Article

Introducing the HERACLES Ontology—Semantics for Cultural Heritage Management

Tobias Hellmund [1],*, Philipp Hertweck [1], Désirée Hilbring [1], Jürgen Mossgraber [1], George Alexandrakis [2], Paraskevi Pouli [2], Amalia Siatou [2] and Giuseppina Padeletti [3]

[1] Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB, 76131 Karlsruhe, Germany; philipp.hertweck@iosb.fraunhofer.de (P.H.); desiree.hilbring@iosb.fraunhofer.de (D.H.); juergen.mossgraber@iosb.fraunhofer.de (J.M.)

[2] Foundation for Research and Technology-Hellas FORTH, 700 13 Iraklio, Greece; alexandrakis@iacm.forth.gr (G.A.); ppouli@iesl.forth.gr (P.P.); amalia.siatou@gmail.com (A.S.)

[3] ISMN, Consiglio Nazionale delle Ricerche CNR, 00185 Rome, Italy; gpadeletti@gmail.com

* Correspondence: tobias.hellmund@iosb.fraunhofer.de

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Abstract: Cultural Heritage (CH) (In the context of this paper, we consider cultural heritage built tangible cultural heritage, such as buildings or monuments.) is an important source of identity for humankind and needs to be conserved for future generations. Climate change (CC) will morph the environmental landscape, thus leading to climate stress imposed on CH. Experts from different domains, including, but not limited to, material scientists, conservators and managers of cultural heritage collaborate to find out how CC affects CH and how potentially harmful impacts can be mitigated. To find and understand correlations and effects of different factors, researchers collect and analyse vast amounts of data. Still, experts often cannot exchange or make efficient use of data since it often is unstructured, incompatible, or its plain existence is simply unknown. This article introduces means to achieve consent about available knowledge, to exploit synergy effects through the combination of available information and to provide a flexible multisource information platform in collaborative cultural heritage management projects. In the context of the European project HERACLES (HERACLES—HEritage Resilience Against CLimate Events on Site. Further information: http://www.heracles-project.eu/), an application-ontology was developed. The ontology facilitates reuse and integration of data through structuring and representing its semantics. The involvement in the HERACLES project guaranteed end-user driven development, practical results and encompassment of all domains represented in the project.

Keywords: cultural heritage; climate change; ontology; knowledge base; semantics

1. Introduction

Cultural Heritage Preservation is a knowledge-based discipline. Predictions, interpretations and conclusions can only be made by comparing data at hand against existing knowledge. Since Cultural Heritage Preservation presents, due to the very nature and history of its preservation subjects, a number of challenges it requires an interdisciplinary approach. Researchers from different domains collaborate using their own set of sensors and methods, computational models or vocabulary [1]. This causes a vast variety and flow of information [2]. Ontologies provide means to canalize and reuse information: in the context of the Semantic Web, ontologies are used to enable machines to *understand* what kind of information is at hand, thus enabling them to efficiently query data through semantic filters [3] (pp. 68–72), [4].

This article introduces the HERACLES Ontology for the preservation of cultural heritage in the context of climate change. It helps with integrating and retrieving data in the field of cultural heritage

preservation considering the effects of climate change. The article describes both the conceptual approach to designing the ontology, as well as the ontology itself. Furthermore, an overview of the utilization of the ontology is given. For a comprehensive introduction to the semantic web, its basic concepts and main goals, we suggest [5]. More technical details can be found in [6,7].

The paper is structured as follows: Section 2 will give an overview of related ontologies, discuss their data model and their background. Section 3 describes the methodological approach of engineering the HERACLES ontology and how the HERACLES partners and end-users collaborated in the design process. Section 4 introduces the data model of the HERACLES ontology. The introduction of the main classes and relationships, as well as examples of data from use-cases, will give overview of the ontology, its capabilities and possible application cases. Section 5 discusses the ontologies metrics and gives an outlook about future research.

2. Related Work

HERACLES requires the knowledge of experts from many different domains. Therefore, it was not surprising that a thorough literature research did not find an ontology covering all necessary domains, the authors intend to represent within the HERACLES project. Nevertheless, we researched ontologies describing sub-domains of the HERACLES project. In the following section, we present a set of examined ontologies.

The International Committee for Documentation, an institution of the International Council of Museums, developed the CIDOC Conceptual Reference Model (CIDOC CRM) [8]. It is an ontology intended to facilitate the integration of heterogeneous cultural heritage information. Developed by CIDOC since 1996, it has continuously been refined since. It provides a general data structure describing cultural heritage and information of interest, whereas the starting point and benchmark are museum documentations and exhibition objects shown in museums. It aims to stay supra-institutional and without 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. The ontology is far too complex for the HERACLES project and focuses exhibition objects within museums, not built at a large-scale heritage.

Acierno et al. introduce in [9] a CIDOC CRM based ontology, extending it by adding buildings and building elements with the help of a fine-grained model, which introduces horizontal and vertical building components. It also adds investigation processes with the goal of conservation of cultural assets to the domain set. Furthermore, a direct connection between a Building Information Modelling Software and the classes describing buildings was established, which yielded a knowledge enriched 3D model of the researched artefacts. Both building design and knowledge-enriched visualisation are high-grade outcomes and deserve further examination. Acierno published the approach after the development of the HERACLES Ontology.

Zhang et al. introduce an ontology based knowledge framework for engineering materials and the selection of materials for specific purposes [10]. The focus lies within choosing materials for manufacturing processes and omits sensitivies and 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 [1].

In the context of the MONDIS project, Cacciotti et al. developed the Monument Damage Ontology [11]. The ontology serves for both conventional documentation of monuments, as well as describing monument damages. 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. Nevertheless, actions for the mitigation of damages come up short: though the authors try to give suggestions on how to handle damages, these are firstly based on historical data and, secondly, the semantics have to be analysed by the reader: no explicit semantics for conservation methods are introduced in the ontology.

So far, no ontology offers a holistic description for the management of CH and safeguarding CH from climate change effects. Though CIDOC-CRM is an international standard for the description, we chose to design an application-ontology keeping the strengths and weaknesses of the examined ontologies in mind.

3. Designing the HERACLES Ontology

Several methodologies for the design of ontologies have been around for quite a long time, as introduced in [12]. To develop the HERACLES Ontology, we chose a workshop approach, in which end-users specified their requirements to the ontology, based on the methodology of Grüninger and Fox [13]. In this methodology, *competency questions* (CQs) delimit the area of interest and are used to test the capabilities of the ontology. CQs offer an intuitive way to describe the challenges that are part of the daily work of the end-users. We firstly used the CQs to delimit the area of interest; necessary domains had to be identified and sharply confined to avoid overloading [7] (p. 309). Secondly, since many ontologies are too general and oversimplified to be useful for practitioners [9], we used them to ensure practicability. To ensure practicability, we involved the platform end-users, based on their expertise (monitoring of CH, material analysis and development, meteorology, researchers, conservation, risk assessment, management etc.), in designing the ontology from the very beginning. Through making use of their knowledge, the HERACLE ontology aims to be ready to use for the HERACLES use-cases and, through the end-users expertise, we aim for an outcome applicable for other built cultural heritage facing the challenges of climate change as well.

A group session with 20 participants manifested the baseline of the ontology. During the workshop, the end-users identified the necessary domains. Table 1 shows the chosen domains for the HERACLES ontology. Section 4 will introduce classes and properties and describe their content in depth.

Table 1. The domains of the HERACLES Ontology.

(Tangible) Cultural Heritage Assets	Preservation Actions
Materials	Climate Change Effects
Damage	Sensors and Measurements
Risk Assessment	Standard Operating Procedures/Guidelines
Stakeholders and Roles	-

After identifying the required domains, semantic classes and their relationships amongst another were formed to build the semantic categorization. Eventually, additional descriptions of the classes were developed to enrich the ontology and to facilitate human comprehension of the data model. During the whole design process, we followed the principle of minimalism and only introduced classes or relationships, where they appeared necessary for the end-users and their respective test-beds. Through this, we tried to achieve the goal of an application-ontology.

In the workshop, the Fraunhofer IOSB developed system WebGenesis, which hosts the ontology, was used. WebGenesis is shown in Figure 1. It offers a means to create, visualize and explore ontologies. The usage of this platform leads to quick understanding for the participants. Therefore, the workshop participants were able to actively take part in the development and effectively give feedback about the semantics of the model. During the project, WebGenesis and the most recent version of the ontology were—and still are—available for every relevant participant to collect further suggestions or corrections by the end-users. The picture below shows a screenshot of WebGenesis hosting the HERACLES Ontology. On the left side, content stored in the Knowledge Base is shown. On the right side, the user has the possibility to create and manipulate an ontology picture; through displaying the relationships between classes s/he needs to see, the user gains understanding of the area of interest. Below the ontology picture, for completeness, every instance, for which the entry has an object property, is shown.

Figure 1. WebGenesis hosting the HERACLES Ontology.

To offer end-users a work of reference, video lessons demonstrating the functions of the platform were created. After the platform end-users gained some experiences using the platform, a second workshop took place. The workshop was held to search for further potential of the ontology and gather the user's feedback. Suggestions and (new) requirements of the end-users were put on record through a set of competency questions: the questions were based on typical problems the experts faced during their work and form the baseline of what the HERACLES ontology shall be able to answer. The box below (Figure 2) shows an exemplary set of questions the ontology is capable to answer.

Competency Question 1: Which measurements have been taken on a building element in between two points in time?

Competency Question 2: What kind of material samples have been carried out on a specific over layer material?

Competency Question 3: Which research methods have been applied to a specific material sample?

Competency Question 4: Which damages are recorded about a CH?

Competency Question 5: Which sensors provide measurements about a CH?

Competency Question 6: Which stakeholder carried out a measurement?

Competency Question 7: Which risks exist for a CH?

Figure 2. An exemplary set of Competency Questions.

Having set the structure of the ontology, we gradually fed measurements and new results into the knowledge base to validate the functionality of the system. Due to the very nature of the project, new measurement techniques were tested and developed. This changed the requirements of the end-users to the data model. To be able to represent the newly acquired data, the model was changed accordingly. This contemporaneous process accompanied all other tasks during the project and led to continuous refinement of the ontology throughout the project.

4. The HERACLES Ontology

The following section introduces the HERACLES ontology. In the first section, an overview about the design pattern of the ontology pictures will be given. The second section introduces all classes of the ontology in detail including their relationships. It contains pictures to enhance the readers' comprehensibility about the relationships. The class illustrations do not contain every property to

enable the reader to keep track of the matter. For simplification, datatype properties and inverse properties are omitted. Class hierarchies appear where they seem reasonable.

4.1. Quick Guide to Reading Ontology Pictures

In Figure 3, dashed arrows indicate a relationship (*object property*). Continuous arrows depict a baseclass-to-sub-class relationship.

Figure 3. Subject-predicate–object relation and parentclass–childclass relation.

In Figure 4, instances of classes are shown in light-blue edged boxes. A colon separates the content of the box. The first part gives the name of the instance. The latter part gives the name of the class the instance belongs to. Frost_2018_01_13 is an instance of class Effect. The class Effect relates through property causes damage to the class Damage. Frost_2018_01_13 is related through causes damage to instance Crack_1, an element of class Damage. The meaning/semantics behind this triple is intended to indicate, that Frost_2018_01_13 caused Crack_1.

Figure 4. An example for instances and relations.

In the ontology, we distinguish between the classes Entity and Entity Type. An Entity Type represents the various types an instance of Entity can be instantiated as. This modelling enables several types of Entity to compound. An instance Damage_1 of class *Damage* for example can have both *Damage Types* discoloration and flaking. The actual manifestation of the damage is instance of class Entity. Through this approach, the ontology can categorize instances of Entity with the same type in Entity Type, as shown in Figure 5.
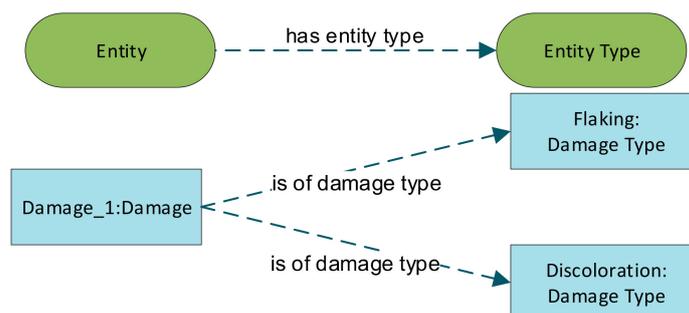
Figure 5. Entity and Entity Type and an exemplary instance of Damage with two Damage Types.

4.2. Core Classes of the HERACLES Ontology

The core classes of the ontology consist of *Cultural Heritage, Cultural Heritage Element*, *Damage* and *Effect*, as well as the domain *Material* and *Action* (see Figure 6). *Damage* and *Effect* model the harms through changes in abiotic climate factors that occur on a *Cultural Heritage*. *Action* mitigates *Damage* that occurred on a *Cultural Heritage Element*. In order to prevent damage or prepare the *Cultural Heritage*, procedures, represented by *Action*, can be applied to *Cultural Heritage Element*. *Cultural Heritage Element* links all actions, damages or materials to the *Cultural Heritage*.
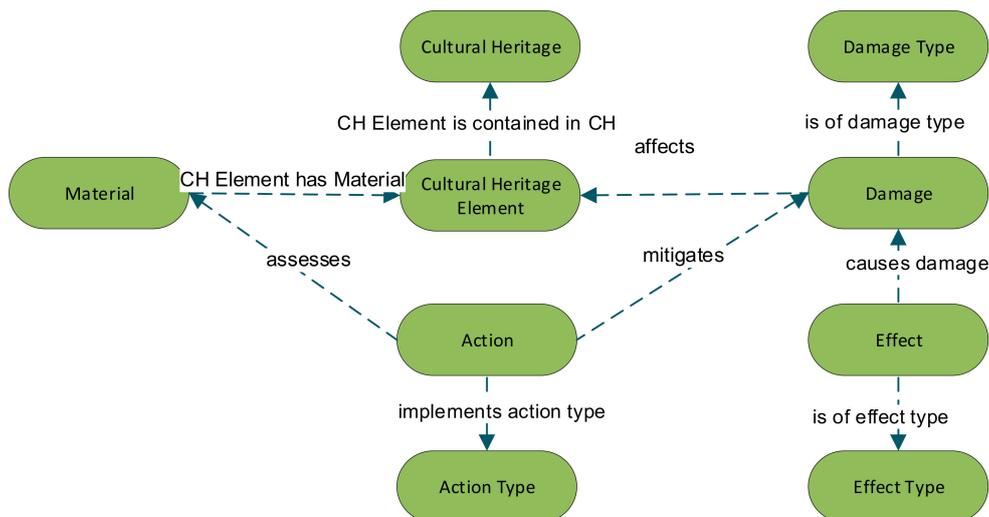
Figure 6. The core ontology.

4.3. Cultural Heritage

The class *Cultural Heritage* (Figure 7) allows for representing cultural heritages whose protection or management needs to be described. As stated in the UNESCO Convention concerning the Protection of the World Cultural and Natural Heritage from 1972, world heritage contains both cultural heritage as well as natural heritage [14]. The HERACLES project, and therefore the ontology, focuses on cultural heritage. The UNESCO separates cultural heritage into both tangible and intangible items. In the respective ontology, we target tangible cultural heritage. The subclass *Asset* of the parentclass *Cultural Heritage* represents all tangible cultural heritages. If a use case desires the integration of intangible cultural heritage, a second subclass of *Cultural Heritage* can be integrated. We chose this approach to hold capacities for an eventual expansion available.
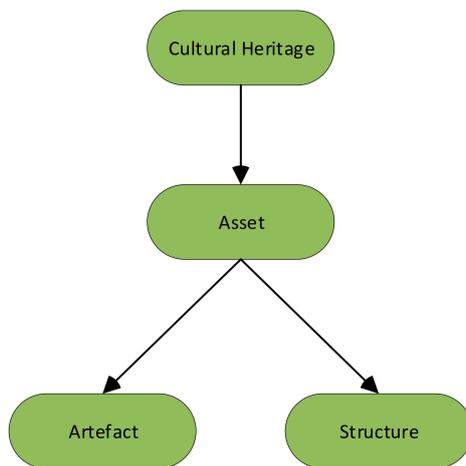
Figure 7. The domain Cultural Heritage.

Artefact describes cultural heritage monuments like works of monumental sculpture and paintings, elements or structures of archaeological nature, inscriptions and so forth. *Structures* eventually contains humankind-made structures, like *Monument* or *Building.* The structure arose due to the specifications of the HERACLES project and suited the needs of the project best.

4.4. Cultural Heritage Properties

Cultural Heritage has properties contained in Cultural Heritage Properties (Figure 8). To this point, the ontology distinguishes Vulnerability, Cultural Heritage Value and Visitor Numbers. Vulnerability and Cultural Heritage Value are introduced for the determination of Risk, which quantifies possible threats to the cultural heritage. The HERACLES project employs the total economic value analysis for the value assessment of a CH. The economic value is stored as Cultural Heritage Value. This class again contains both Direct Economic Value and Indirect Economic Value. Direct Economic Value describes the economic value created by admission charges or other sources of directly generated profit. The latter describes the economic effect by an enhanced community image, leading to, for example, positive tourism effects and social interaction. A further cultural heritage property is the vulnerability of a cultural heritage to an Effect. The vulnerability to a specific hazard is expressed by the likelihood of an actual damage occurring during the occurrence of an event. This likelihood can be calculated for the whole asset or for discrete sections of the CH. Visitor Numbers is the key performance indicator for the number of persons visiting the asset.
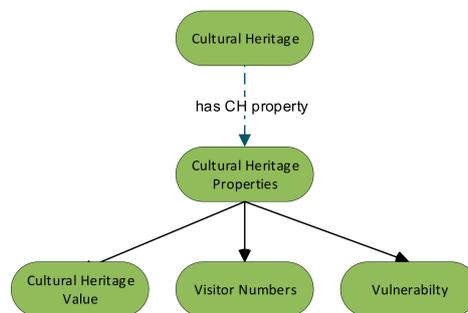
Figure 8. Cultural heritage properties of a cultural heritage.

4.5. Cultural Heritage Elements

The class *Cultural Heritage Element* allows spatial discretisation of a *Cultural Heritage*. The *Cultural Heritage Element* describes a spatial part of *Cultural Heritage*. It includes constructional parts of the building such as walls, rooms or ceilings but also special elements, upon which a scientist lays special focus. A *Cultural Heritage Element* is the object from which a *Measurement* takes samples of a *Material*, or where *Damage* can occur. The concepts are shown in Figure 9.

A *Cultural Heritage Element* can contain another *Cultural Heritage Element*. A wall can be part of room, which again can be part of a building wing.

Figure 10 shows three instances of a *Cultural Heritage Element*. *Building_Wing_1* contains *Room_S020* and *Room_S019*, which contains *Wall_2*. These instances can have measurements or damages attached: In this example, *Building_Wing_1* is affected by damage *Flaking_1*; *Room_S019* is affected by *Discoloration_2;* from *Wall_2* samples of material, *Limestone_1* and *Limestone_2*, have been taken.
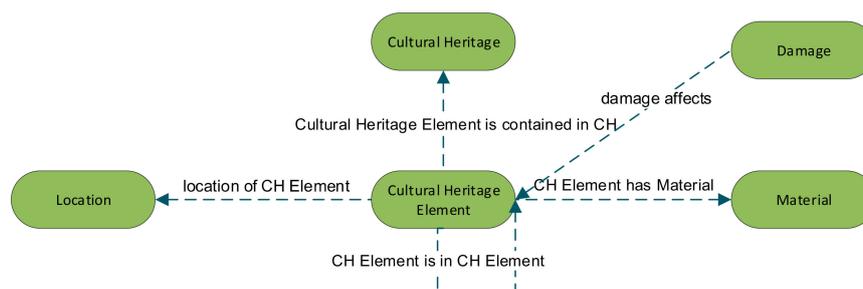

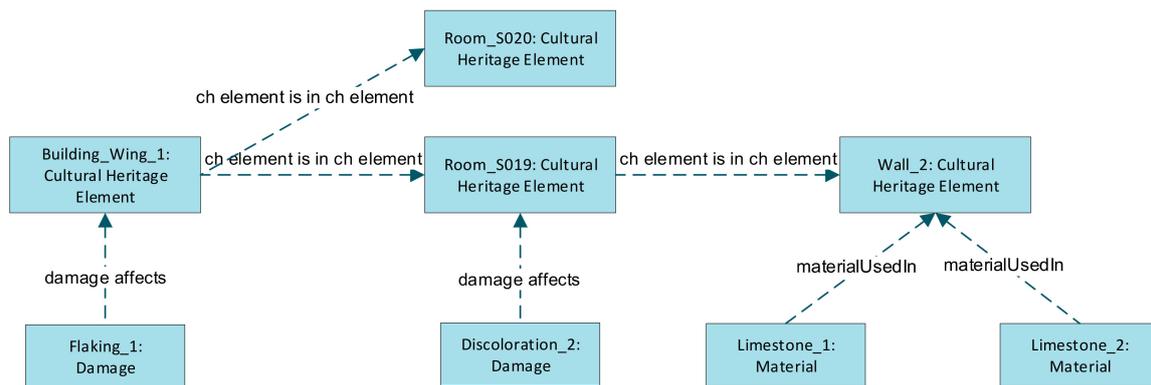**Figure 9.** The domain Cultural Heritage Element.

Figure 10. An example for possible instances in the Cultural Heritage Element domain.

4.6. Damage and Damage Type

The class *Damage* (Figure 11) describes actual changes that occurred on an instance of the class *Cultural Heritage Element* due to an event. In the adjacent class *Action*, the actions mitigating a specific damage are represented. The class *Damage Type* contains several descriptions of damages that can occur to a cultural heritage. By this modeling, we enable the ontology to categorize damages into several types and choose from *Action Type*, for which mitigation action might be appropriate.
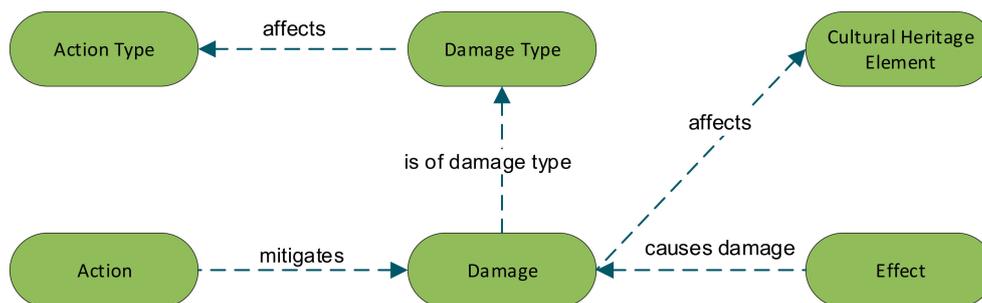
Figure 11. The domain Damage.

4.7. Effect and EffectType

Effect (Figure 12) contains all occurrences of abiotic factor induced climate events. This can be a real instance of a flood that occurred at some point in time or a real storm that hit the coast. *Effect Type* implements a differentiation between all effects. Instances in *Effect Type* are predefined and contain elements, such as *Heat Wave*, *Flooding*, *High Sea Level*, *Land Slide* and *Waves*. An instance of *Effect Type* can cause different instances of *Damage Type*, which enables us to predict or suggest possible damages caused by an incoming *Effect*. An actual occurrence of *Effect* can, but does not have to, cause an actual occurrence of *Damage*. An *Effect* is further described by a *Parameter*, a measurement of the surrounding physical phenomena.

Another important trait of *Effect* and *Effect Type* is both causing and being precondition for themselves. *Heavy precipitation* for instance can lead to a *Flooding* or a *Landslide*.

Figure 13 shows an example for damage on a *Cultural Heritage Element*, namely *Palace of Gubbio_Wall*. A damage *Crack_1* has been observed. *Crack_1* is of damage type *Structural Damage*. It occurred due to the effect *Frost_2018_1_13*. *Frost_2018_1_13* has the parameter *Temperature_1*. *Temperature_1* has attached *Parameter_Value_1*, with "-3.3"^^*xsd:float*, "$°Celsius$"^^*xsd:String*, "2018-01-13T14:30:00.000"^^*xsd:dateTime*, which refers to a temperature of -3.3 °C, recorded on 13 January 2018. The effect *Frost_2018_1_13* has another parameter *Humidity_1*, with *Parameter_Value_2*,

which has the values *"23.3"^^xsd:float*, *"%"^^xsd:string*, *"2018-01-13T14:30:00.000"^^xsd:dateTime"*, indicating the recording of the relative humidity of 23.3% on 13 January 2018.
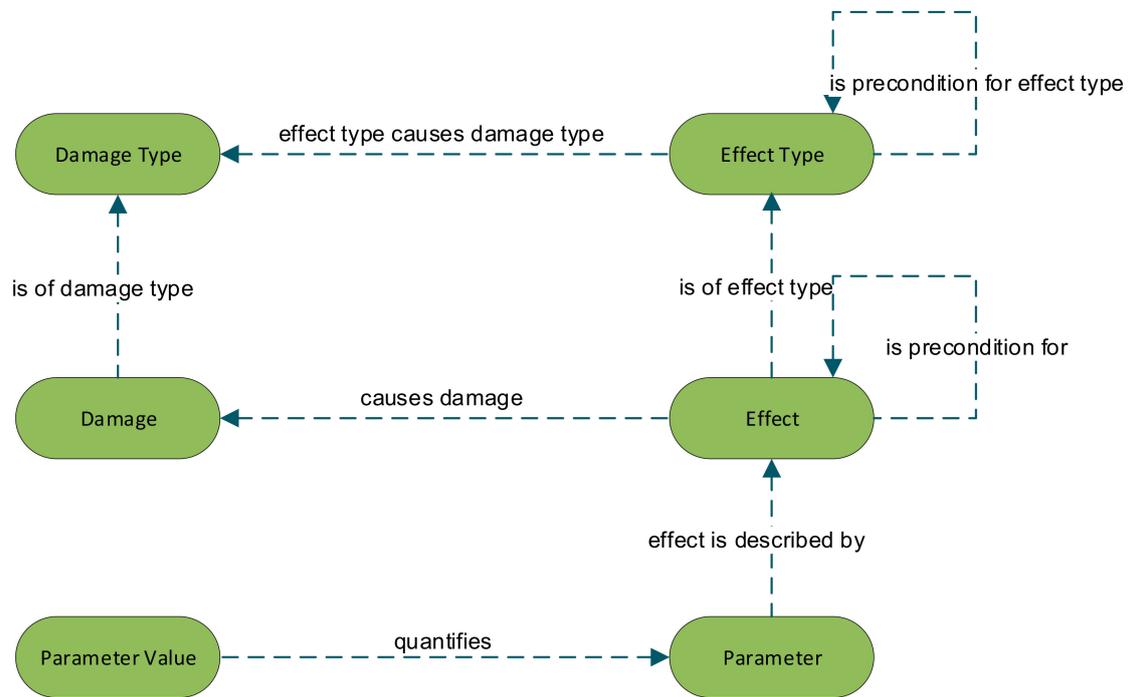

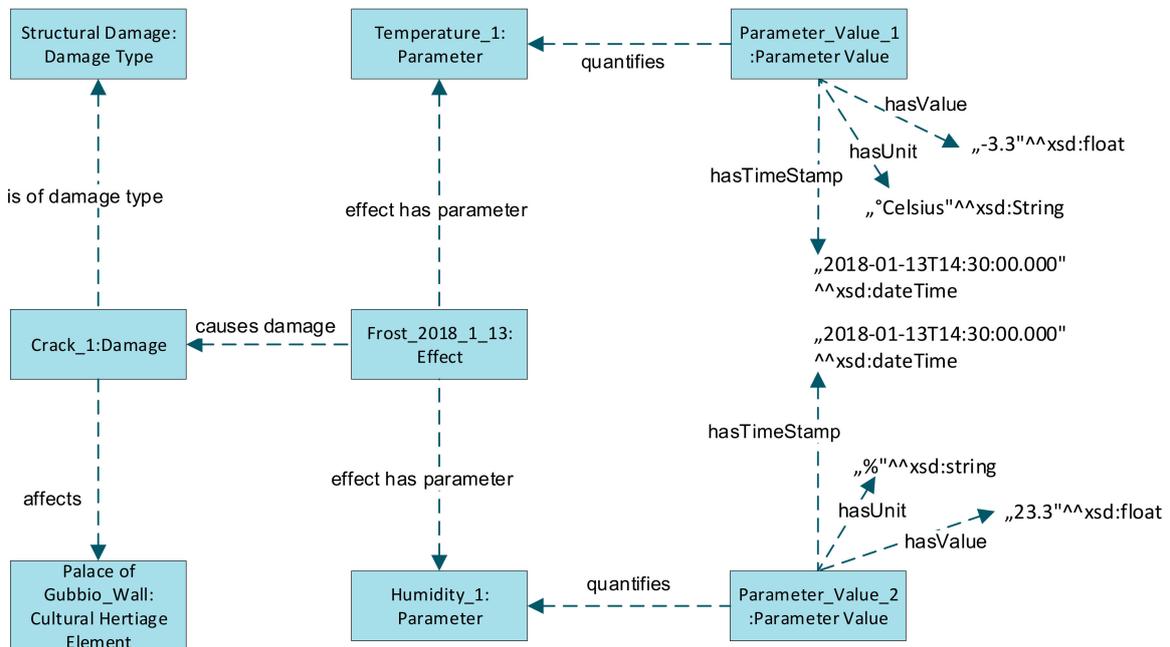**Figure 12.** The domain Effect.

Figure 13. An example for an example occurring on a CH.

4.8. Action and Action Type

An *Action* describes measures taken with the goal to monitor, analyse or preserve cultural heritage. *Action Type* categorizes *Action*. An *Action Type* can be included in a *Guideline*. Figure 14 shows the referring concepts.
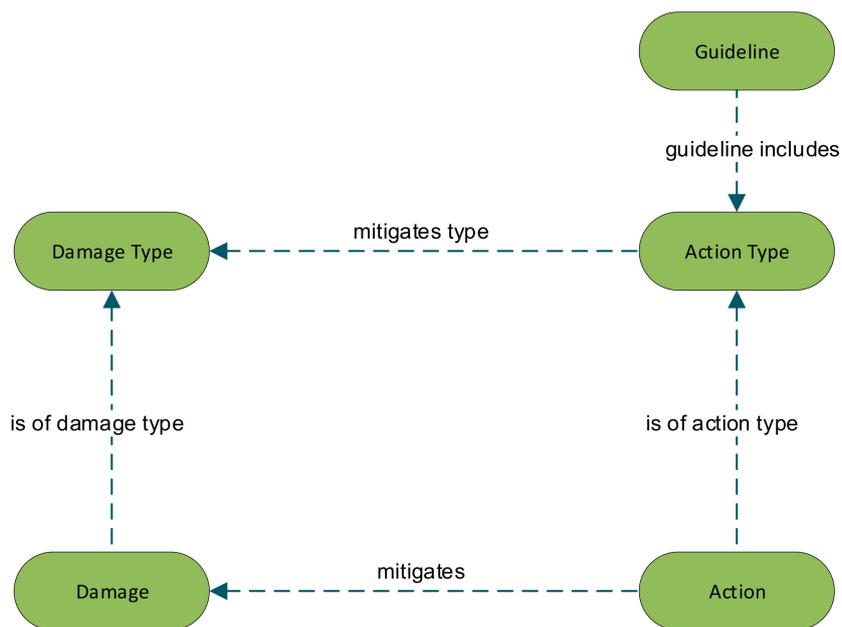
Figure 14. The domain Action.

An *Action* taken can be categorized as *Analysis and Diagnosis*, *Preventive Conservation*, *Remedial conservation* and *Restoration conservation*, subclasses of *Action Type*. An action in *Analysis and Diagnosis* can be a *Lab Test*, *Measurement Campaign* or *Simulation*, to name a few examples for one of the classes. By mapping potentially good conservation practices and types of damages, we enable our ontology to give suggestions on how to handles specific damage types. See Figure 15 for a conceptualization.
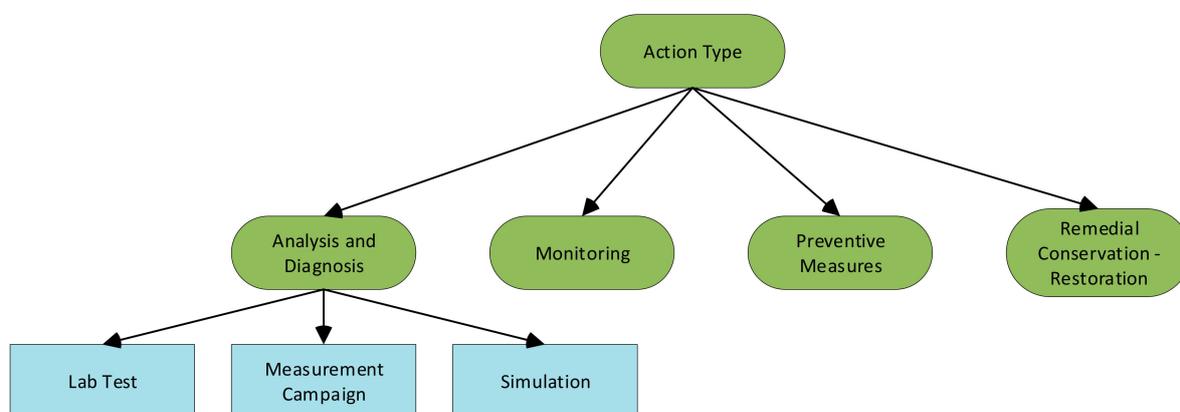
Figure 15. A closer look on the domain Action Type.

4.9. Material and Material Type, Material Property, Material Use

An integral part of the ontology is the domain of materials. This data model was developed in the light of the HERACLES project and—dependent on the use-case that the ontology shall be applied in—might require changes to structure information in a different project.

The class *Materials* (Figure 16) represents all different materials in the domain of cultural heritage management. It contains both the building material of the cultural heritage, as well as material that is used or analysed to conserve, protect, and maintain the heritage.
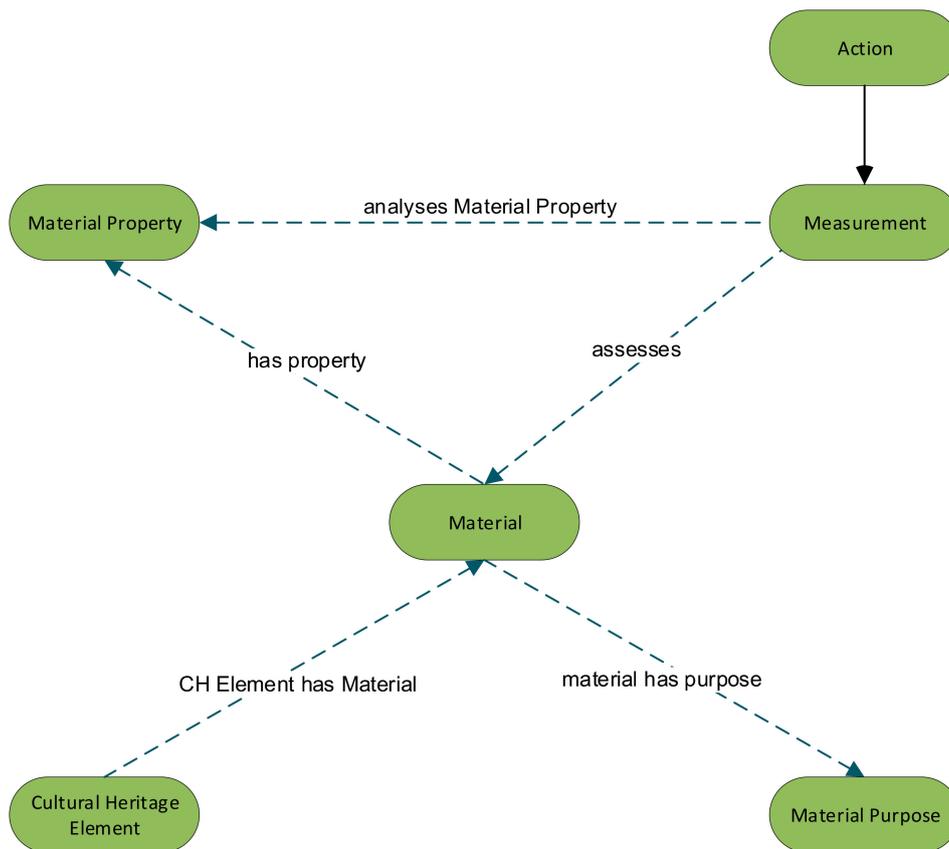
Figure 16. The domain Material.

Material Property incorporates the qualitative and quantitative characteristics of materials, especially those making them the preferred solution for a specific case of application. We distinguish between the properties that occurred until now in the HERACLES environment. A *Measurement* analyses the *Material Property* of a *Material*.

The child classes of *Material Property* have child-classes themselves. For instance, *Mechanical Property* has two child classes named *Compressive Strength* and *Hardness*. To keep the picture concise, they are omitted in Figure 17.
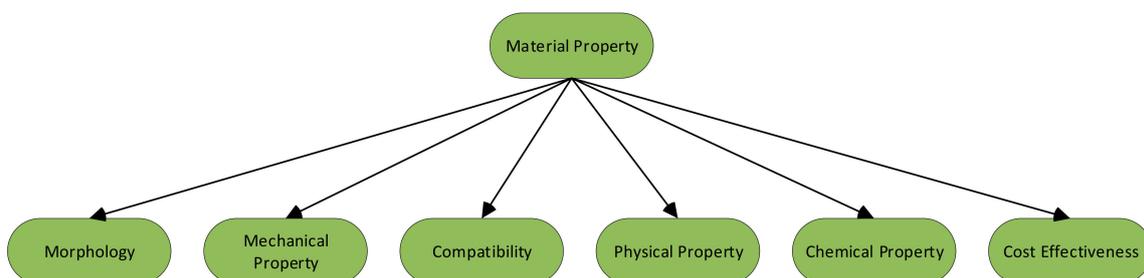
Figure 17. The domain Material Type Property.

An analysed material can have several properties, such as mechanical or chemical properties. The example in Figure 18 depicts a material *Limestone_1*, which has two properties: *Compressive Strength of Limestone* and *Hardness of Limestone*. Both instances have the datatype property *hasValue* attached. The graphic indicates the analysed material has a compressive strength of 115 N/mm^2 and a hardness of 4 on the Mohs scale.
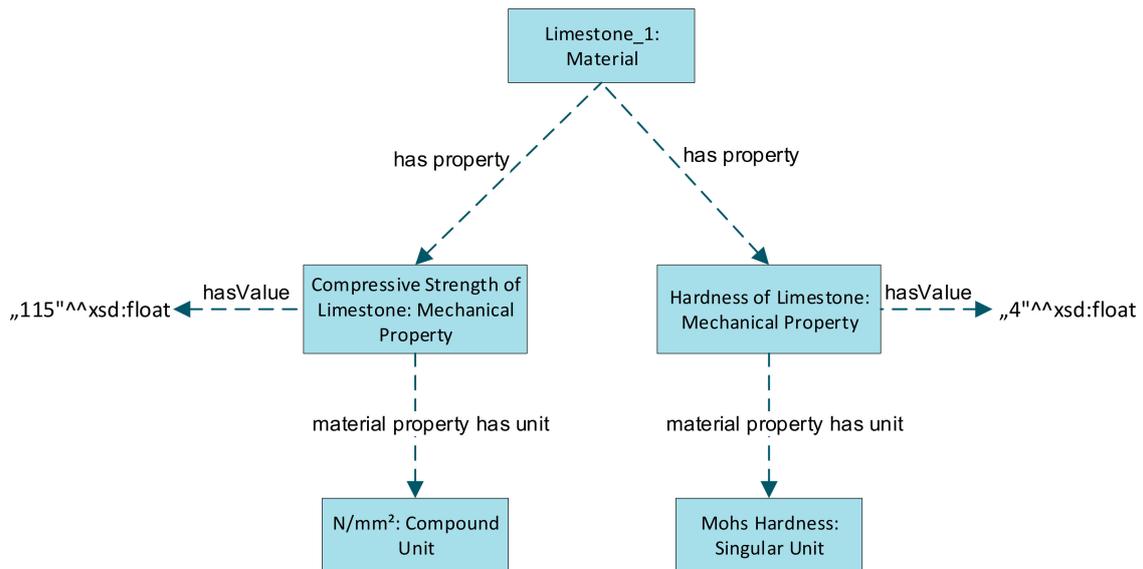
Figure 18. A possible set of instances in the domain Material.

4.10. Stakeholder

The domain *Stakeholder* represents all relevant stakeholders in the HERACLES project (Figure 19). Stakeholders can be single persons, represented by the class *Person*, or part of an *Organization*, that take action of responsibility for a *Cultural Heritage*. An *Organization* can employ entities from the class *Person*. An *Organization* can contain other *Organizations*, for instance a union or association. In *Organizations*, the ontology distinguishes between entities from *Private Sector* (e.g., conservation contractor), *Civil Society* (e.g., NGO for Cultural Heritage), and *Public Sector* (e.g., Ministry of Culture).
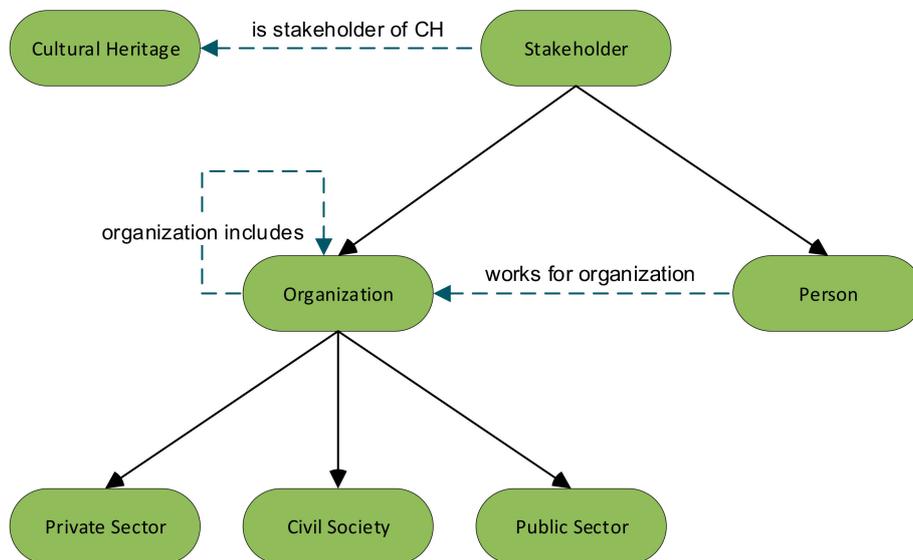
Figure 19. The domain Stakeholder.

4.11. Risk and Risk Assessment

The class *Risk* contains the expected value of harm for economic activity or environment of a cultural heritage. Risk is conceptually presented with the following basic equation:

$$Risk = Vulnerability \times Exposure,$$

where Vulnerability refers to the subclass *Vulnerability* and Exposure to the subclass *Cultural Heritage Value* of *Cultural Heritage Properties*. The concepts are shown in Figure 20.
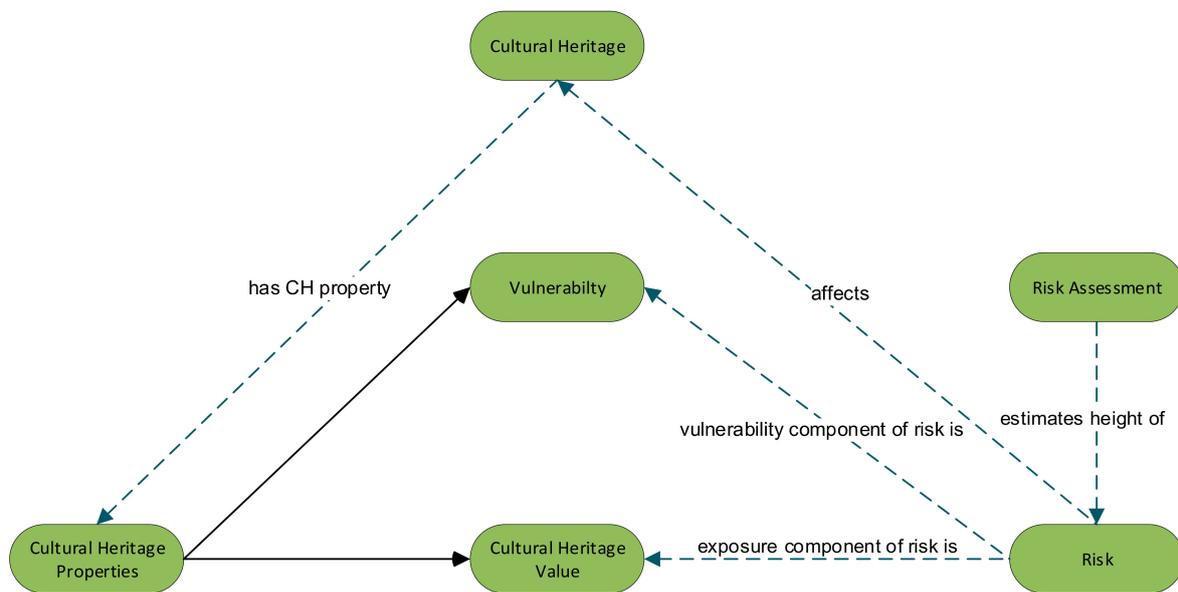

Figure 20. The domain Risk and Risk Assessment.

The basis for comparing diverse environmental risks and for ranking policy alternatives is *Risk Assessment*. Analysts must translate diverse outcomes into a common unit of analysis (*Risk*). Methods like cost–benefit analysis for restoration actions and willingness-to-pay (WTP) methods can produce the necessary outcomes.

4.12. Location

Location represents the necessary spatial information (Figure 21). It describes all relevant locations such as the position of a *Sensor* or where a *Measurement* has been taken.
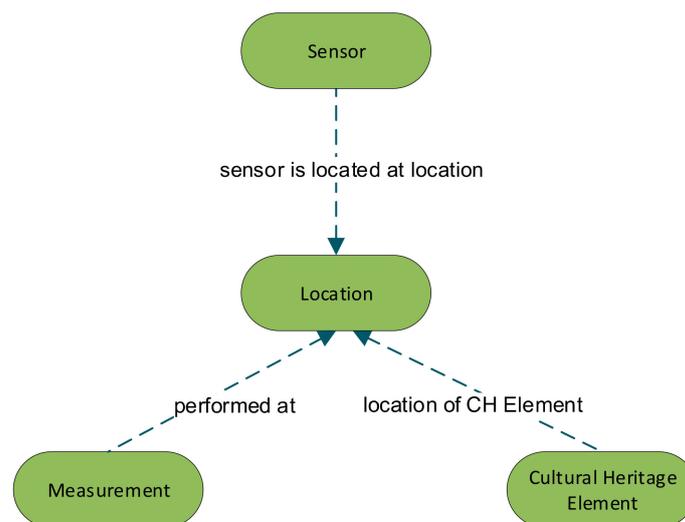

Figure 21. The domain Location.

5. Discussion

At this point, we differentiate 100 classes, 102 object properties (inverse properties, yield in sum 204 object properties) and 48 datatype properties. The ontology helps distinguishing climate change effects and their respective threats to cultural heritage. It supports CH management by including steering mechanisms for CH preservation damages and risks. By modelling actions and appropriate action types, it can record both actions and offers the suggestion of conservation actions. The same holds for material: the analysis of a material can be stored in semantic categories. Building on this knowledge and the differentiation of material and its purpose, suggestions regarding appropriate conservation material can be made. The model offers flexibility in monitoring the CHs health, no matter the data source or where measurements have been taken (in situ and ex situ).

6. Conclusions

In this paper we have presented an application-ontology, which was developed through consequent end-user focus. In the next phase of the HERACLES project, an evaluation of its components will be due in the next months. Here, further feedback about the ontology will be generated. The feedback will be retrieved by the means of four use-cases, one per test-bed. Since the use-cases have been considered in the ontology development since the very beginning of the project, the applicability to the test beds is given. Yet, through the expertise of the end-users, we aim for an ontology, which can easily transferred to other CH assets. Even after the end of the project, the ontology will continue serving as backbone of the HERACLES Knowledge Base. The end-users can continue using the platform and structure their newly generated knowledge according to the HERACLES ontology.

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