Implementing the HERACLES Ontology

An Ontology as backbone for a Knowledge Base in the Cultural Heritage Protection Domain

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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. In this paper we introduce the HERACLES Ontology, which structures data and explicitly links adjacent data. Furthermore the implementation of the HERACLES Ontology within the HERACLES Knowledge Base is described. Use cases and benefits of the application are given. The ontology comprises 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 – HERACLES, Ontology; Knowledge Base; Ontology Visualization; Cultural Heritage; Ontology Population

I. INTRODUCTION

Cultural Heritage protection requires multidisciplinary teamwork – as discussed in our Paper at the SemaPro 2018 a common language is required. An ontology helps to explicitly express the knowledge of different domains. The presented ontology has been refined and brought to use in several modules, which we are going to introduce in this paper [1].

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 [2], [3]. 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.

Section II, "Related Work" discusses Information and Communication Technologies (ICT) and existing ontologies and vocabularies in the CH domain.

Section III, "The HERACLES Project" introduces the project in which the ontology is developed and used.

Section IV presents the creation and content of the HERACLES ontology. It covers all relevant domains and expands the previous contribution by adding *Cultural Heritage Elements, Damages,* and *Reporting* to the Concepts.

In Section V, we present the HERACLES Knowledge Base (KB) and the HERACLES Mobile Application, in which the semantic application of the HERACLES ontology proves beneficial.

Finally, Section VI, "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 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 [4].

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 [5].
- Diadrasis, a nonprofit organization, has developed an online application entitled Viaduct [6], 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 [7].
- 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 [8].
- NARCISSE, a 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 [9].
- 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 [10]. 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.

During this, the ontology developed by The International Committee for Documentation, an institution of the International Council of Museums, CIDOC Conceptual Reference Model (CIDOC CRM) was analyzed. CIDOC CRM is an ontology intended to facilitate the integration of heterogeneous cultural heritage information [11]. It is designed since 1996 and has been continuously refined since. It offers for cultural heritage and information of interest a general data structure, whereas the general purpose are museum documentations and exhibition objects shown in museums. CIDOC CRM is supra-institutional and can be applied independent of any local context. The ontology is very progressive at structuring information about the origins of an asset, e.g., the creation of an artefact or its chronological classification. Yet, the ontology was too complex and heavy-weight for the HERACLES project; furthermore, it focused mainly on cultural heritage as object in an element in an exhibition. Nevertheless, CIDOC CRM can be extended with additional models, such as the CRM scientific observation model, or the CRM model for archeological buildings.

Acierno et al. introduce in [9] ontological work based on CIDOC CRM. The ontology presented ontology expands the previously named model by adding buildings and elements of buildings through a fine-grained model, which contains horizontal and vertical components. Further, it adds workflows aiming at the conservation of cultural assets. Based on this ontology, a connection between a Building

Information Modelling Software and the classes describing buildings was established, which yielded into a knowledge enriched 3D model of the researched artefacts. Both building design and knowledge-enriched visualisation are high-grade outcome and deserve further examination.

Zhang et al. introduce an ontology based framework for a KB about materials and their compatibilities [13]. This domain is important to the HERACLES Project, since conservators and restaurateurs often have to find appropriate materials with custom properties, on order to repair and protect cultural heritage and not worsen its preservation state and aesthetics. The focus of this work lies within choosing materials for manufacturing processes and omits sensitivities or compatibilities of material combinations. Since the compatibility of conservation materials used in cultural heritage preservation is an important aspect, Zhang's ontology does not meet our requirements.

In the MONDIS project, Cacciotti et al. developed the Monument Damage Ontology [14]. It is suitable for both conventional documentation of cultural heritage, as well as describing damages occurring on cultural heritage. The proposed modelling enables the ontology to distinguish between the consequences of an effect (e.g., crack or flaking*)* and the mechanisms that led to it (e.g., temperature changes or acid rain). The description of damages and their occurrence seems to be well suited for describing damages on CH. Also, the authors give suggestions on how to handle damages, which are mainly based on historical data. Here, the semantics have to be analysed by the reader: no explicit semantics for conservation methods are introduced in the ontology.

However, no holistic approach had been undertaken, modelling all required domains in an application oriented project. Fearing that including new concepts into existing ontologies would lead to complexity, it was decided to not supplement existing ontologies, but to create a new ontological model from scratch trying to keep it as concise as possible. The ontology was developed in a workshop with stakeholders of the project with in-depth domain knowledge background, as described by Moßgraber et al. [15]. 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 [16], the materials ontology from Ashino [17] and Open Geospatial Consortium (OGC) standards such as the SensorThings Application Programming Interface (API) [18] and the Internet of Things (IoT) Tasking Capability [19].

III. The HERACLES Project

The main objective of the HERACLES project was 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) [20].

This was 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 was provided. It facilitated the integration of innovative measurements improving CH resilience, including new solutions for maintenance and conservation [21].

The validation has taken place on 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.

The HERACLES project endured from May 2017 until April 2019. The webpages are still available and will deliver information until 2021 [20].

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.

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.

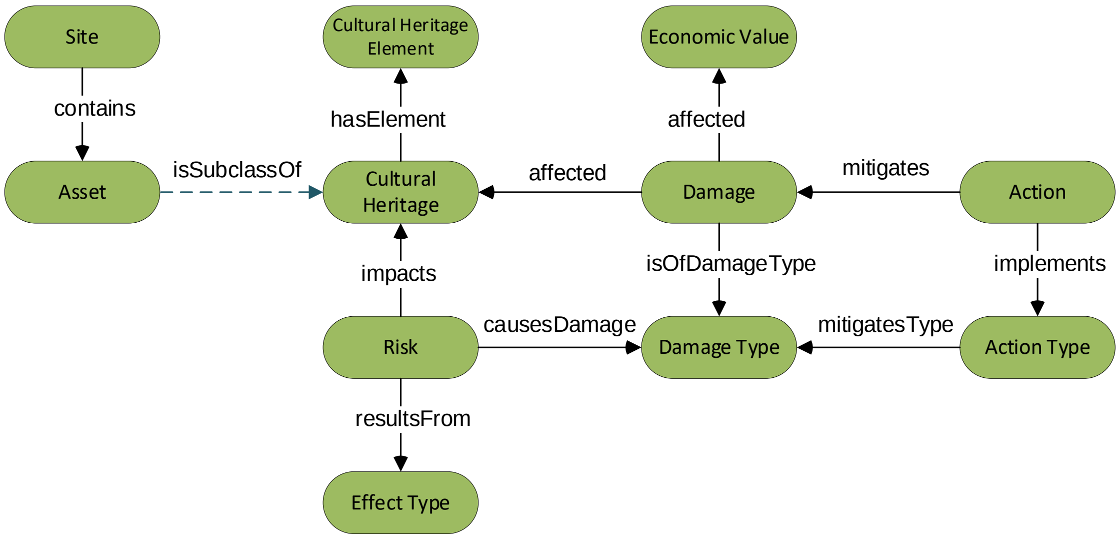

Figure 1. The main concepts and their object properties of the HERACLES ontology.

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 1, 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.

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 2). 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 Town wall", can be included.

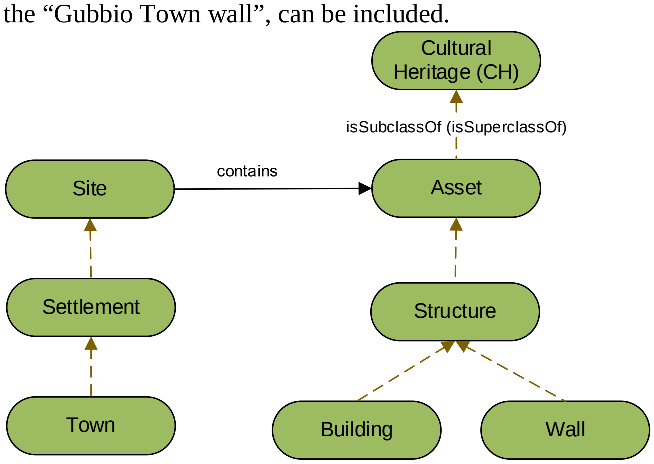

Figure 2. Cultural Heritage Asset

B. *Cultural Heritage Element*

In the run of the HERACLES Project, it became clear that a Cultural Heritage often grows naturally in the run of time and has different trait, characteristics, materials and so forth. To take this into account, the class *Cultural Heritage Element* was introduced (Figure 3). It describes parts or subparts of a *Cultural Heritage*, whereas a *Cultural Heritage Element* can also contain another *Cultural Heritage Element*. An example would be the Venetian Fortress in Heraklion, which consists of different floors, which again have different rooms.

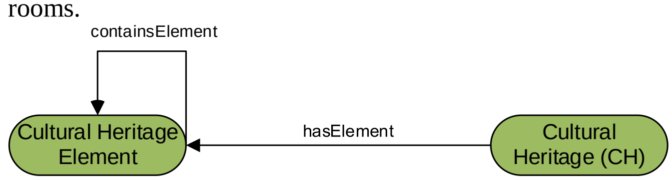

Figure 3. A Cultural Heritage is made up from several Cultural Heritage Elements, which can again contain other Cultural Heritage Elements.

C. *Climate Change Effects*

In Figure 4, the distinction between potential, meaning things that may occur and facts, in the sense of actual occurrences, is emphasized. This distinction applies to effects 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 4 is given in Figure 5. The parameter *Heavy Precipitation* can lead to *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.

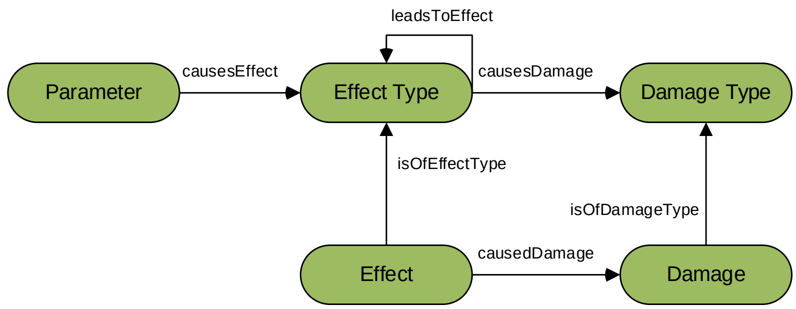

Figure 4. Distinguishing Effect and Damage, Effect Type and Damage Type

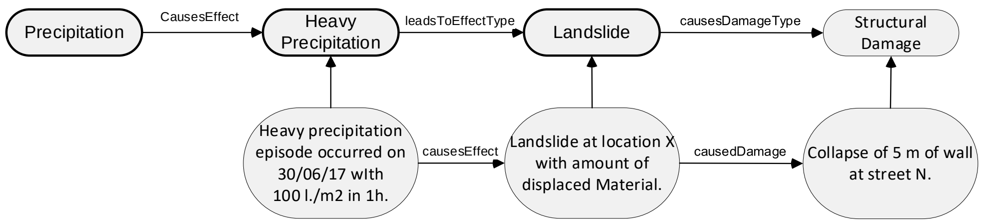

Figure 5. Example for effects and caused damage and their types.

D. *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. The SensorThings API is a modern standard for providing an open and unified way to connect IoT devices, data and applications over the Web [18]. 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 6) 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.

E. *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 7).

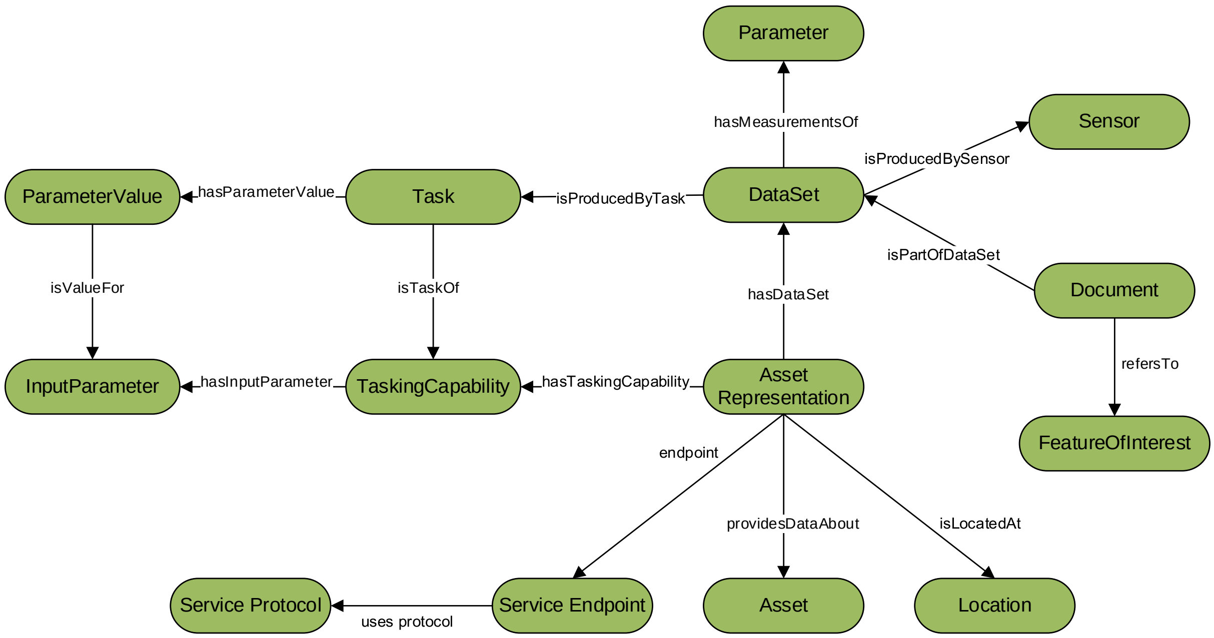

Figure 6. Classes for managing metadata of sensors, models and measurement campaigns.

F. *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 8.

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.

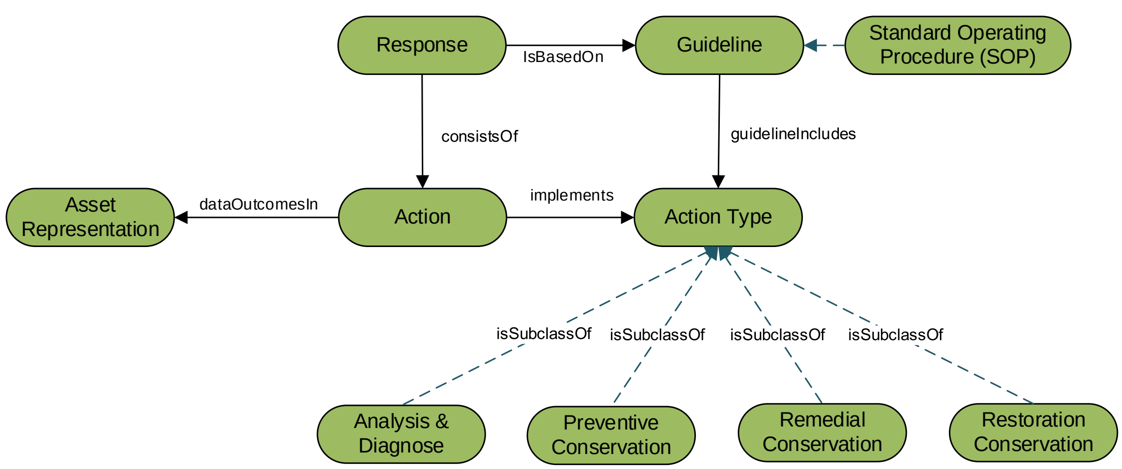

Figure 7. Maintenance and response actions

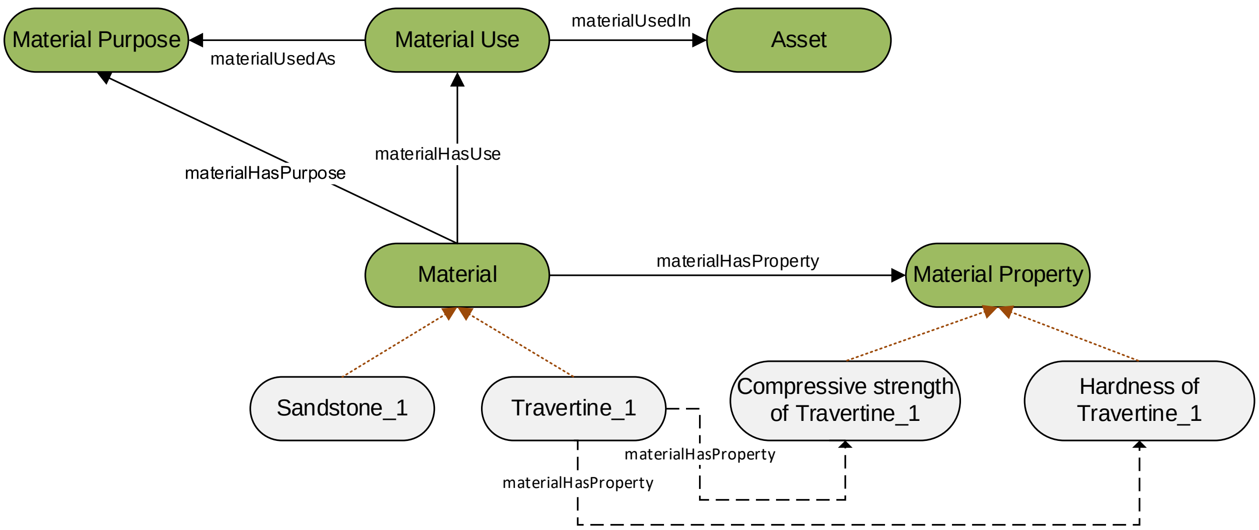

Figure 8. Classes keeping material information

G. *Damages*

An important aspect is modelling damages in this project (Figure 9). A *Damage* affects a *Cultural Heritage*, which is caused by a specific *Effect*, such as a wet-dry cycle or rapid temperature changes (see Figure 4). The twofold approach allows categorizing *Damages* into *Damage Types*. *Damage* is the actual manifestation of the occurring damage. Through the generic categorizations, it is possible to give suggestions for specific *Action Types* that proved successful in the past on the same *Damage Type.*

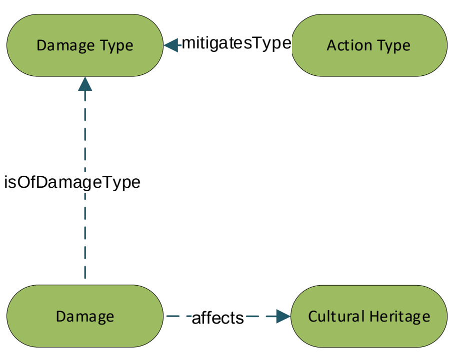

Figure 9. Classes for damages and its causes

H. *Reporting*

The classes required for reporting are depicted in Figure 10. A *Report* reports for a *Cultural Heritage*. It has a relation to a specific *Damage Type*, where the type of the reported *Damage* is specified. Section V describes the usage of this part of the ontology by means of the HERACLES Mobile Application.

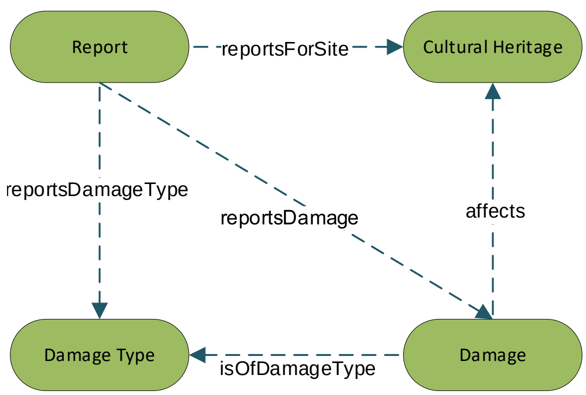

Figure 10. Classes describing the domain Reporting

I. *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 I).

TABLE I. ONTOLOGY METRICS

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

V. Applying the HERACLES Ontology

This section extends the original paper from the SemaPro 2018. Uses cases, directly related to the HERACLES Ontology are described below. The first Section V.A introduces the semantic integration of data according to the HERACLES ontology. The subsequent Section V.B shows scenarios, in which data is retrieved from the ontology.

A. *Structuring Data through the HERACLES Ontology*

The HERACLES KB offers input forms, through which data can be semantically integrated (Figure 11). If, for example, the creation of a new Asset is required, the input form offers text fields for textual descriptions. Links to other instances (as allowed by the ontology) can be created through selecting the appropriate elements in lists. This is a simple creation possibility for non-technical users. The picture below shows the creation of an example instance. It contains a unique name, as well as a display name. Representations of this instance are shown in the *Has representation* list.

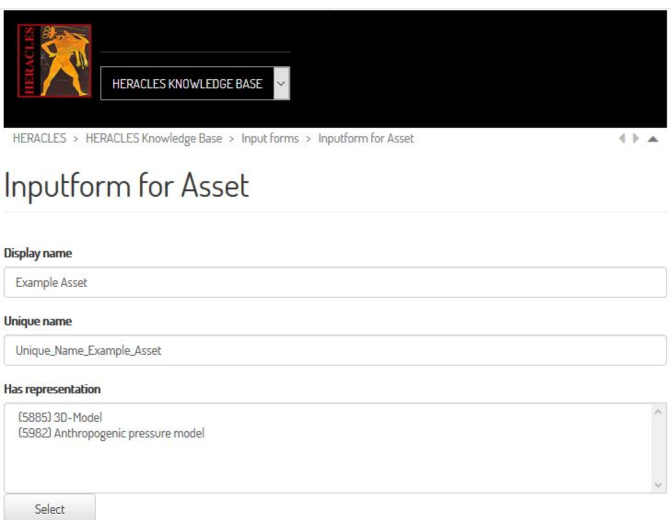

Figure 11. The manual creation of an instance and its relationships

Besides the manual possibility, an online endpoint was established. By sending messages per HTTP in the appropriate structure to this endpoint, instances in the ontology can be created or deleted. The structure must adhere to the HERACLES Ontology; otherwise, it is not accepted. By using the built-in authentication mechanisms of the KB component, the access to these commands can be restricted to certain users depending on their associated roles. A new Cultural Heritage instance for example, could be reported through the message shown in Figure 12. The key *defaultprefix* contains the value of the namespace of the HERACLES Ontology. The element *newInstance* is created as instance of *CulturalHeritage*. The KB assigns the new instance the unique name *newHeritage* and display name *newHeritage*. The key *text* contains a free description of *newHeritage*.


```
{
"defaultprefix" : "http://iosb.fraunhofer.de/heracles-kb/",
    "data": {
        "newInstance" : {
            "type" : "CulturalHeritage",
            "properties" : {
            "instanceDisplayName" : "newHeritage",
            "instanceUniqueName" : "newHeritage",
            "text" : "Description"
            }
        }
    }
}
```


Figure 12. Using the online endpoint for machine to machine communication

B. *Applying the HERACLES Ontology*

The ontology serves as the backbone of the HERACLES KB. Every entry in the KB is also an instance stored according to the ontology. Therefore, all relationships to other instances are directly available.

In Figure 16, an excerpt from an entry of the KB is shown. The page contains a customized view, showing pictures and quick links to the most important relations. On the right side, all relationships are shown. These are, for example, damages impacting this heritage, reports about this heritage or sensors monitoring this heritage.

If the user wishes, s/he can create ontology pictures, which give quick access to the most important or used related instances. Figure 13 shows the report *testReport*, which reports a damage of type *salt accumulation*. A click on the boxes will lead the user to the respective entry, where a view as shown in Figure 15 will give all available information and related data.

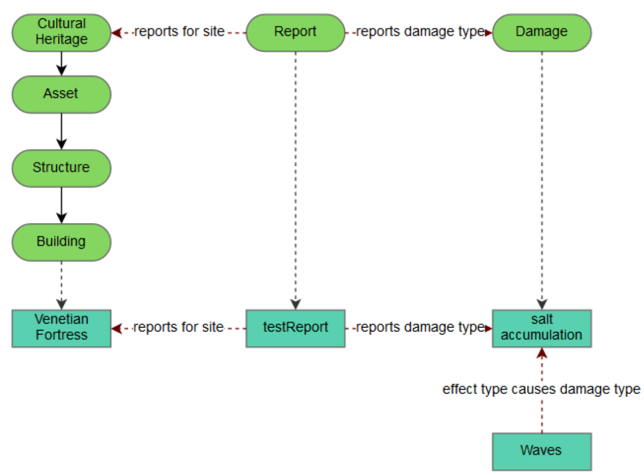

Figure 13. An ontology picture customized for the Venetian Fortress showing a report reporting about a salt accumulation

Depending on the user's authorization status, s/he can manipulate the pictures by dragging and dropping or through right clicking, as shown below in Figure 14.

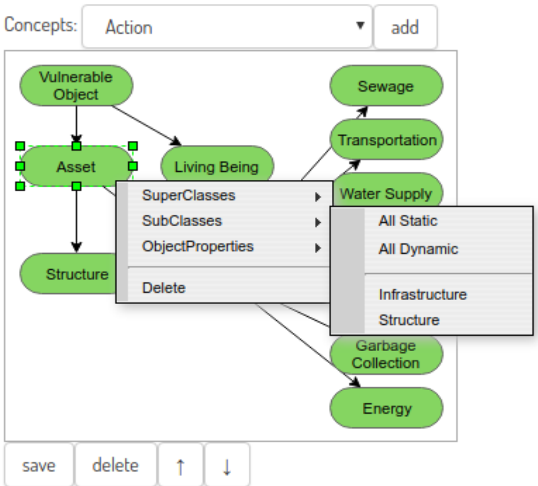

Figure 14. Tool with graphical ontology visualisation

The endpoint mentioned in Section V.A is, amongst other technology, used by the HERACLES Mobile Application. This app allows the user to report damages on site from the surveilled cultural heritage. The location, including the description by the researcher on site, as well as additional pictures, videos or speech messages are transferred to the knowledge base where they are presented to the cultural heritage manager. Through the semantic structure, not only the report, but also the heritage it belongs to, as well as the reported damages are presented.

The picture below shows a *testReport* that has been sent through the HERACLES Mobile Application. It contains the damage type, the heritage it is reported for and a picture of the reported damage.

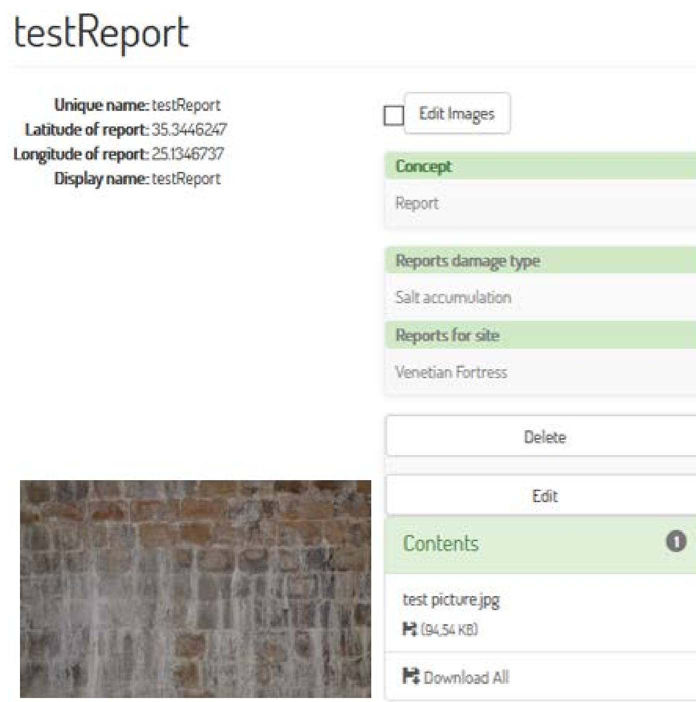

Figure 15. The instance page for a hypothetical *testReport*

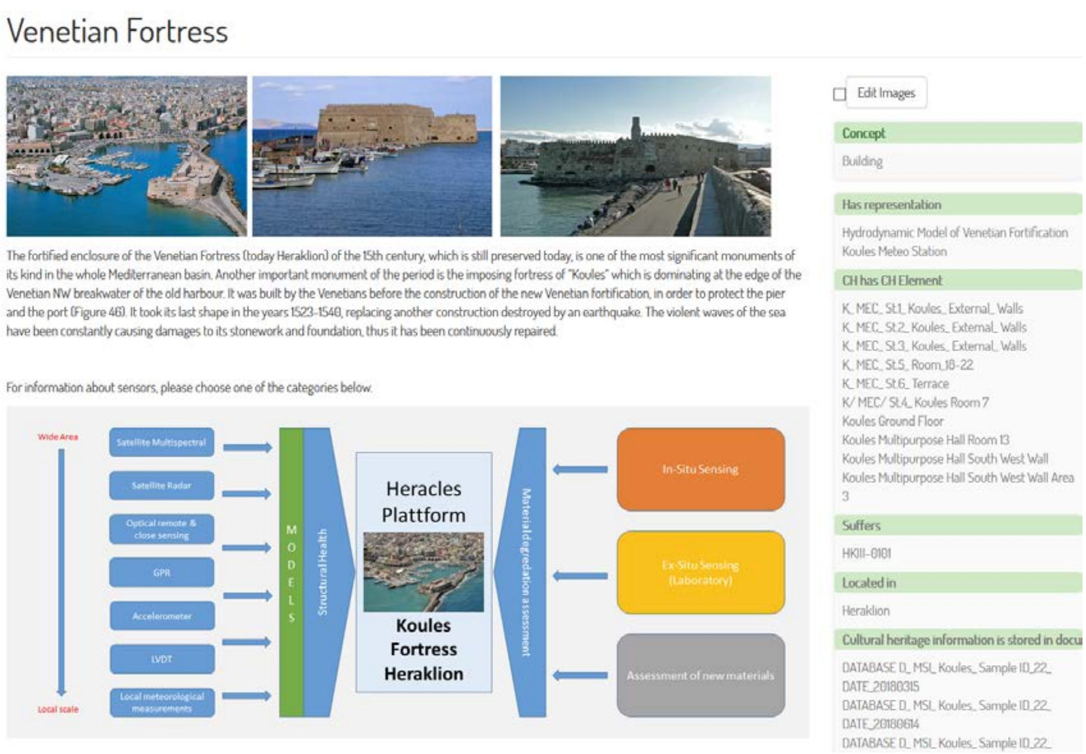

Figure 16. An instance page for a cultural heritage showing all related data

Figure 17. Using metadata for map views

Metadata, such as the location is used to visualize the position of reports on a map (Figure 17). A click on the icon will lead the user to the entry of *testReport*, as shown in Figure 15.

VI. 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. Furthermore, it gave an introduction to the usage possibilities of an ontology. Bringing it all together in a Knowledge Base gives both a commonly agreed on vocabulary, as well as a browsable data structure, in which collaborators can access all related data. This brings up connections and makes correlations understandable. Though the HERACLES Project ended in April 2019, the ontology can be the basis for further research projects, which need to tackle the problems of climate change effects and involve data from heterogeneous domains. As written in III, the HERACLES Platform, and therefore the HERACLES Ontology, have been validated at hand of four different use-cases, in which the ontology comprised and linked all collected data [20].

Apart from future possibilities, the ontology is implemented in the HERACLES KB, in which project end-users continue working. The ontology is set from now and will serve as structure for future data, which is going to be integrated into the KB.

Future projects could focus on reasoning about, or integrating rules into the ontology, to make use of its full potential. Action should 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 [22], where the interested reader is encouraged to examine it.

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