Ontology-based Representation of Crisis Management Procedures for Climate Events

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ABSTRACT

One of the most critical challenges faced by authorities during the management of a climate-related crisis is the overwhelming flow of heterogeneous information coming from humans and deployed sensors (e.g. cameras, temperature measurements, etc.), which has to be processed in order to filter meaningful items and provide crisis decision support. Towards addressing this challenge, ontologies can provide a semantically unified representation of the domain, along with superior capabilities in querying and information retrieval. Nevertheless, the recently proposed ontologies only cover subsets of the relevant concepts. This paper proposes a more "all-around" lightweight ontology for climate crisis management, which greatly facilitates decision support and merges several pertinent aspects: representation of a crisis, climate parameters that may cause climate crises, sensor analysis, crisis incidents and related impacts, first responder unit allocations. The ontology could constitute the backbone of the decision support systems for crisis management.

Keywords

Crisis management, ontology, semantic integration, decision support, description logics.

INTRODUCTION

The effective management of a climate-related crisis (e.g. flood, earthquake, forest fire, etc.) entails serious challenges for the authorities, the efficient handling of which is a key aspect for public security. One of the most critical challenges is the overwhelming flow of incoming information from artificial and human sensors (Babitski et al., 2011). The former type of sensors includes e.g. video footage from static cameras, water level and temperature measurements from deployed devices, while the latter type mostly includes social media posts, a rapidly increasing means for conveying information as a crisis incident unravels (Reuter & Kaufhold, 2017). All this vastly heterogeneous information has to be processed by the authorities and the numerous organizations involved in a crisis, in order to filter any meaningful items that could facilitate crisis management.

Towards addressing this challenge, recent trends in Crisis Information Management Systems (CIMS) turn to the use of *ontologies* for facilitating decision support during a crisis (Liu et al., 2013). Ontologies serve as the foundation for providing a semantically unified representation of concepts and relationships that is shareable by different users and is processable by machines (Grimm et al., 2011). Furthermore, ontologies are often associated with state-of-the-art logical reasoning services, which provide superior capabilities in querying and information retrieval, as opposed to standard SQL-based applications (Babitski et al., 2011). Finally, since nowadays a non-trivial subset of the knowledge and data useful to support a decision is available (in heterogeneous formats) in the Web, a further advantage of using an ontology-based representation is that it facilitates the integration of structured knowledge and data available on the Web (Rospocher & Serafini, 2012). This trait is also very useful with regards to information streams coming from social media.

The need to address the interoperability challenge in crisis management has led to the development of a diverse variety of relevant ontologies that provide interoperability in specific scenarios. A thorough overview of recent existing approaches is given in (Liu et al., 2013). However, although crisis management pertains several aspects (climate conditions, unit assignments, incidents and impacts, etc.), and, despite the variety in modelling approaches, the drawback with the proposed ontologies is that they cover only specific aspects relevant to their use case. Consequently, the resulting ontology-based systems have a narrow practical focus and provide only limited decision support to the authorities.

In this context, this paper proposes a lightweight ontology for climate crisis management, which adopts features from the most prominent existing models, but is more “all-around” and complete, merging all pertinent aspects of crisis management: representation of a crisis (along with climate parameters that may cause climate crises), sensor analysis, crisis incidents and related impacts, first responder unit allocations. The ontology constitutes the backbone of the decision support system developed in the context of the beAWARE EU-funded project[1] focusing on crisis management of climate events.

The rest of the paper is structured as follows: The next section presents existing prominent ontologies for crisis management, and discusses the comparative advantages of our proposed ontology. Next, an overview of the project’s user requirements is given, mapping the latter to ontology functional requirements. The ontology is presented in full detail in the next section, followed by a respective evaluation. The paper is concluded with final remarks and directions for future research.

RELATED WORK

The advent of semantic technologies (Hendler, 2009) has led to the widespread adoption of ontology-based approaches in numerous domains, including crisis management, amongst others. Several relevant ontologies have been proposed in literature, e.g. *SOFERS* (Liu et al., 2014), *ISyCri* (Truptil et al., 2008), and the approaches by Lauras et al. (2015), Mescherin et al. (2013), and Zavarella et al. (2014). A recent thorough review of the state of the art in crisis management ontologies is given in (Liu et al., 2013).

Besides the above, two of the most prominent approaches in crisis management and response are *MOAC* (Limbu, 2012) and *SoKNOS* (Babitski et al., 2011). MOAC (Management of a Crisis Vocabulary), is a lightweight vocabulary that provides terms for linking crisis information from three different sources: (a) traditional humanitarian agencies, (b) volunteer and technical committees, (c) disaster affected communities. The vocabulary has been developed based on contributions from various key stakeholders, like the Inter Agency Standing Committee (IASC)[2], the Global Shelter Cluster[3], and the Ushahidi platform[4], who were also involved

[1] http://beaware-project.eu/

[2] https://interagencystandingcommittee.org/iasc/

[3] https://www.sheltercluster.org/

[4] https://www.ushahidi.com/

in assessing MOAC's usability, functionality, and structure.

SoKNOS, on the other hand, is a set of ontologies ensuring that newly created information, as well as integrated sensor information, is semantically characterized, supporting the goal of a shared and semantically unambiguous information basis across organizations managing crisis incidents. The central SoKNOS ontology is a core domain ontology defining the basic vocabulary of the emergency management domain. Additional dedicated ontologies are used for representing resources and damages, and deployment regulations defining the relations between resources and damages. Furthermore, for the definition of system components, ontologies of user interfaces and interactions as well as geo sensors have been developed. Based on the aforementioned ontologies, additional specialized application ontologies can be defined for each application used in the disaster scenario. As indicated by the authors, all ontologies in SoKNOS have been developed in close cooperation with domain experts, such as fire brigade officers.

Finally, another highly relevant approach, albeit rather outdated, is the *BACAREX* ontology (de la Asunción et al., 2005), which is part of the SIADEX framework for facilitating the design of plans for fighting forest fires. More specifically, BACAREX is a heavyweight ontology of planning objects and activities related to the forest fighting plan in the Andalusian regional government. For every object stored, the ontology records both operational (e.g. geographic coordinates of the object) and informational metadata (i.e. information that may be needed by the technical staff during a forest fire incident, e.g. the radio channel of the responder responsible for a specific forest sector).

Overall, the ontologies reported above share the drawback of covering only a subset of the notions involved in climate-related crisis management (climate conditions, unit assignments, incidents and impacts). Contrary to these existing approaches, our proposed ontology consists of modules for representing *all* aspects pertinent to crisis management. Nevertheless, and as described in more detail in the next section, our proposed model adopts concepts from some of the existing ontologies as well, predominantly from MOAC and SoKNOS.

USER REQUIREMENTS AND ONTOLOGY COMPETENCY QUESTIONS

The basis for the creation of a climate-related crisis management ontology are the needs and requirements of the domain experts. The user requirements were extracted by domain experts in the context of an EU project, which aims at developing a framework providing various services before, during, and after the occurrence of natural disasters. A common methodology has been used to define the use cases and requirements of the system, starting with the identification of the status of available tools through an existing situation analysis, in order to clarify the current digital landscape concerning emergency service requirements. The requirements of the pilot cases at hand were studied by identifying and interviewing stakeholders concerned with integrated risk management (municipalities, regional/local civil protection agencies, etc.), focusing on their needs and the current gaps both in the situational awareness and command and control aspect of the disaster response.

Table 1. Subset of the user requirements.

UR#	Requirement name	Requirement description
UR_107	Localize video, audio and images	Provide authorities with the ability to localize videos, audio and images sent by citizens from their mobile phones.
UR_108	Localize task status	Provide authorities with the ability to localize first responders' reports regarding the status of their assigned tasks.
UR_109	Localize tweets	Provide authorities with the ability to localize Twitter messages concerning a crisis event.
UR_110	Localize calls	Provide authorities with the ability to localize phone calls to an emergency number concerning a crisis event.
UR_111	Detect elements at risk from video	Provide authorities with the ability to detect and count elements at risk (e.g. cars and people) from video and images sent from mobile phones and social media.
UR_120	Map of rescue teams and task evaluation	Display to authorities the location in time of first responder teams and provide the ability to evaluate in real time the execution of the assigned tasks with a global visualization of the activities performed.

First, a common structure and a related terminology were established; as a consequence, a general emergency situation is subdivided in scenarios, use cases and requirements. In detail, an *operational scenario* is defined as the environmental and ecological context of the natural disaster and its impact on the elements at risk and stakeholder assets. Furthermore, a *use case* is defined as a conceptual description of intended or expected utilization of the system to prepare for, respond to, or act upon the occurrence of the scenario or various aspects therein. This use case is defined and specified from an operational user's point-of-view. Finally, *user requirements* describe expectations, requests, and guidelines for functionalities, capabilities, and features of the system that would facilitate successful completion of the use cases. In the following, the list of requirements extracted from all the use case descriptions was clarified and shared among the domain experts (i.e. rescue teams, water management authorities). Table 1 contains an indicative subset of the user requirements, which the ontology can currently respond to; the full list of user requirements can be found in beAWARE deliverable D2.1 (Norbiato et al., 2017). These user requirements are catalogued as [*UR_xzz*], where *x* is the identifier of the scenario in which the requirement originated, and *zz* is the serial number of the requirement.

The user requirements are mapped to the ontology's *Competency Questions* (*CQs*). A competency question is a natural language sentence that expresses a pattern for a type of question people expect an ontology to answer (Uschold & Gruninger, 1996). The answerability of CQs hence becomes a functional requirement of the ontology. Based on the list of user requirements above, the ontology is able to respond to several CQs, such as providing the location of a specific media item (e.g. a tweet, video, image etc.), or indicate the number and type of vulnerable objects detected from videos.

THE PROPOSED ONTOLOGY

As already discussed previously, the proposed ontology semantically represents three key aspects of climate-related crisis management: (a) climate-related natural disasters and associated climate conditions, (b) analyses of data coming from human and artificial sensors, (c) unit assignments and mission status. This section delves deeper into the respective representations.

Ontology Language

The ontology language deployed for developing the proposed ontology is *OWL 2* (*Web Ontology Language*), a declarative knowledge representation language for formally describing a domain of interest, representing ontologies with formally defined meaning and semantics (W3C, 2012). OWL 2 is a W3C recommendation based on the solid mathematical background of *Description Logics* (Baader, 2003), and, thus, it currently constitutes the most popular ontology language.

For representing a given domain via OWL 2, one has to come up with a set of core terms, and to agree on their meaning as well as on their interrelations. The vocabulary (terminology), together with the interrelationships, constitutes the main context of an OWL 2 document. OWL 2 offers the following modelling building blocks:

- *Classes* provide an abstraction mechanism for grouping objects with similar characteristics, and denote the set of objects comprised by a concept. There may be diverse criteria for grouping objects/individuals and one individual may simultaneously belong to several classes. Classes can also form a hierarchy of more generic (superclasses) and more specific (subclasses) notions.
- *Individuals* of an OWL class (also referred to as class instances) are the objects belonging to this class.
- *Properties*, which are further categorized into: (a) *Object properties* that describe single individuals, class memberships, and how classes and individuals can relate to each other based on their instances; (b) *Data properties* that describe single individuals by asserting specific data values, either from pre-defined data types (e.g. string, integer, boolean, etc.) or within a data range expression defined by the user; (c) *Annotation properties* that give additional description to the domain being modelled, without having any effect on the logical aspects of the ontology.

Representing Natural Disasters

The representation of climate-related natural disasters in the proposed ontology is illustrated in Figure 1. Class "*Natural Disaster Type*" represents the various types of disasters, e.g. floods, forest fires, storms or earthquakes etc. Disasters may lead to other disasters (via property "*leads to*"); for instance, a heat wave may lead to forest fires, or storms may lead to floods. Each type of disaster is characterized by certain climate parameters, represented via class "*Parameter*"; for example, solar radiation and temperature are two parameters that characterize a heat wave. The scheme for representing environmental and meteorological conditions is based to some extent on the *PESCaDO* ontologies (Rospocher & Serafini, 2012), and, more specifically, we adopted a number of related properties from classes *EnvironmentalData* and *EnvironmentalNode*.

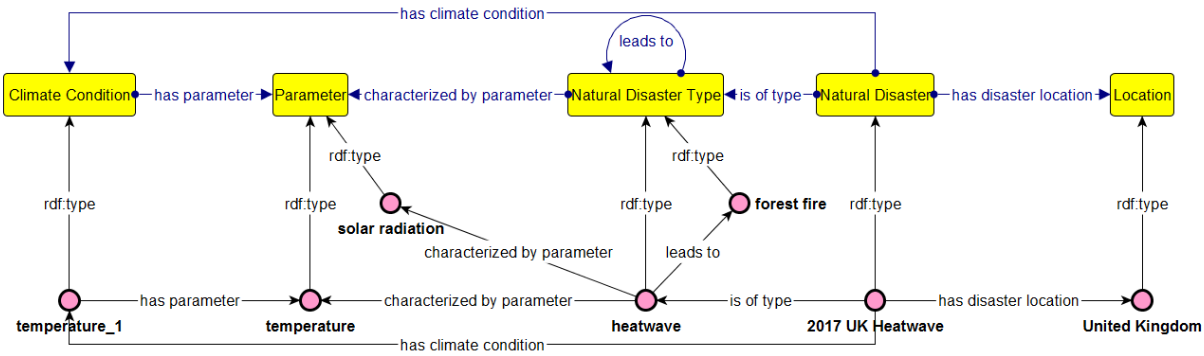

Figure 1: Representation of climate-related natural disasters in the proposed ontology.

Moreover, the actual manifestation of a natural disaster is represented via class "*Natural Disaster*", an instance of which has specific climate conditions with specific values. The figure displays a sample temperature measurement, which was recorded during the 2017 UK heatwave[5] (17-22 June). Note that in Figure 1 and in the following two figures, data properties are omitted for reasons of brevity.

Representing Analyzed Data

Besides the representation of climate-related natural disasters and pertinent notions, the proposed ontology also encompasses information relevant to the analysis of input data coming from the various sensors of the framework. This information is fed to the ontology from the various analysis components; the core constructs in the ontology are illustrated in Figure 2.

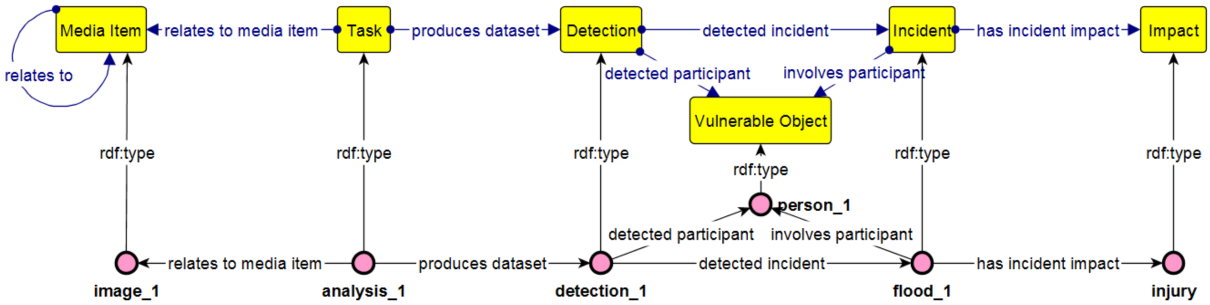

Figure 2: Representation of analyzed data in the proposed ontology.

Class "*Media Item*" represents an item of analyzed data, which is related to some analysis task (via class "*Task*"). Media items can be pieces of text, images, videos, or even social media posts, all of them submitted during the occurrence of a climate crisis. The analysis of the respective items (text analysis, image analysis or video analysis) produces a "*Detection*" dataset containing all relevant information (e.g., an object detection task may produce a dataset of detected incidents, objects, and confidence scores). The figure also demonstrates an example of a video analysis instance, where a potentially injured person is detected in the flood.

Note that the ontology already contains a complete typology of vulnerable objects (e.g. assets, stakeholders, infrastructure, buildings etc.), impacts and incidents, as well as various other properties (e.g. severity levels, confidence scores, detection timestamps etc.), that are not displayed in Figure 2 for reasons of brevity. Part of this scheme for representing disaster impacts is inspired by *MOAC* (Limbu, 2012), mainly classes *AffectedPopulation*, *CollapsedStructure*, *CompromisedBridge*, *Deaths*, *InfrastructureDamage* and properties *affectedby* and *impact*. Moreover, for categorizing damages and resources we were based on *SoKNOS* (Babitski et al., 2011), and, more specifically on the SoKNOS approach for representing damages and their association to resources (Babitski et al., 2009).

Representing Unit Assignments

The third component of the proposed ontology is responsible for semantically representing response unit assignments. The adopted representation is based on the approach proposed by the *OASIS* project (Couturier & Wilkinson, 2005), mainly the part for representing mission assignments to units and associating missions to

[5] http://www.bbc.com/news/uk-40353118

incidents taking place during the climate crisis.

Figure 3 displays the respective concepts in the proposed ontology. First responders (class "*Responder*") are assigned one or more missions (class "*Mission*"), which in turn relate to incidents that involve participating entities (class "*Vulnerable Object*"). A mission is also characterized by start and end time, status and mission priority; these properties are omitted from the figure but reside in the ontology.

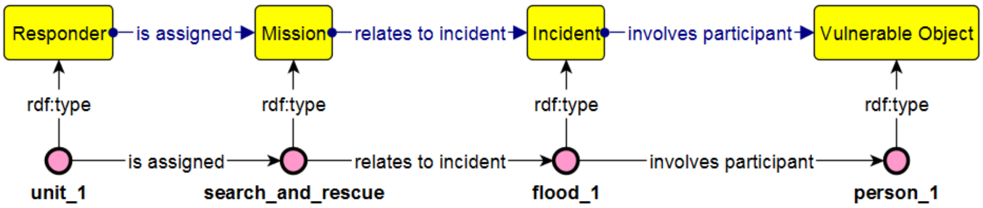

Figure 3: Representation of mission assignments to first responder units in the proposed ontology.

Finally, Figure 3 also displays a specific unit, which has been assigned the rescue mission of the injured person trapped in the flood (see Figure 2).

ONTOLOGY EVALUATION

This section presents an evaluation of the ontology, as far as *quality* and *structure* are concerned.

Evaluating the Consistency and Quality

For evaluating the consistency and overall quality of the ontology we used *OOPS!* (*OntOlogy Pitfall Scanner*), an online tool for detecting the most common pitfalls[6] in ontologies (Poveda-Villalón et al., 2014). After analyzing the ontology, OOPS! provides an indicator for each pitfall detected, according to their possible negative consequences, and suggests modifications in order to improve the ontology quality. The system detects (a) *critical pitfalls* affecting the ontology's consistency, which are crucial to be corrected; (b) *important pitfalls*, which are not equally critical, but are considered as important to be corrected; (c) *minor pitfalls*, which do not cause any critical problems, but correcting them will improve the quality of the ontology. Table 2 presents the pitfalls detected by OOPS! while evaluating our ontology, along with a brief description of their meaning and the number of cases for which they were specified.

Table 2. Ontology pitfalls detected by OOPS!.

No	Pitfall description	Results
1	*Missing annotations* (*Minor*): Ontology terms lack annotation properties that would improve the ontology understanding and usability from a user point of view.	76 cases
2	*Missing disjointness* (*Important*): The ontology lacks disjoint axioms between classes or between properties that should be defined as disjoint.	Applies to whole ontology
3	*Inverse relationships not explicitly declared* (*Minor*): This pitfall appears when any relationship (except for symmetric properties) does not have an inverse relationship defined within the ontology.	19 cases
4	*Symmetric or transitive object properties* (*Suggestion*): The domain and range axioms are equal for each of the following object properties. Could they be symmetric or transitive? "*leadsTo*", "*relatesTo*".	2 cases

Regarding pitfall #1, OOPS! detected 76 cases where annotations and descriptions were missing. To overcome this pitfall and to improve the ontology's expressiveness, we assigned human readable annotations to every defined concept in the ontology, with the adoption of properties `rdfs:label` and `rdfs:comment`.

Concerning pitfall #2, the tool warned on the absence of disjoint axioms. Specifying that classes are disjoint enables a system to validate the ontology more efficiently. We fixed this shortcoming by introducing disjointness between subclasses of the "*Task*" and "*Vulnerable Object*" classes.

[6] A catalogue of common pitfalls is given at http://oops.linkeddata.es/catalogue.jsp

Pitfall #3 issued a warning on the absence of pairs of inverse properties for all of the object properties in the ontology (19 cases in total). The pitfall was resolved by introducing the corresponding pairs of inverse properties into the ontology, in order to improve its completeness.

Pitfall #4 consisted of a suggestion about two specific object properties (see Figure 1 and Figure 2, respectively). In order to resolve this issue, we made the former property symmetric and the latter transitive.

Evaluating the Structure

For evaluating the structure, we relied on *OntoMetrics*[7], an online framework that validates ontologies based on established metrics. Table 3 presents the results derived from the analysis by OntoMetrics. *Base Metrics* comprise of simple metrics, like the counting of classes, axioms, objects etc.; these metrics show the quantity of ontology elements. *Schema metrics*, on the other hand, address the design of the ontology; metrics in this category indicate the richness, width, depth, and inheritance of an ontology schema design.

Starting with the base metrics, the total count of classes and properties indicates that the proposed ontology is rather a lightweight model, which could be easily adopted by various applications, contrary to heavier "monolithic" ontologies that pose significant challenges in integration. Furthermore, *DL expressivity* refers to the Description Logics variant the ontology belongs to (see also section "*Ontology Language*"). $SI^{(D)}$ indicates a simple ontology (universal restrictions, limited existential quantification) with inverse, transitive, and datatype properties.

Table 3. Ontology metrics produced by the OntoMetrics tool.

Base Metrics	Class count	38
	Object property count	37
	Data property count	22
	SubClassOf axioms count	21
	Disjoint classes axioms count	2
	Inverse object properties axioms count	18
	Transitive object property axioms count	2
	Symmetric object property axioms count	1
	DL expressivity	$SI^{(D)}$
Schema Metrics	Attribute richness	0.578947
	Inheritance richness	0.657895
	Relationship richness	0.609375
	Axiom/class ratio	10.184211
	Class/relation ratio	0.59375

Regarding schema metrics, the measurements in the table are adopted from (Gangemi et al., 2005) and (Tartir et al., 2010). *Attribute richness* is defined as the average number of attributes per class and can indicate both the quality of ontology design and the amount of information pertaining to instance data. The more attributes that are defined the more knowledge the ontology conveys. *Inheritance richness* is defined as the average number of subclasses per class and is a good indicator of how well knowledge is grouped into different categories and subcategories in the ontology. This measure can distinguish a horizontal ontology (where classes have a large number of direct subclasses) from a vertical ontology (where classes have a small number of direct subclasses). The respective value in the table indicates that the proposed ontology is somewhere in between; this is reasonable, since the ontology covers many aspects (breadth) while thoroughly modelling some of them (depth). *Relationship richness* refers to the ratio of the number of non-inheritance relationships (i.e. object properties, equivalent classes, disjoint classes) divided by the total number of inheritance (i.e. subclass relations) and non-inheritance relationships defined in the ontology. This metric reflects the diversity of the types of relations in the ontology. Finally, *axiom/class ratio* and *class/relation ratio* describe the ratio between axioms-classes and

[7] https://ontometrics.informatik.uni-rostock.de

classes-relations, respectively, and are indications of the ontology's transparency.

Compliance with User Requirements

As discussed in section "*User Requirements and Ontology Competency Questions*", user requirements are mapped to CQs that the ontology is expected to answer. Following the methodology proposed in (Zemmouchi-Ghomari & Ghomari, 2013), we translated the CQs into SPARQL queries (Harris & Prud'hommeaux, 2013) and evaluated the retrieved results. Table 4 includes an indicative set of CQs, along with their SPARQL translation and an evaluation of the retrieved result sets.

Table 4. Indicative CQs and SPARQL translation.

Competency Question	SPARQL query	Correct?

What is the location of each media item?	`SELECT ?item ?location WHERE {`
	`?item rdf:type :MediaItem .`
	`?location rdf:type :Location .`
	`?item :hasMediaLocation ?location .`
	`}`
		Yes

What is the location and mission status of each rescue team?	`SELECT ?team ?location ?status WHERE {`
	`?team rdf:type :Responder .`
	`?location rdf:type :Location .`
	`?mission rdf:type :Mission .`
	`?team :hasResponderLocation ?location .`
	`?team :isAssignedMission ?mission .`
	`?mission :hasMissionStatus ?status .`
	`}`
		Yes

Which affected vulnerable objects were detected in a specific video?	`SELECT ?object WHERE {`
	`?object rdf:type :VulnerableObject .`
	`?dataset rdf:type :Dataset .`
	`?task rdf:type :Task .`
	`?dataset :detectedParticipant ?object .`
	`?task :producesDataset ?dataset .`
	`?task :relatesToMediaItem :video_1 .`
	`}`
		Yes

What is the impact and affected vulnerable objects of a specific incident?	`SELECT ?incident ?impact ?object WHERE {`
	`?incident rdf:type :Incident .`
	`?impact rdf:type :Impact .`
	`?object rdf:type :VulnerableObject .`
	`?incident :hasIncidentImpact ?impact .`
	`?incident :involvesParticipant ?object .`
	`}`
		Yes

The set of CQs currently includes 29 queries translated into SPARQL, all of which have been evaluated positively. Nevertheless, as the project progresses, the ontology will naturally further expand, resulting in additional CQs being added to the original set of queries.

Publicly Available Version of the Ontology

A publicly available version of the ontology will shortly be released on the project's website, along with the respective project deliverable which is due June 2018, containing the ontology documentation and sample instantiations of the notions discussed.

CONCLUSIONS AND FUTURE WORK

This paper argued that existing ontologies for climate-related crisis management only cover subsets of the pertinent concepts, and proposed a lightweight ontology for semantically integrating all the relevant notions:

representation of a crisis, along with associated climate parameters, sensor analysis, crisis incidents and impacts, and first responder unit allocations. The paper also presented how the proposed ontology satisfies the requirements of the end users and discussed on the validation of the ontology. The ontology is already being deployed in the context of an EU-funded project, and can potentially serve as the underlying knowledge base for any crisis management system, providing authorities with superior decision support capabilities.

Regarding directions for future work, and besides iterative refinements to the model that will take place as the project progresses, further research will focus on the reasoning techniques, which will be applied on top of the ontology, in order to facilitate decision support. Our first aim is to provide mechanisms for generating automated warnings (including reports) based on the current situation and respective context stored in the knowledge base. Another imminent step is to have the end-users evaluate the ontology-based decision support and the recommendations provided by it. This assessment will take place in a few months' time, when the first pilot deployments will be evaluated in the field, and our findings will then be publicly released.

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