HeRO: A Semantic Framework for Heritage Risk Assessment in the SIRIUS Project

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Abstract

In recent decades there has been a change in perspective towards risk assessment in cultural and environmental heritage. Despite the positive impact of heritage on various aspects of society, it is often neglected in disaster risk management, mostly due to lack of strategies in sharing common methodologies and process knowledge. The SIRIUS project, centered in Ravenna (Italy), aims to localize global disaster management guidelines applied to cultural and environmental heritage. In the context of SIRIUS, a pattern-based OWL 2 DL ontology called the Heritage Risk Assessment Ontology (HeRO) is being developed to standardize risk assessment procedures and manage complex heritage risk data. In this contribution, its effectiveness is demonstrated through an in-depth exposition of its modules and an example scenario, promising practical application in an upcoming web-based tool. Future work involves semantic expansion, alignment with other heritage risk assessment methodologies, and further testing.

Keywords

Heritage Risk Assessment Ontology, SIRIUS Project, ABC Methodology, Ontology Development, Risk Assessment, Data Modelling, Cultural Heritage, Environmental Heritage, Digital Humanities

1. Introduction

In recent decades there has been a change in perspective towards risk assessment in cultural and environmental heritage [1]. The need to include cultural heritage at all levels in disaster risk management policies highlights the importance of collaboration between cultural heritage and disaster management organizations for enforcing effective action to safeguard heritage assets against top-level hazards such as climate change [2]. Cultural and environmental heritage have significant positive impacts on poverty reduction, sustainable development, economic prosperity and post-disaster resilience [3]. Despite this awareness, heritage is often not taken into account in disaster risk management planning, resulting in preventative measures being regularly overlooked [4]. Obstacles include the lack of validated management strategies, the need to consider multiple risk scenarios, and a lack of mechanisms and resources for knowledge sharing [5] [6].

The aim of the SIRIUS project[1], started by the Department of Cultural Heritage at the University of Bologna, is to prepare local adaptations of global guidelines for disaster risk management in the context of cultural and environmental heritage. Headquartered in Ravenna, Italy, the project uses the city as a pilot case study to collect and visualize risk-related data, share operational expertise, and raise public awareness. Ravenna is located in the Emilia-Romagna region on the Adriatic Sea and is often affected by sea level rise, subsidence and seismic activity. A recent flood in May 2023, which caused an estimated €9 billion in damage across Emilia-Romagna, highlights the region's vulnerability to the challenges of climate change and the need for recovery and sustainable management. With this in mind, the SIRIUS project explores how to promote greater community awareness through the development of a platform that assesses the risk associated with cultural heritage and efficiently disseminates this information to the public.

As a result, ATLAS - a tool for adding, managing and visualizing cultural heritage risk data - is being developed to help professionals with risk prevention and mitigation. As a first experimental step, a

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scaled and modified configuration of the ABC method [7] was used to identify and analyze risks based on various parameters. It also incorporates other assessment frameworks related to the field of cultural heritage, including the Ten Agents of Deterioration [8] and the principles listed in the Nara document [9]. Above all, the domain under consideration must be appropriately modeled and expressed in a way that facilitates computation, data management, and access to both the research community and the public. This, however, poses a number of challenges. As it turns out, risk assessment is a crucial and intricate process that involves identifying potential hazards, assessing their impact in terms of loss of value, and creating mitigation plans. Because risk and value are multifaceted concepts involving multiple perspectives, subjective judgments, and quantitative analysis, modeling them is problematic [10].

An ontology-based data model [11] was used to prepare ATLAS for efficient management of complex data related to heritage risk assessment. For a given domain of knowledge, ontologies act as formal representations [12] containing entities, properties, and logical rules that capture fundamental domain components and the interactions between them, and their main function is to develop a shared method for data representation and processing between computer systems in artificial intelligence, knowledge representation, and semantic web applications [13].

Considering the aforementioned premises, this study addresses the following research questions (RQs):

- **RQ1**: How can a precise machine-readable representation of the risk assessment process, as specified in the ABC methodology, be formulated according to the scientific and communicative needs of SIRIUS?
- **RQ2**: How can a representation of data entered and generated during the risk assessment process be modeled to ensure functionality within an application designed for domain experts, regardless of their technical proficiency?

To answer these questions, the article introduces the Heritage Risk Assessment Ontology (HeRO), a OWL 2 DL ontology intended to provide a framework for modeling machine-readable descriptions of risk assessment procedures.

The rest of the article is structured as follows. A summary of some of the most significant studies on ontology modeling in the field of risk assessment in general and in the more specific context of cultural heritage is given in Section 2. The process by which HeRO has been designed and developed is followed in Section 3. HeRO is introduced in broad strokes in Section 4, and its application is demonstrated in Section 5 through an example. In Section 6, conclusions are drawn regarding the work completed along with recommendations for future initiatives that will support SIRIUS goals.

2. Related work

In the existing literature, some authors [14] explore how ontologies can be used to formalize knowledge about risk assessment and management. These ontologies are largely based on the same motivations, which include the difficulty of finding, using, and sharing interoperable vocabularies for the purpose of organizing disaster management data, which in turns prevents collaboration among stakeholders and access to integrated disaster-related data. Therefore, most ontologies try to solve these problems by modeling terms that are commonly used in the risk management field, such as “Risk”, “Danger”, “Value”, and so on.

The Common Ontology of Value and Risk [10] is a ontology that formalizes the assumptions on value and risk. It aims to disentangle three perspectives: an experiential perspective, which describes value and risk in terms of events and their causes; a relational perspective, which emphasizes the subjective nature of value and risk; a quantitative perspective, which projects value and risk on measurable scales, allowing for quantitative analysis and comparison. While the model manages to cover most aspects related to both risk and value, it still lacks ways to represent concepts heavily dependent on methodological processes, such as risk mitigation and treatment.

A leaner, more modular approach is taken by [15] and [16], whose solutions are both based on the extensive use of Ontology Design Patterns (ODPs) [17]. While the former mainly focuses on the development of a specific ODP called Hazardous Situation[2] that is specifically designed to model the nuances of hazards and hazardous events, the latter reuses numerous ODPs to represent disaster situations and presents new reusable generalised patterns to describe high level constructs, such as quality dependence and event classification. Although these models are solid and promise interesting uses for the task at hand, they lack the specific emphasis on the "process" and "methodology" that aligns with the requirements of the SIRIUS project.

With regard to risk assessment in the field of cultural heritage, most ontologies are either inspired by or based on the CIDOC Conceptual Reference Model (CIDOC CRM)[3] [18], a foundational ontology widely used in the cultural heritage sector that provides a framework for representing and integrating information about cultural heritage artifacts and events [19]. However, risk assessment as a conceptual construct is not currently represented in CIDOC. Although work is being done to close this gap[4], current CIDOC-based ontologies are either very complex and verbose, or do not have the particular nuances needed to express process information according to a semi-quantitative assessment methodology such as the ABC method.

HERACLES [20] is an ontology for sharing knowledge related to the protection and safeguard of cultural heritage that is at risk from climate change. It addresses many different scenarios, including reporting, damages, and assets descriptions. In addition, it was implemented and verified in a functional knowledge management system. Nonetheless, it does not fully model the methodological processes of assessment, with the exception of certain activities such as maintenance and response actions.

To promise smooth data handling and presentation in the upcoming ATLAS web application, the data model of said application relies on a new semantic model called the Heritage Risk Assessment Ontology (HeRO). HeRO was developed following a twofold approach: first, it needed to accurately reflect the complexities of the heritage risk assessment process, which includes risk identification, analysis, and appraisal of metrics such as frequency and magnitude of risks (RQ1). Second, it should meet accountability and usability standards for practical implementation in a user-friendly, scientifically accurate application (RQ2). HeRO is largely organised as a collection of sub-classes and sub-properties of existing entities drawn from various existing ODPs. When necessary, new entities were defined to represent specific aspects highlighted in the ABC method, such as the classifications of the Agents of Deterioration and the Layers of Exposure. Otherwise, entities were reused exactly as they were if neither entity creation nor entity subsumption was required.

3. Methodology

3.1. Ontology development

The Simplified Agile Methodology for Ontology Development (SAMOD) [21] is an iterative process for developing fully documented and tested ontologies. It comprises three key phases: 1) development of a modelet formalizing a scenario within the domain of discourse and creating a test case that includes the modelet and supplementary resources such as glossaries, diagrams, and query examples; 2) merging of the modelet with the existing model from the preceding iteration, if it exists; 3) refactoring of the new model resulting from the merge step. At the end of each phase there is a testing step that includes model, data, and query tests. Successful completion of these tests is a prerequisite before proceeding to the next step. Each phase ends with the formal implementation of the ontology in its current state, referred to as a "milestone". These milestones incorporate all previous test cases, duly updated. In this way, the ontology turns out to be both compliant with the objectives it needs to address and easily extendable to a more precise description of the domain through further iterations.

[2]https://semantic.cs.put.poznan.pl/ontologies/oshdo/HazardousSituation.owl
[3]http://www.cidoc-crm.org/cidoc-crm/
[4]At the time of writing, the representation of risk assessment in conservation through CIDOC CRM is being addressed in this open issue: https://www.cidoc-crm.org/Issue/ID-482-cidoc-crm-interfacing-risk-assessment-in-conservation

3.2. Imported models

A number of ODPs and other commonly used semantic models were imported to form the basis of HeRO. As indicated at the end of the previous section, HeRO either subsumes its classes and properties under existing entities of other ODPs, or defines new ones - mostly individuals for certain categorisations - when these are not available, or simply reuses existing entities when no further specification is required.

`Classification ODP` [5] was used to represent the classification of risks according to different frameworks. In particular, agents of deterioration, layers, and risk types are considered concepts, while the particular relationships between a risk and these categories are different ways to classify that risk according to those categories.

`Participation ODP`[6] was used to express the participation of an agent to a risk assessment activity. In HeRO, agents are treated as objects participating in an event, while risk assessment activities are considered events that have agents as participants.

`Observation ODP`[7] was used to represent the situation in which the asset is observed within some contextual parameters during the context step. In particular, the concepts of temporally-defined observation and contextual parameter are refined and placed in the risk assessment domain.

`Region ODP`[8] was used to represent the various dimensional values and qualities taken into consideration during a risk assessment activity. In HeRO, measures related to risk such as frequency, fractional value loss, exposure and magnitude are all dimensional qualities (called "regions") characterised by having certain estimates as data values.

`Time Indexed Situation ODP`[9] was used to represent the activities that are part of a risk assessment process according to the ABC method. In particular, activities such as risk contextualisation, risk identification, risk analysis and value assessment are all considered time-indexed situations. Most of their relations with other elements (such as risks, values, and so on) are all properties that define the contexts for such situations.

`Time Interval ODP`[10] was used to represent the concept of period of time, characterised by a start date and an end date. In HeRO, the concept of time interval was directly reused along with its related properties in conjuction with the Time Indexed Situation ODP in order to provide a time parameter to a risk assessment activity.

Friend Of A Friend (FOAF)[11] [22] was directly reused for modelling utility entities, such as agents and documents, to be integrated into other patterns, like Participation ODP.

4. Results

4.1. Current status

The Heritage Risk Assessment Ontology (HeRO)[12] is an OWL 2 DL ontology that aims at providing a framework for modeling machine-readable descriptions of risk assessment activities for heritage risk management. To this end, it leverages, adapts and formalises methodological frameworks widely known in the cultural heritage domain, such as the ABC method.

The ABC method [7] is a risk management strategy that helps set priorities for preventive conservation by giving experts the ability to create a comprehensive picture of all risks, prioritise them, or find cost-effective ways to address them, create trustworthy documentation for upcoming reviews and monitoring, promote teamwork and participation, integrate scientific knowledge with institutional memory, and effectively communicate with decision makers. It is organised in five main steps. The

[5] http://www.ontologydesignpatterns.org/cp/owl/classification.owl
[6] http://www.ontologydesignpatterns.org/cp/owl/participation.owl
[7] http://www.ontologydesignpatterns.org/cp/owl/observation.owl
[8] http://www.ontologydesignpatterns.org/cp/owl/region.owl
[9] http://www.ontologydesignpatterns.org/cp/owl/timeindexedsituation.owl
[10] http://www.ontologydesignpatterns.org/cp/owl/timeinterval.owl
[11] http://xmlns.com/foaf/0.1/
[12] https://w3id.org/sirius/ontology/hero/1.0.0/

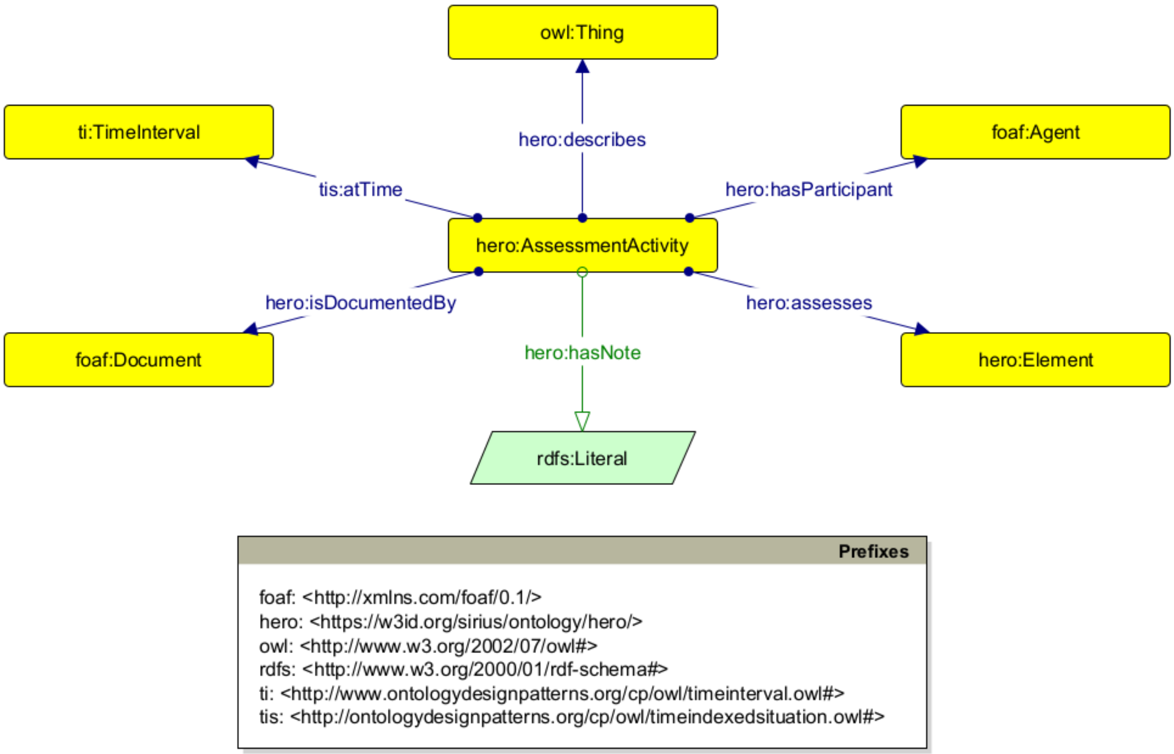

Figure 1: A visual diagram of the assessment activity.

first is the *Context* step, which involves the description of all relevant aspects of the context in which the heritage asset is being observed and evaluated for risks. The second is the *Identify* step, which involves the identification of each risk by classifying it in terms of the damage it can cause, its type and its localisation with respect to the asset itself. The third is the *Analyze* step, which involves the quantification of the chance of occurrence and expected impact of each risk, according to a series of measures. The fourth is the *Evaluate* step, which involves the evaluation of each specific risk in terms of some criteria to determine which takes priority over the others. The last step is the *Treat* step, which involves the planning and execution of risk reduction plans.

As previously mentioned, HeRO draws constructs from ODPs and uses them as super classes and super properties of its own entities to accurately represent the processes outlined by the ABC methodology, as well as the concepts and relations implicitly expressed in such processes. For example, an instance of an "assessment activity" in HeRO is described as a situation that is temporally parameterised and involves the evaluation of an asset considering a relevant assessment element. As a result, as illustrated in Figure 1, it has been modelled as a subclass of `TimeIndexedSituation` and `Event` (`hero:AssessmentActivity`), which describes an asset (`owl:Thing`) and assesses an "element" (`hero:Element`), a conceptual category that includes risks and values. Additionally, an assessment activity is designed to take place within a specific time frame (`ti:TimeInterval`) and involves the participation of one or more agents (e.g. a person, a group, an institution) (`foaf:Agent`). Lastly, information about an assessment activity can be recorded in text (via the data property `hero:hasNote`) and in documents (`foaf:Document`) as well.

So far, four iterations of SAMOD have been used to develop both the ATLAS data model and HeRO, with each iteration yielding a module that explains a specific step of the ABC method. The HTML documentation of HeRO was created using the Wizard for Documentation of Ontologies (WIDOCO) [23], which was utilized to extract the provenance information, labels, and comments from the ontology elements. HeRO's logical consistency was assessed using the OntOlogy Pitfall Scanner (OOPS) [24], which ultimately only found a small number of minor pitfalls connected to the other reused models (e.g.

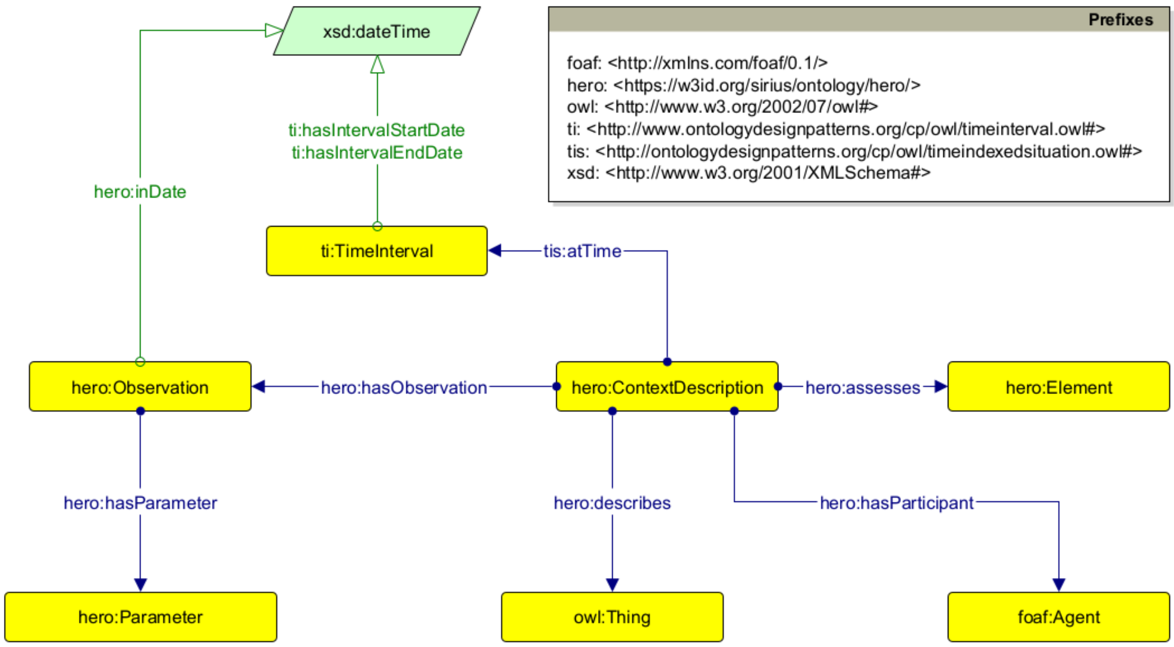

Figure 2: A visual diagram of the context step activity.

g. certain properties used in the Time Interval, Observation and Region ODPs have a missing domain or range). The visual diagrams illustrating the results of each iteration were produced with the Graphical Framework for OWL Ontologies (Graffoo) [25]. The terminology and assertion components, as well as HeRO itself, were compiled with Protégé [26] and expressed in Terse RDF Triple Language (Turtle)[13], a serialisation that provides syntactic sugar to the Resource Description Framework (RDF)[14] language. The complete documentation created during the development of the ATLAS data model and HeRO is available on GitHub[15].

4.2. First iteration: Context step activity

As illustrated in Figure 2, the modelet developed by the end of this iteration enables the description of an activity during the *Context* step. In particular, a `hero:ContextDescription` is an assessment activity in which something (`owl:Thing`) - such as an heritage asset - is described, within a certain time period (`ti:TimeInterval`), while some agent participates in it (`foaf:Agent`), through some kind of observation (`hero:Observation`), on the basis of some contextual parameter (`hero:Parameter`), such as the physical environment of the asset, its socio-cultural context, and so on.

Competency questions used in this iteration include:

- **CQ 1.1**: What is the contextual information of the heritage asset in terms of its type and description?
- **CQ 1.2**: Which documents provide information about the contextual details of the heritage asset?
- **CQ 1.3**: Who are the stakeholders involved in the contextualisation activity related to the heritage asset, and how are they identified?

4.3. Second iteration: Identify step activity

As illustrated in Figure 3, the modelet developed by the end of this iteration enables the description of an activity during the *Identify* step. In particular, `hero:IdentificationDescription` is an

[13]https://www.w3.org/TR/rdf12-turtle/
[14]https://www.w3.org/TR/rdf11-primer/
[15]http://purl.org/sirius/ontology/model-documentation

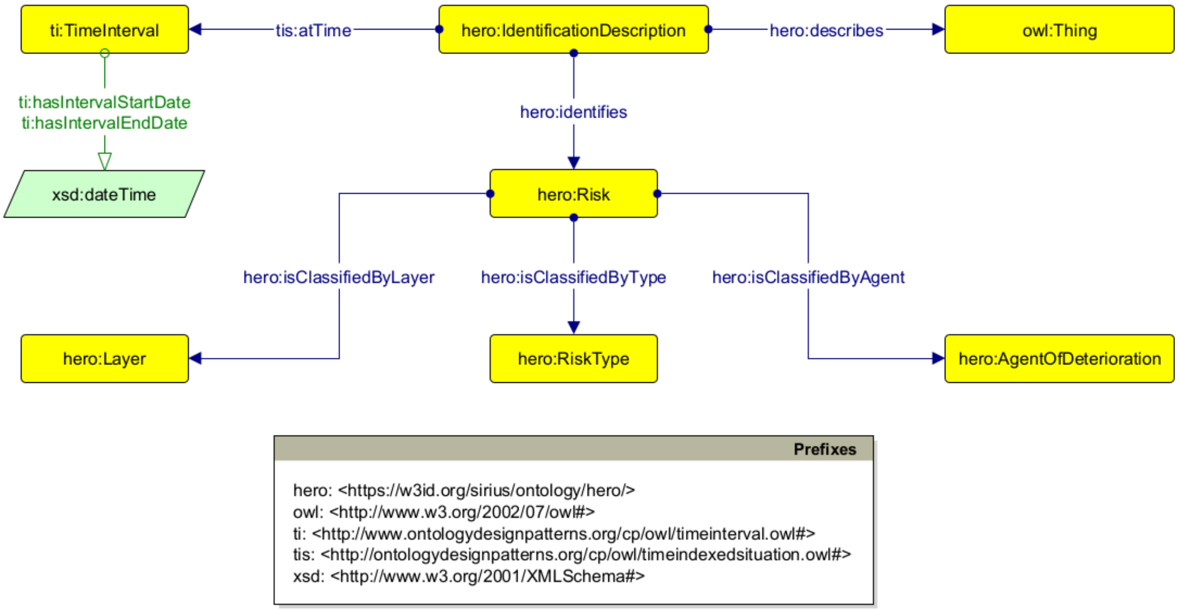

Figure 3: A visual diagram of the identify step activity.

assessment activity in which something (`owl:Thing`) is being examined in order to identify some risk (`hero:Risk`), within a certain time period (`ti:TimeInterval`). A risk, in turn, is characterised by being classified in terms of type (`hero:RiskType`), layer (`hero:Layer`) and agent of deterioration (`hero:AgentOfDeterioration`).

Competency questions used in this iteration include:

- **CQ 2.1**: What are the textual descriptions assigned to the risks, the agents of deterioration classifying them, and their types?
- **CQ 2.2**: Which risks are identified within the layers of the site or region, along with their types, the documents documenting them, and the start and end dates of the time intervals in which they have been identified?

4.4. Third iteration: Analyse step activity

As illustrated in Figure 4, the modelet developed by the end of this iteration enables the description of an activity during the *Analyse* step. In particular, the expected loss of value and the frequency or rate of occurrence for various risks are measured using a set of numerical scales known as the ABC scales. The three components of the ABC scales are Component "A" ("frequency" in HeRO), which measures the rate of occurrence or frequency of damaging events, and Components "B" and "C" ("fractional value loss" and "exposure"), which measure the expected loss of value to the heritage asset. The sum of "A," "B," and "C" determines the magnitude of risk. Thus, a `hero:AnalysisDescription` is an assessment activity for something (`owl:Thing`), in which some risk (`hero:Risk`) is analysed within a certain period of time (`ti:TimeInterval`) in order to quantify a set of measures (`hero:Measure`), each representing either the magnitude of the risk (`hero:Magnitude`), its frequency (`hero:Frequency`), the expected loss of value for each part that constitutes the asset (`hero:FractionalValueLoss`), or the fraction of the heritage asset value that will be affected by the risk (`hero:Exposure`). Each measure is characterised by a series of estimates that express the best (`hero:hasLowEstimate`), worst (`hero:hasHighEstimate`) and most likely (`hero:hasProbableEstimate`) scenarios.

Competency questions used in this iteration include:

- **CQ 3.1**: What are the probable estimates of the A-score, B-score, and C-score for each risk affecting each heritage asset, and what are the documents and textual notes recording them?

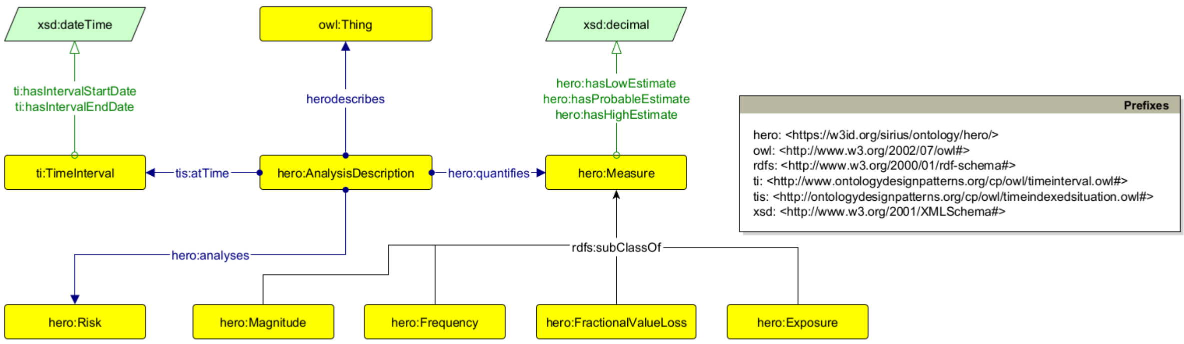

Figure 4: A visual diagram of the analyse step activity.

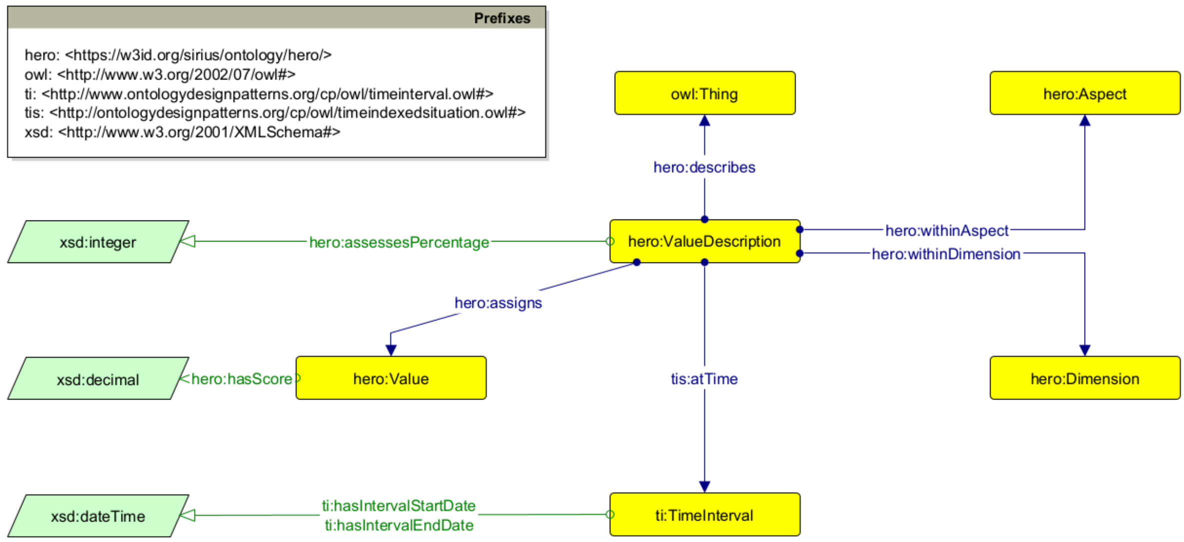

Figure 5: A visual diagram of the value assessment activity.

- **CQ 3.2**: What are the low, probable, and high estimates of the magnitudes of risk for each risk associated with each heritage asset?
- **CQ 3.3**: What are the low, probable, and high estimates of the A-score, B-score, C-score, and magnitude of risk for each risk affecting each heritage asset?

4.5. Fourth iteration: Value assessment activity

As illustrated in Figure 5, the model developed by the end of this iteration enables the description of value assessment activities. Although value assessment is not an actual step in the ABC methodology, it is nonetheless an essential task that must be completed in order to contextualize and analyze risks. It consists in examining the contributing values that embody the perceived significance of the asset. In particular, a `hero:ValueDescription` is a time-indexed situation for something (`owl:Thing`) wherein a value (`hero:Value`) is assessed within a given period of time (`ti:TImeInterval`) in terms of its aspect (`hero:Aspect`) and dimension (`hero:Dimension`). The “aspect” is a facet of the context that contributes to the overall understanding and assessment of an asset value (like the material composition of the asset or its function), while the “dimension” is a facet of a heritage asset that contributes to the overall understanding and assessment of its value (such as its artistic qualities or its social role). The data property `hero:hasScore` is used to assign a numerical score to each value.

Competency questions used in this iteration include:

- **CQ 4.1**: What are the contributing values assigned to an asset?

- **CQ 4.2**: What is the score of a contributing value?
- **CQ 4.3**: What are the dimension and the aspect of a contributing value?

5. Example: measures of heritage risk

As stated in the introduction, HeRO was created primarily to address the requirements scoped within the SIRIUS project and to be tackled while developing the ATLAS tool. This subsection provides an illustration of one potential use of HeRO to help address these questions.

In order to fully comprehend each identified risk, the *Analyse* step entails measuring each risk individually and estimating its likelihood of occurrence and expected impact. To do this, a specialist quantifies the expected loss of value and the frequency or rate of occurrence for various risks using numerical scales, also known as the ABC scales. The ABC scales are composed of three components: component 'A' measures the frequency of risk, while components 'B' and 'C' together measure the expected loss of value to the heritage asset implied by such risk (fractional value loss and exposure, respectively). More specifically:

- `Frequency` (A) indicates how often the event is expected to occur, i.e. the average time between two consecutive events, or how many years it will take for a certain level of damage to accumulate;
- `Fractional value loss` (B) indicates the size of the expected loss of value in each item of the heritage asset affected by the risk;
- `Exposure` (C) indicates how much of the heritage asset value is affected by the risk.

The expert will determine the magnitude of risk (MR), a metric that indicates the likelihood that each risk will result in a loss of value to the heritage asset, after assigning a score to each of the three risk components using the ABC scales. The expert must gather and evaluate data from documents, ranging from local statistics to scientific papers, in order to quantify each risk factor.

As with other phenomena described using scales - such as the Richter scale for earthquake intensity - for expressing wide-ranging values, both the components and magnitude of risk are expressed using logarithmic scales ranging from 1 to 5 (with half-steps in between). Each unit on these scales represents a factor of ten. For instance, on the frequency (A) scale, a score of 5 signifies a one-year interval between events or reaching the expected loss, while a score of 4 represents a ten-year interval, and so forth. On the fractional loss of value (B) scale, a score of 5 indicates a 100% loss of value, a score of 4 signifies a 10% loss, and so on. Similarly, on the exposure (C) scale, a score of 5 corresponds to 100% of the current asset value, a score of 4 corresponds to 10%, and so forth.

The goal of risk assessment is to estimate future value loss to the heritage asset while taking into account the inherent uncertainty. The ABC scales offer scores for the most likely, worst case, and best case scenarios for each risk component in order to convey this uncertainty. This yields three scores — low, most likely, and high — for every component, presenting the risk magnitude with three MR values — low, most likely, and high — indicating the degree of uncertainty.

HeRO makes it simple to compute risk measures and express the resulting data. To illustrate this, the following section discusses a HeRO application example that involves quantifying a set of measures and analyzing risks. The example is based on test data taken from [27], adapted to our case study, and encoded in Turtle. Every entity that makes reference to the test data has a unique base URI that is shortened by the prefix `ex` and corresponds to their particular SAMOD iteration[16]. The Turtle sources can be accessed by the general public at the `data` directory on the GitHub repository. Specifically, Listing 1 illustrates a small snippet of the ensuing situation, expressed in Turtle.

A museum is at serious risk from a large fire. National statistics indicate that a significant fire is predicted to occur roughly every 300 years, as indicated by the A-score, which ranges from A=2 (low estimate) to A=2.5 (probable estimate) to A=3 (high estimate). Because the museum's structure and contents are combustible, a complete or nearly total loss of value is expected for every item damaged in

[16] http://purl.org/sirius/ontology/data/example

the fire. This is represented by the B-scores of B=4.5 (low estimate), B=5 (probable estimate), and B=5 (high estimate). As a measure of the influence on the value of the heritage asset, the C-score goes from C=4.5 (low estimate) to C=5 (probable estimate) to C=5 (high estimate). Using MR=12 (low estimate), MR=12.5 (probable estimate), and MR=13 (high estimate), the degree of risk is evaluated.

Theft is yet another risk for the museum. In this example, staff notes indicate that the collection has suffered 3 theft events affecting objects on display in the past 75 years, estimating an average time of 25 years between theft events. The A-score in this case would be A=3 (low estimate), A=3.5 (probable estimate), A=4 (high estimate). A stolen item results in a complete loss of value for the museum and its public. The B-score is B=4.5 (low estimate), B=5 (probable estimate), B=5 (high estimate). The most probable scenario is the opportunistic theft of a small object of the collection displayed without protection. The C-score is C=1.5 (low estimate), C=2 (probable estimate), C=2.5 (high estimate), indicating a tiny fraction of the heritage asset value affected per event. The magnitude of risk is MR=9 (probable estimate), MR=10.5 (probable estimate), MR=11 (high estimate).

```
  ex:analysis-fire rdf:type owl:NamedIndividual ,
                            hero:AnalysisDescription ;
                 hero:analyses ex:museum-fire ;
                 hero:describes ex:museum ;
                 tis:atTime ex:2020-10-10 ;
                 hero:quantifies ex:museum-fire-a ,
                                 ex:museum-fire-b ,
                                 ex:museum-fire-c ,
                                 ex:museum-fire-mr .

ex:museum-fire-a rdf:type owl:NamedIndividual ,
                          hero:Frequency ;
                 hero:isDocumentedBy ex:national-statistics ;
                 hero:hasHighEstimate 3 ;
                 hero:hasLowEstimate 2 ;
                 hero:hasNote "National statistics from different
                 countries show that the average time between
                 large fire events for museums with basic fire
                 control measures is about 300 years. The A-score
                 in this case would be A=2.5, indicating an
                 expectation of a large fire once every 300
                 years."^^rdfs:Literal ;
                 hero:hasProbableEstimate 2.5 .

ex:museum-fire-b rdf:type owl:NamedIndividual ,
                          hero:FractionalValueLoss ;
                 hero:hasHighEstimate 5 ;
                 hero:hasLowEstimate 4.5 ;
                 hero:hasNote "Considering the combustible nature
                 of the museum building and its contents, a total
                 or almost total loss of value is expected in
                 each item affected by the fire."^^rdfs:Literal ;
                 hero:hasProbableEstimate 5 .

ex:museum-fire-c rdf:type owl:NamedIndividual ,
                          hero:Exposure ;
                 hero:hasHighEstimate 5 ;
                 hero:hasLowEstimate 4.5 ;
                 hero:hasNote "Given the characteristics of the
                 building and its contents, it is expected that
                 all or most of the heritage asset and its value
                 would be affected in the event of a large
                 fire."^^rdfs:Literal ;
```

```
                  hero:hasProbableEstimate 5 .

ex:museum-fire-mr rdf:type owl:NamedIndividual ,
                           hero:Magnitude ;
                  hero:hasHighEstimate 13 ;
                  hero:hasLowEstimate 11 ;
                  hero:hasProbableEstimate 12.5 .
```

Listing 1: A snippet of the situation described in the third iteration. An analysis activity analyses the risk of a museum fire and quantifies a series of measures.

Because of the way HeRO was modeled, it is relatively easy to query the data and return needed information for each measure. Listing 2 displays the SPARQL formalisation of CQ_3.3: "What are the low, probable, and high estimates of the A-score, B-score, C-score, and magnitude of risk for each risk affecting the heritage asset?"

```
SELECT ?risk ?measure_class ?low_est
?probable_est ?high_est
WHERE {
  ?analysis_description hero:analyses ?risk ;
                  hero:quantifies ?measure .
  ?measure a ?measure_class ;
                  hero:hasLowEstimate ?low_est ;
                  hero:hasHighEstimate ?high_est ;
                  hero:hasProbableEstimate ?probable_est .
  FILTER (
    ?measure_class = hero:Frequency ||
    ?measure_class = hero:FractionalValueLoss ||
    ?measure_class = hero:Exposure ||
    ?measure_class = hero:Magnitude
  )
}
```

Listing 2: The SPARQL query formalised from CQ 3.3, which yields the risk quantified by each measure, the type of measure, and its estimates.

As part of each iteration, a Jupyter Notebook[28] document has been used as a query testing ground for assessing the correctness of the formal competency questions and addressing the particular requirements they expressed. Table 1 displays the results yielded by the query CQ_3.3.

Table 1
The results of CQ 3.3, representing the low, medium and high estimates for each measure of the risks.

Risk	Measure_class	Low_est	Probable_est	High_est
Museum fire	Frequency	2	2.5	3
Museum fire	Fractional Value Loss	4.5	5	5
Museum fire	Exposure	4.5	5	5
Museum fire	Magnitude	11	12.5	13
Museum theft	Frequency	3	3.5	4
Museum theft	Fractional Value Loss	4.5	5	5
Museum theft	Exposure	1.5	2	2.5
Museum theft	Magnitude	9	10.5	11

Within a practical web application, these results would hold significant value for decision making. They could be shown through multiple visualisation techniques, such as structured data tables and tornado graphs, for a clear presentation of low, medium and high estimates for different risk measures in different scenarios. Additionally, the inclusion of narrative documentation provided by the expert serves as a critical complement to the quantitative data, providing insight and expertise necessary for strategic risk management. Finally, having this data expressed as machine-readable statements allows for the explicit representation and sharing of knowledge related to heritage risks. This also improves documentation and communication of the data, facilitates the integration with external systems, ensures flexibility in the representation of information, and facilitates the overall interoperability and scalability of the application.

6. Conclusions

HeRO aims to create a better system for publishing, organizing, and analyzing data about heritage risk assessment. It was developed with SAMOD, an agile methodology for ontology development oriented towards reuse of existing semantic models and patterns, and offers a fully reproducible, extensible, and dynamic ontological model. It takes into account future expansions to cover more information within the domain of heritage risk assessment, while ensuring the faithful addition, management, and visualization of heritage risk data.

For the task at hand, the approach has proven to be both effective and efficient. HeRO guarantees a machine-readable representation of the risk assessment process as intended by the ABC methodology. This was demonstrated by the overview of the different development iterations (**RQ1**). Furthermore, the heritage risk measurement example (*Analyse* step) demonstrates how even complex scenarios can be modeled using HeRO in a relatively simple manner and — more importantly — can be queried successfully using basic queries that can be easily integrated into a future web application (**RQ2**).

Nevertheless, the model is still in its infancy, and thus is limited in both its expressiveness and applicability in real-world scenarios. There are still many modules that need to be integrated in order to represent a full risk assessment process, including how to mitigate risks. Thus, more work is needed to expand and improve the model's semantics. This involves modelling the subsequent steps, such as the *Evaluate* step for determining risk prioritisation and the *Treat* step for planning risk reduction. In addition, the overarching workflow must be arranged into a logical structure, possibly by integrating HeRO with the Publishing Workflow Ontology (PWO)[17] [29]. Another current limitation that could lead to interesting future developments is HeRO's potential adaptability to diverse cultural contexts. Right now, the model is being developed with a precise type of heritage asset (physical, immovable) in mind and still within a western preservationist framework [6]. Thus, it certainly can be interesting to further explore the model's applicability to other forms of heritage (such as intangible cultural heritage) and how it can capture the shifting interpretation of concepts such as "risk" and "preservation" within different cultural contexts. Finally, along with confirming HeRO's adherence to FAIR principles [30], it is imperative to start experimenting with possible alignments to other heritage risk assessment methodologies, such as QuiskScan [31] and NICHE [32].

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