Work" discusses Information and Communication Technologies (ICT) and existing ontologies and vocabularies in the CH domain. Section 3, "The HERACLES Project" introduces the project in which the ontology is developed and used in a Knowledge Base (KB) including two testbed case studies. Section 4 presents the creation and content of the HERACLES ontology. Since not all aspects can be covered in this paper, the focus lies on risk management, sensors, models, assets, materials and response actions. Finally Section 5, "Conclusions and Future Work" recapitulates our findings and discusses directions for future developments.

II. RELATED WORK

During the last 20 years, there has been an increasing interest and demand for specialized scientific technologies and methodologies in the CH field. An increasing number of experts from different scientific disciplines, such as curators, archaeologists, conservators, art historians, scientists and engineers, are involved in the analysis and study of CH assets and monuments, each one of them using his own

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specialized terminology. To overcome the communication gap among the CH experts, it is important to develop tools able to solve this issue. Information and Communication Technologies can support this interdisciplinary research [3].

Firstly, electronic handbooks, web-based knowledge platforms together with mobile phone applications, expert and decision support systems have been developed to improve the handling of the data and to promote the dissemination and a better understanding of the scientific information from the technical investigations. Above all, these ICTs facilitate the cooperation between CH experts. Two examples of Web knowledge tools, platforms and applications, developed by CH organizations and museums, are the following:

- An interactive website by the TATE Gallery presents information about the artworks identity, the materials, the structure and the construction technology, the description of the conservation steps, the investigation procedures, the results and the assessment of their condition state [4].
- Diadrasis, a nonprofit organization, has developed an online application entitled Viaduct [5], which classifies and explains a number of analysis and dating methods and provides basic information about the investigation methods and the related glossary.

In parallel, a correct and controlled terminology has become particularly important in the electronic documentation and presentation of the assets and of their restoration. In this respect, a number of thesauri, terminology glossaries, vocabularies and databases have been introduced, for example:

- The Art & Architecture Thesaurus (AAT) is a structured vocabulary used to improve the understanding of the terms about art, architecture, and material culture [6].
- The European illustrated glossary of conservation terms for wall paintings and architectural surfaces (EwaGlos) is an illustrated glossary of conservation terms translated in eleven languages. The core of the glossary includes approximately 200 definitions of the terms frequently used in the field of the conservation/restoration of the wall paintings and of the architectural surfaces [7].
- NARCISSE, an European project, has developed a very high-resolution image bank, dedicated to the art treasures of Europe major museums. A multilingual glossary of terms about the conservation of paintings, illustrated with various spectral images, was developed [8].
- POLYGNOSIS is a web-based knowledge platform, designed and implemented with an educational orientation, concerning the optical and laser-based investigation methods for the study of CH objects [9]. POLYGNOSIS handles information related to the analysis of the studied materials and in this respect it offers an important background for the HERACLES ontology regarding the characterization of materials.

The design process of the HERACLES ontology included the research and analysis of existing ontologies.

The CIDOC Conceptual Reference Model (CRM) is a model, which provides definitions and a formal structure for describing the concepts and relationships used in cultural heritage documentation [10]. CIDOC CRM can be extended with additional models, such as the CRM scientific observation model, or the CRM model for archeological buildings.

However, so far, no attempts have been undertaken to model the risks and the effects of climate change on CH buildings and monuments, the caused damage and the materials most suitable for restoration. We fear that the inclusion of missing ontological concepts like weather phenomena, risk analysis and crisis management into the already existing models will result in added levels of complexity to the existing ontologies. Therefore, the approach followed in HERACLES has been to create a new ontological model from scratch trying to keep it as concise as possible. The ontology has been developed in a workshop with stakeholders of the project with in-depth domain knowledge background, as described by Moßgraber et al. [11]. Hereby, it incorporates all domains that are relevant for the end-users. The following sources have been used as reference material for the new ontology: the SWEET ontologies developed at the NASA Jet Propulsion Laboratory [12], the materials ontology from Ashino [13] and Open Geospatial Consortium (OGC) standards such as the SensorThing Application Programming Interface (API) [14] and the Internet of Things (IoT) Tasking Capability [15].

III. The HERACLES Project

The main objective of the HERACLES project is to design, validate and promote responsive systems and solutions for effective resilience of CH against climate change effects, considering as mandatory premise a holistic, multidisciplinary approach through the involvement of different expertise (end-users, industry, scientists, conservators, restorators and social experts, decision, and policy makers) [16]. This will be pursued with the development of a system exploiting an ICT platform able to collect and integrate multisource information. With the help of this platform, complete and updated awareness is provided. It will also facilitate the integration of innovative measurements improving CH resilience, including new solutions for maintenance and conservation [17]. The validation is executed in four test sites, namely Heraklion in Crete with the Minoan Palace of Knossos and the Venetian Sea Fortress of Koules and Gubbio in Italy with Consoli Palace and the town walls. These test beds represent key study cases for the climate change impact on European CH assets. The strength of HERACLES solutions is their flexibility in evaluating a large quantity of different pieces of information utilized via explicit semantic modelling tailored to the specific CH assets needs. In this context, end-users play a fundamental role. Through consequent end-user focus, we aim to develop a complete, yet flexible system that is able to embrace other test-beds as well. End-users have an active part in the project activities and have permanent access to the

HERACLES KB, which implements the HERACLES ontology presented in this paper. Through the ontology, the stored and retrieved knowledge from the KB is language independent.

IV. DESIGN OF THE HERACLES ONTOLOGY

As outlined in the section "Related Work" we decided to create a new concise ontology model. To identify the ontological classes and relations, a workshop was held, which brought together all stakeholders of the project with their different research and domain knowledge backgrounds. This group consisted of about 20 persons. For a workshop, this number is considered too large, but was necessary due to the different required domains.

Stakeholders could assist during the design process of the ontology through an easy to use online collaboration tool with graphical ontology visualization and functions to facilitate the creation of instances (Figures 1 and 2).

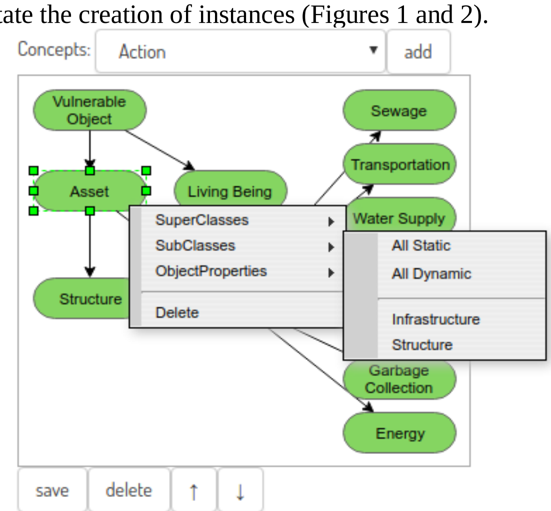

Figure 1. Tool with graphical ontology visualisation

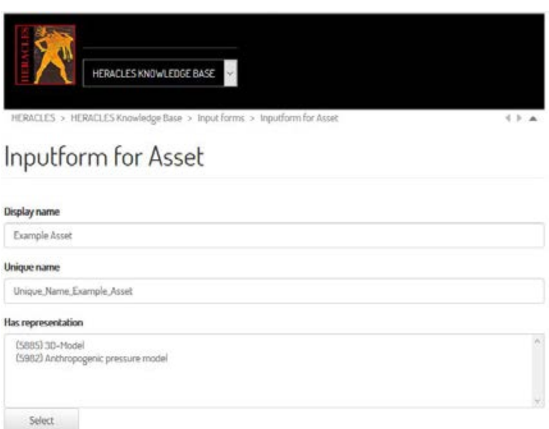

Figure 2. Instance creation

The following graphical conventions are used for the description of the HERACLES ontology:

- Green boxes represent concepts; grey boxes represent instances.
- Continuous arrows represent semantic relationships between concepts or instances. Inverse relationships are omitted for better readability. A label next to an arrow describes the relationship.
- Dashed arrows link subclasses to parent classes.
- Dotted arrows link instances to their concepts.

Concepts in the ontology are accompanied by attributes (datatype properties). For example, an asset can have geographical coordinates or a construction period. For the sake of brevity, these are omitted in the ontology pictures.

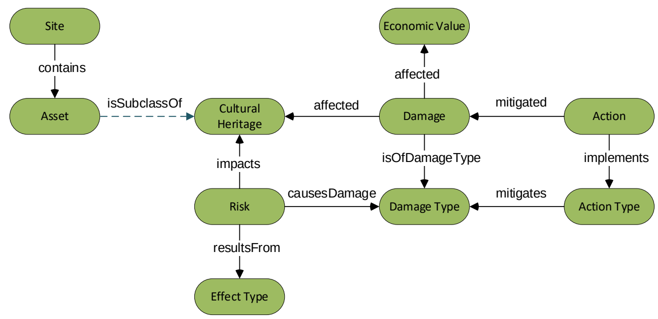

Figure 3. The main concepts and their object properties of the HERACLES ontology.

The central elements in the ontology are the CH assets that need to be protected against the effects of climate change. As shown in Figure 3, a top-level class is defined to refer to any kind of CH. Risks arise from climate change effects which can cause damages to CH. As seen in Figure 3, a distinction is made between types of potential damage ("Damage Type") and actual damage ("Damage"). The system also records potential mitigation actions and actual performed actions.

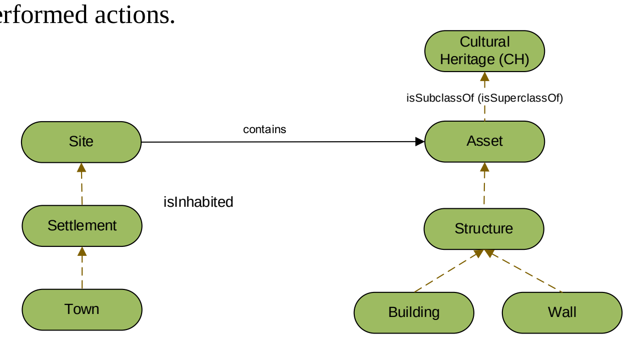

Figure 4. Cultural Heritage Asset

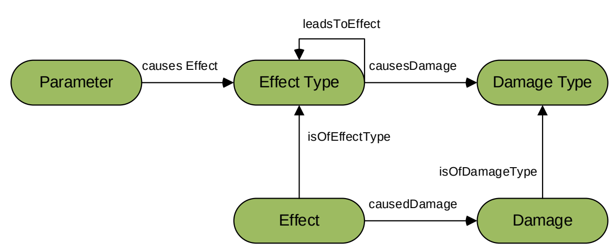

Figure 5. From effect to damage, distinction between potential and actual fact

A. Cultural Heritage Assets

Assets, which are the focus of the project, are a subclass of CH. The Asset concept is further refined with the concept Structure and, below that, Monument, Building or Wall (see Figure 4). Via these classes, the actual instances of the test beds of the HERACLES project, like the "Knossos Palace", the "Palazzo dei Consoli", the "Venetian Fortification" and the "Gubbio Townwall", can be included.

Assets are located in Sites, which are classified into more specialized classes like a Settlement.

B. Climate Change Effects

In Figure 5, the distinction between potential, meaning things that may occur and facts, in the sense of actual occurrences, is emphasized. This distinction applies to effects ("Effect Type" vs. "Effect") and damage. As an example, the ontology may contain flood as a potential effect type that may damage an asset. Besides that, the flood episodes that occurred in specific years are also registered as actual occurrences in the KB. The ontology contains the relationships between potential effects ("Effect Type"), follow-up potential effects ("leadsToEffect") and the potential damage ("Damage Type") they may cause. An example with instances for the classes shown in Figure 5 is given in Figure 6. Heavy Precipitation can lead to a Landslide. If such a Landslide hits an asset, it can result in Structural Damage. A specific event is shown below these generic types: A heavy precipitation episode occurred at a specific date and time, which caused a landslide in a specific area, which hits a wall and destroys it.

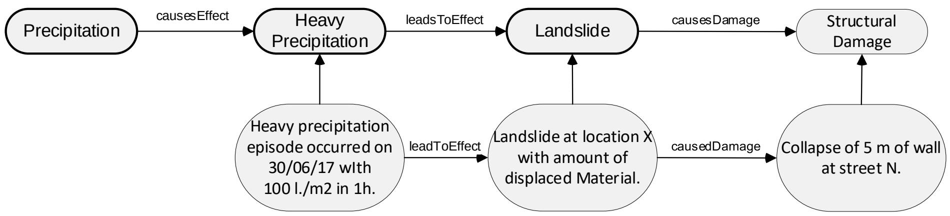

Figure 6. Example for effects and caused damage and their types.

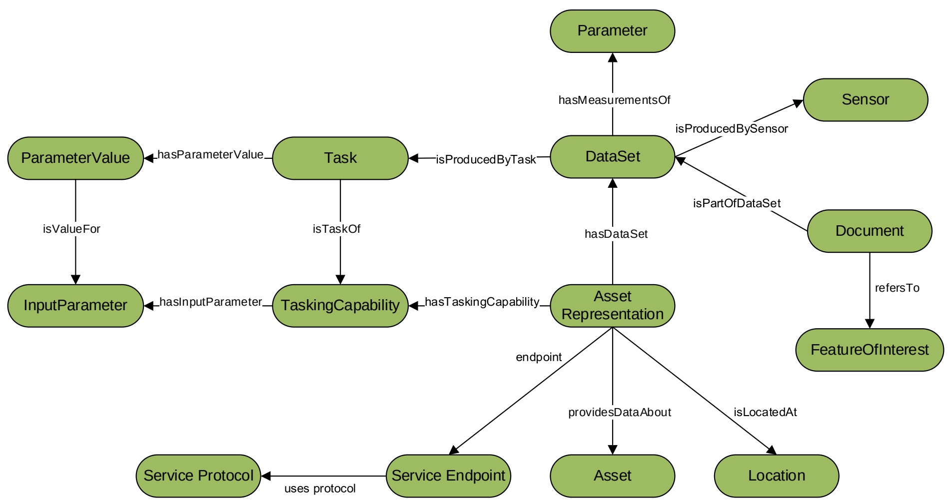

Figure 7. Classes for managing metadata of sensors, models and measurement campaigns.

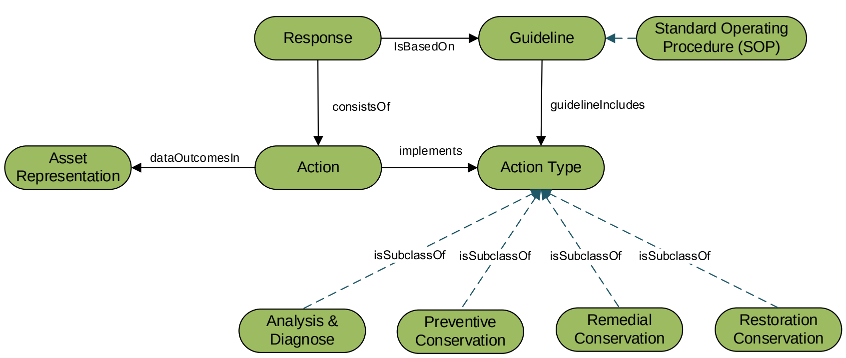

Figure 8. Maintenance and response actions.

C. Sensors and Simulation models

To capture climate change relevant parameters, sensors were modelled according to the SensorThings API standard, which was presented by the OGC [14]. The SensorThings API is a modern standard for providing an open and unified way to connect IoT devices, data and applications over the Web [15]. Therefore, the initial design of the ontology classes for dealing with sensor metadata is based on the data model of the SensorThings API standard. It is reasonable to follow the same standard for developing the ontology for simulation models. In practice, requesting the execution of a model is equivalent to tasking an actuator to perform a particular task but, since the tasking part of SensorThings API was not yet available, it is not considered in the paper. For this reason, the adaptation of the ontology is based on the "Internet of Things Tasking Capability" [16], in which an extension of the SensorThings API for tasking actuators is proposed.

The central concept in the diagram (see Figure 7) is the "Asset Representation". An Asset Representation is an entity that provides data about an asset. It can be regarded as a proxy that enables access to the available data about an asset, for example, temperatures in a building, images and measurements of the building obtained in a measurement campaign or the results from a structural model. The actual sensor measurement is stored in an observation, which is connected to a data stream. The four classes on the left in Figure 7: TaskingCapability, Task, InputParameter and ParameterValue, provide support to store and manage metadata about the models. The TaskingCapability provides a human-readable description of the model together with information regarding the API that the model provides. In the HERACLES platform, there is an additional abstraction layer, namely the KB, which manages the metadata of the available models and sensors.

D. Maintenance and Response Actions

Situational awareness is achieved through continuous monitoring of the status of the CH assets combined with the results provided by the simulation models, which enable risk assessment. Evaluation of the information provided by the system and on-the-field observations enable the identification of actual or potential problems, for instance, when a risk level threshold is trespassed or a damage is observed. The modeling of such problems has been included in the ontology.

Maintenance actions not related to an issue also need to be documented. In this way, the structure of the ontology can serve as a register of past actions that can be used to better understand the current situation and support the decision making process. Suggested actions are documented in formalized guidelines, which are often supported by a specific law; these are the Standard Operating Procedures (SOPs) (see Figure 8).

E. Materials

Since materials have an influence on how an asset is affected by climate effects in terms of its resilience to weathering and ageing, it is important that the ontology also models information about materials and the KB contains information about materials and of which materials an asset consists of. The material area can be ground for experimentation of new solutions to be applied for maintenance and restoration/conservation of CH assets.

The classes to keep materials information in the KB are provided in Figure 9. The level of detail regarding the information about the composition, structure and properties of the materials needs further discussion with both materials experts and end users. Nevertheless, it should be noted that some ontologies associated with the handling of material related information already exist [10]. Whereas the detail of such specialized ontologies may be too excessive for its application in our use cases, they provide a reference to develop a model for the HERACLES platform. At the same time, since the aforementioned ontologies are not designed with a specific application field in mind, extra classes and properties may be necessary in the HERACLES platform for its utilization in the context of CH conservation.

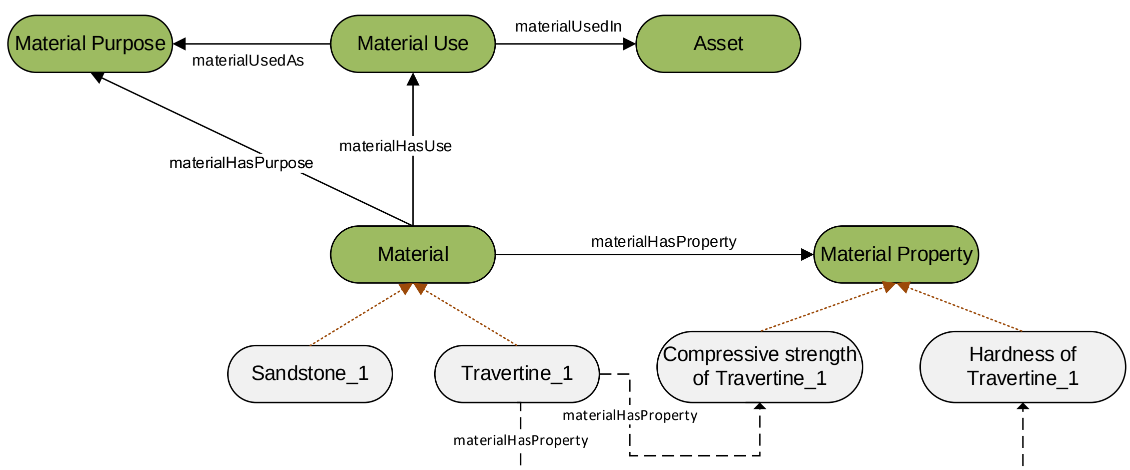

Figure 9. Classes keeping material information

F. Ontology Metrics

This section provides the metrics of the current state of the HERACLES ontology. It includes *general* metrics like the number of classes, data/objects properties and individuals and *annotation axioms* like the numbers of annotation property. Inverse properties are excluded in this listing (see Table 1).

TABLE I. ONTOLOGY METRICS

Metric	**Value**
Class count	109
Object property count	102
Data properties count	49
Individual count	141

V. CONCLUSIONS AND FUTURE WORK

This paper presented the design of the HERACLES ontology, which aggregates multiple domains and therefore, required the interaction of multiple domain experts. Using a tool, which supports online collaboration with graphical ontology visualization, creation of input forms, etc. speeds up this process. The ontology is the basis for further research projects, which need to tackle the problems of climate change effects and involve a set of heterogeneous sensors and processing algorithms. Furthermore, it can be used as basis for the suggestion of materials that comply with historic building materials and can be used to restore the structural health of cultural heritage assets. Apart from future possibilities, the ontology offers functionalities that are already in use: the consolidation of information describing the situation at a cultural heritage site rises situational awareness and the graphic display of concepts serves as full-fletched and navigable glossary for the project partners.

Besides the various additions to the ontology model discussed above, further work will be performed to fill the Knowledge Base using the developed ontology. Additionally, research will focus on the reasoning techniques, which will be applied to the semantic data to automatically suggest necessary preservation actions. Another imminent step is to have end-users evaluating the ontology-based decision support providing possible recommendations. This assessment will take place in a few months' time, when the first pilot deployments will be evaluated in the field. Action will also be taken on mapping concepts from the HERACLES ontology to other prominent models, like the CIDOC-RM, to guarantee interoperability and facilitate the ontology's reuse.

The ontology has been published here [18], where the interested reader is encouraged to examine the ontology.

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