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A Modular Ontology for Semantically Enhanced Interoperability in Operational Disaster Response

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Abstract

Up to now, the world has witnessed how inadequate communication capabilities can adversely affect disaster response efforts. There are various Emergency Responders (ERs) that potentially must work together towards a successful resolution of the disaster. However, the different terminologies and technical vocabularies that are being exchanged between the ERs may lead to a misunderstanding and lack of semantic integrity. Yet, understanding the semantics of the exchanged data is one of the major challenges. The purpose of this work is to define the complex knowledge of the ERs by proposing a common and modular ontology shared by all the stakeholders so as to come up with a common shared vocabulary in order to ensure semantic interoperability between ERs. In this paper, we present POLARISCO and we discuss how it was developed using Basic Formal Ontology as an upper-level ontology and Common Core Ontology as a mid-level ontology to define each module.

Keywords

Semantic interoperability, modular ontology, upper-level ontology, mid-level ontology, disaster response.

INTRODUCTION

When a disaster occurs, a streamlined operational response organization is crucial to handle the disaster effectively. So as to respond within seconds, an appropriate and effective response depends on a detailed plan with clearly articulated roles and responsibilities. It involves a complex network of diverse Emergency Responders (ERs) from different Emergency Response Organizations (ERO) such as firefighters, police, health care services, etc. In fact, numerous after-action reports from major disasters (11 September 2001 and 13 November 2015 terrorist attacks, Hurricane Katrina, etc.) have cited communication difficulties among EROs as a major failing and challenge. The absence of adequate communication and information sharing between the involved actors in disaster response may lead to a break down at the operational response, stakeholders will not know what is happening exactly which will consequently extend the time required to bring a full resolution of the disaster while time is an important factor that has to be considered. Respectively, communication during a disaster is primordial. Information is the most valuable commodity during disaster response. ERs necessitate an ample need for timely information sharing and data exchange to obtain a real-time operational picture of the situation. But, each ERs has its own technical vocabulary. As a result, this discrepancy of information leads to a misunderstanding, a deficiency of semantic interoperability and lack of information sharing among the different actors. This can make the operational response process slow and inefficient. In this work, we aim to define the complex knowledge of the different ERs (firefighters, police, gendarmerie, health care services, etc.) so as to come up with a common shared vocabulary in order to provide the appropriate information at the right place and in the right moment (van Borkulo et al., 2006). Once this task is fulfilled, ERs can operate together and especially can understand each other in any critical situation which is the key to a better operational response (Zlatanova et al., 2004). To do so, a modular ontology has been developed to explore the semantics of the different ERs in the context of the project POLARISC (Plateforme OpérationnelLe d'Actualisation du Renseignement Interservices pour la Sécurité Civile) (Elmhadhbi et al., 2018). It is a French project which started in 2017. It proposes an interoperable inter-services software solution for reliable and timely information sharing for the operational management of large-scale crisis situations. The focus is about offering to all ERs a real-time operation picture of the situation in order to enable multi-stakeholders and multi-level coordination within the EROs including firefighters, police, gendarmerie, healthcare services, and public authorities. The proposed ontology POLARISCO (POLARISC Ontology) is the core of the system. It will be shared by all the stakeholders in order to enable semantically interoperable information exchange and a common understanding of what is happening on the field. Specifically, it employs Basic Formal Ontology (BFO) as an upper-level ontology and Common Core Ontology (CCO) as a mid-level ontology to present seven ontological modules. This paper is organized as follow. In section2, we overview the main ontologies related to operational disaster response. Section 3 goes into the details of the process of the development of POLARISCO then we present the proposed modules. In section 4, we discuss how POLARISCO is evaluated and is used as a shared vocabulary in a messaging service to enable semantically interoperable information exchange among ERs. Finally, conclusion and future work about our ontology use are presented.

Related work

The different interpretations of data cause semantic heterogeneity. To overcome semantic heterogeneity and to guarantee a consistent shared understanding of the meaning of information, the use of ontologies is crucial (Antunes et al., 2013). Ontologies have been identified as an effective means to implement semantic integration and achieve information interoperability. Ontologies are expressed in a logic-based language, so that accurate, consistent, and meaningful distinctions can be made among the classes, instances, properties, attributes, and relations to reveal the implicit and hidden knowledge in order to understand the meaning of the data. Thus, they offer the richest representations of machine-interpretable semantics for systems and databases. They serve as both knowledge representation and as mediation to enable heterogeneous systems semantic interoperability. With the increasing amount of data coming from different sources, there is a strong need to determine the meaning of the information to be exchanged precisely enough that a software application can interpret them (Nunavath & Prinz, 2017). So many application of ontologies addresses the problem of semantic interoperability, in which we have different users using various software tools that need to cooperate by exchanging data with unambiguous, shared meaning. In the literature, different types of ontologies and meta-models have been proposed to define the concepts related to disaster response. However, these latter are restricted to one EROs or to a specific case or purpose (Liu et al., 2013).

EMERGEL Ontology, proposed in the context of DISASTER project (Casado et al., 2015), mainly focusses on the mapping of different predefined information's artifacts, information representation and language between countries in Europe. It is composed of a core ontology (events, agents), a transversal module (time and space) and a vertical module (organization's specifications). It reuses the class event of the upper-level ontology DOLCE and other vocabularies such as FOAF (Graves et al., 2007) (peoples in an emergency situation) and the Organization ontology. However, this ontology lacks specific operational information (technical vocabulary of each ER). It can be more useful in decision making at the strategic level rather than the operational level. Moreover, Authors in (Fan & Zlatanova, 2011) looked for solving the problem of spatial data heterogeneity in emergency situations and their transmission to stakeholders by proposing an ontology. SoKNOS ontology (Babitski, 2011) includes resource planning, damages, and geo-sensor information. Regarding EDXL-RESCUER ontology (Barros, 2015), it employs EDXL (Emergency Data Exchange Language) to model the coordinating and exchanging of information with legacy systems. The focus is mainly on alerting people. Another ontology is proposed in (Chehade et al., 2018) for representing situations during rescue operations in order to support situations awareness. It aims to support French first responders in data interpretation during rescue operations. However, on one hand, the proposed ontology is not evaluated and implemented yet, on the other hand, it is dedicated only to firefighters and health care staff. In (Chan et al., 2017), authors proposed PS/EM Communication ontology (Public Safety and Emergency Management) in the context of IDA project (Institute for Defense Analyses). They were based on EDXL (Emergency Data Exchange Language) standards including resource messaging distribution element, hospital availability exchange and common alerting protocol. The ontology was constructed by adding specializations of the BFO and CCO classes. However, this ontology doesn't cover all type of communication between ERs, it is focused on alert messages.

To summarize, during our literature review, we found several ontologies developed in the context of disaster response. However, from one hand, these ontologies don't cover the knowledge of the different involved actors (firefighters, health care services, public order forces, public authorities, etc.) in the disaster response process.

From the other hand, they don't define the technical vocabulary that is used in the operational response such as action centers, functional sectors, operational roles, specific means and so on.

POLARISCO ONTOLOGY

In this work, we propose a modular ontology in order to capture the knowledge of the various stakeholders in a formalism reducible to a logic that expresses logical relationships between the different concepts, and to provide a foundation for semantic interoperability between diverse ERs. The aim is to ensure that all parties share the same extent of such derived information. That is, it aims to establish a common understanding of the shared information.

To build the proposed ontology, a methodology that guides and manages the development process is primordial. In fact, the efficiency of an ontology depends extremely on its development methodology. In (Karray et al., 2012), authors discussed the various methodologies proposed in the literature. In this work, we adopted METHONTOLOGY (Fernández-López et al., 1997) as a development methodology. According to (Corcho et al., 2003), it is the most mature approach to build an ontology. This methodology consists of five main steps of development activities: specification, conceptualization, formalization, implementation, and evaluation.

Specification

We started by identifying the purpose of defining this ontology. To do so, interviews were conducted with stakeholders and emergency experts so as to capture their needs and to analyze their experiences feedbacks. So, POLARISCO is a domain ontology built with the main goal of making the best possible definition of stakeholders' technical vocabulary. It was developed for establishing a common shared conceptualization that defines concepts and their relationships to support semantically interoperable information exchange among ERs involved in the process of operational disaster response. Afterwards, once the objectives are fixed, we used Competency questions (CQs) as a technique to define the ontology specifications. CQs consist of a set of question that the ontology must be able to answer (Grüninger and Fox, 1995). SO, POLARISCO should be able to answer the following defined CQs:
CQs1: When did the disaster [X] take place?
CQs2: Where did the disaster [X] take place?
CQs3: Who were the involved ERs in the intervention [X]?
CQs4: Who was the operational commander of the intervention [X]?
CQs5: Who was the public authority that commanded the intervention [X]?
CQs6: What were the acts of the intervention [X] of the ER [Y]?
CQs7: How many victims were resulting from the disaster [X]?
CQs8: What was the state of the victim [X]?
CQs9: What means were used in the intervention [X]?
CQs10: What are the available means?
CQs11: Where was located the action center [X] of the ER [Y]?
CQs12: Who are the sender and the receiver of the message [X]?
CQs13: What is the type of the message [X]?
CQs14: How many beds are available in the hospital [X]?

Regarding the diversity of ERs' vocabularies and process of intervention which may lead to a complexity during the knowledge conceptualization, we adopted the principles of modularization to build our ontology. Modularization is considered as a way to structure and organizing ontologies. Thus, the construction of a large ontology is based on the combination of self-contained, independent and reusable modules (D'Aquin et al., 2007). The main advantages of such a method, are manipulating smaller ontologies, reducing the complexity of ontologies development, and reusing each module independently. The idea is to develop separate ontological modules so that they could stand alone.
Then, to acquire knowledge about the field of disaster response, we conducted interviews with stakeholders of each EROs (firefighters, health care services, police, gendarmerie and public authorities) and we studied their technical resources and feedback documents to get specific and detailed knowledge about concepts, their properties, and their relationships. On the other hand, we studied many ontologies proposed in the field of disaster response to identify the needed terms including EMERGEL and RESCUER-EDXL, EDXL-RM (Resources Messaging), etc.

Conceptualization

In this phase, the domain knowledge is structured in a conceptual model. We first defined five modules to encapsulate the knowledge of the different involved stakeholders namely firefighters' module, health care services module, police module, gendarmerie module, and public authorities' module. Then, we defined a message module to represent the needed knowledge to formalize information exchange among ERs and to improve communication capabilities. After that, we built a Glossary of Terms (GT) for each module by referring to the knowledge elucidated during the acquisition step. Terms include classes, properties, instances, and relations that exist among the different classes. As a matter of fact, we found that there are several terms in common between the stakeholders' defined modules which led us to define a core module named PCO (POLARISC Common Core). It englobes the general terms that all stakeholders share (for example disasters, transmission means, victims, etc.) in order to ensure more semantic interoperability between the modules and to facilitate their integration. Next, we selected an upper level ontology as a foundation that provide the most abstract upper level classes to define the more specific information. In (Elmhadhbi et al., 2018), several upper level ontologies have been discussed and we argued our choice of BFO as an upper-level ontology and CCO as a mid-level ontology. In fact, BFO (Arp et al., 2015) is a realist, formal and domain-neutral upper-level ontology, it is designed to represent at a very high level of generality the types of entities that exist in the world and the relations that hold between them. It is utilized as a starting point for the categorization of entities and relationships by more than 250 domain ontology including an ontology-based system used by the US army. As a starting point, BFO uses the term *entity* as a common representation of anything then there are two main division of the class entity: *Continuants* and *Occurrents* in a single framework as a top level distinction between entities. Continuants are entities that persist through time including three axes; objects (Material entity) or and spatial regions (Immaterial entities) as Independent continuant, functions and qualities as Specifically independent continuant and finally, Generically dependent continuant. Occurrents are entities that happen or develop in time such as process. BFO was then supplemented with a set of mid-level ontologies CCO (Rudnicki, 2016) which are the Information Entity Ontology, the Agent Ontology, the Quality Ontology, the Event Ontology, the Artifact Ontology, the Time Ontology, the Geospatial Ontology, the Units of Measure Ontology, the Currency Unit Ontology, and the Extended Relation Ontology.

So, in POLARISCO, classes of each module were classified according to BFO and CCO classes and properties. Figure 1 illustrates the structure of the proposed modules. The purpose behind the use of BFO and CCO is to provide a common ontological foundation for domain ontologies which describe the most general domain-independent categories of reality. It is advantageous to use a common upper layer of well-defined terms to develop the different modules since the ontology will be shared among the involved stakeholders. Indeed, the use of upper-level ontologies facilitates the alignment between several domain ontologies and enable interoperability between them. In other words, if the ontologies to be mapped are driven from a standard upper-level ontology, this will make the mapping task very easy. In addition, upper-level ontologies play the same role as libraries in software programming tasks. Once they are used, one could reuse the defined concepts and relationships and so as to inherit the inferencing capabilities furnished by them. In this way, developing a domain ontology is an easier task that requires less time than usual. Moreover, the aim is to avoid having several incompatible domain ontologies. The usage of upper-level ontologies for integrating information and sharing knowledge among heterogeneous sources has been motivated in various related works (Baumgartner and Retschitzegger, 2006) (Elmhadhbi et al., 2018).

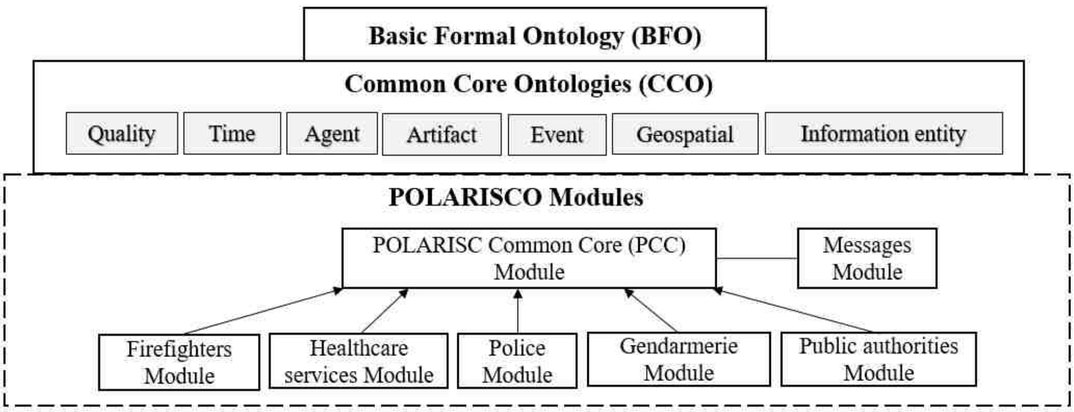

Figure 1. The different modules of POLARISCO

Formalization

After defining the modules and the related GT, in this phase, the conceptual model is transformed into a formal model by establishing relations between concepts. To connect the different concepts, we used a hybrid approach, based on a top-down alignment to the upper-level ontology BFO and the mid-level ontology CCO and a bottomup alignment to define classes of stakeholders' module and message module by reusing PCC module. That is to say, we approach in two ways by generalizing high-level concepts to lower levels and by abstracting the low-level data to the higher level concept. So, BFO and CCO are extended to define POLARISCO modules. In fact, CCO reuse the Relations Ontology (RO) (Smith et al., 2005) which is a collection of OWL2 relations intended to be shared among various ontologies. Moreover, another ontology called RO-Bridge has been developed by adding domains and ranges constraints to the object properties defined in RO to be used to relate BFO classes. The relations of RO-Bridge that are reused in POLARISCO are presented in table 1.

Table 1. The reused RO-Bridge relations

Relation	Domain	Range
"has_role"	Independent continuant	role
"has_quality"	Independent continuant	Quality
"supervises"	Person or organization	Person or organization
"has_participant"	Process	Person
"located_in"	Material entity	Spatial region or site
"occurs_on"	Process	Information entity
"is_part_of"	Independent continuant	Independent continuant

In the following, we represent first the various classes and their relationships of PCC module that will be reused to define each stakeholder module. Figures 2 illustrate a partial view of PCC module. Classes reused from BFO and CCO are marked with a prefix. Concerning the occurrent entities, we first defined a *disaster* as a *process*, it can be *natural* (earthquakes, floods, tsunamis, wildfire, tornadoes, etc.) or *human-made* (explosion, terrorist attacks, chemical threats, etc.). *Acts* are performed to manage disasters in an *action center* which is a sub-class of *spatial region*. ERs' acts are done as part of a real *intervention* or *training*. These two classes are integrated as a process. Concerning the continuant entity, an act is characterized by a *type* depending on the nature of the disaster. Furthermore, a *role* is accorded to each *organization member*. An organization member or an ordinary person can have the role of a *victim*. A *victim* is characterized by a *state*. In addition, *infrastructure* (hospitals and digital radio networks), *mean* (transmission mean such as radio or telephone) and *equipment* (beds) are defined as an *artifact*.

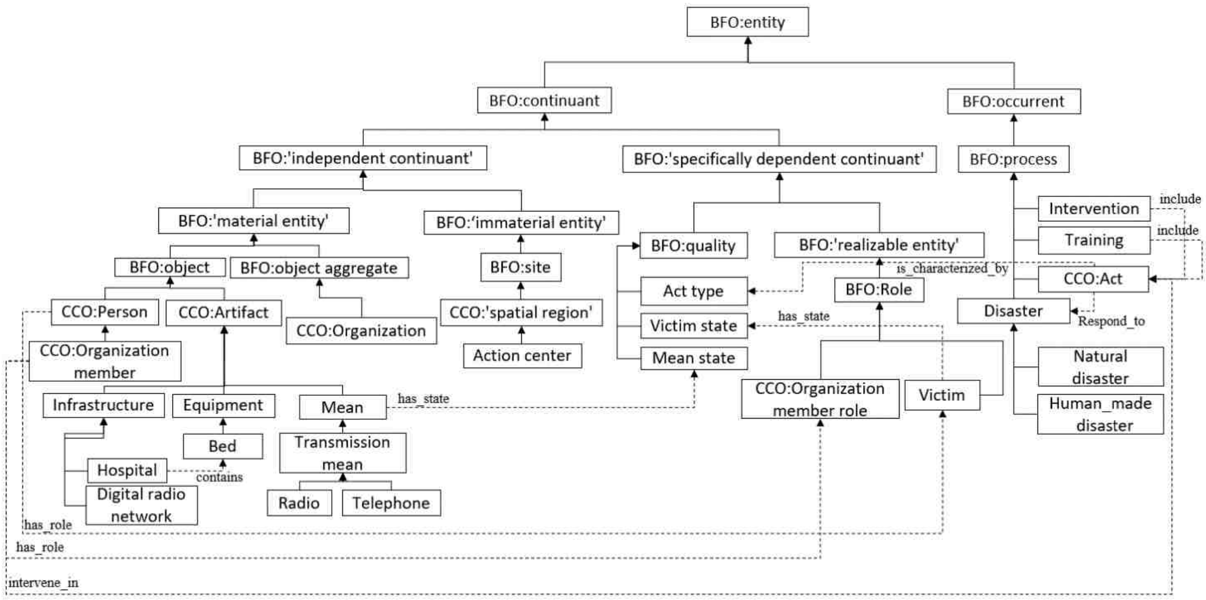

Figure 2. POLARISC Common Core (PCC) module

Concerning the stakeholders' modules, we formalized each one according to the PCC module. That is, we used PCC module as a starting point, and then we added the appropriate concepts related to each module. So, we defined the technical vocabulary of each ER (firefighters, health care services, police, gendarmerie, and public authorities) including mainly roles, commandment, and operational members, services, acts, means and their functions and availability, action centers, etc. Furthermore, we added the interventions' needs in terms of means and staff. Figure 3 shows a partial view of the stakeholders' modules.
Indeed, one of the principles to respect in building useful ontology is that any term of the ontology should be defined in a consistent manner (Arp et al., 2015). So, we defined annotation for each class (definition, the signification of the abbreviation, labels, etc.). Then, we defined relations that exist among the various modules and especially the equivalent classes. Each module has at least one relation with other modules. For example, the public authorities' module is linked to the rest of the stakeholders' modules with the relationship "supervises". That is to say, the interior minister supervises the commandment member of each ER. In fact, annotation and equivalent classes will have a key role later in the messaging service. Specifically, it will enhance communication capabilities and enable the transformation of the exchanged information from one stakeholder to another. So, each stakeholder will receive information according to his own vocabulary.

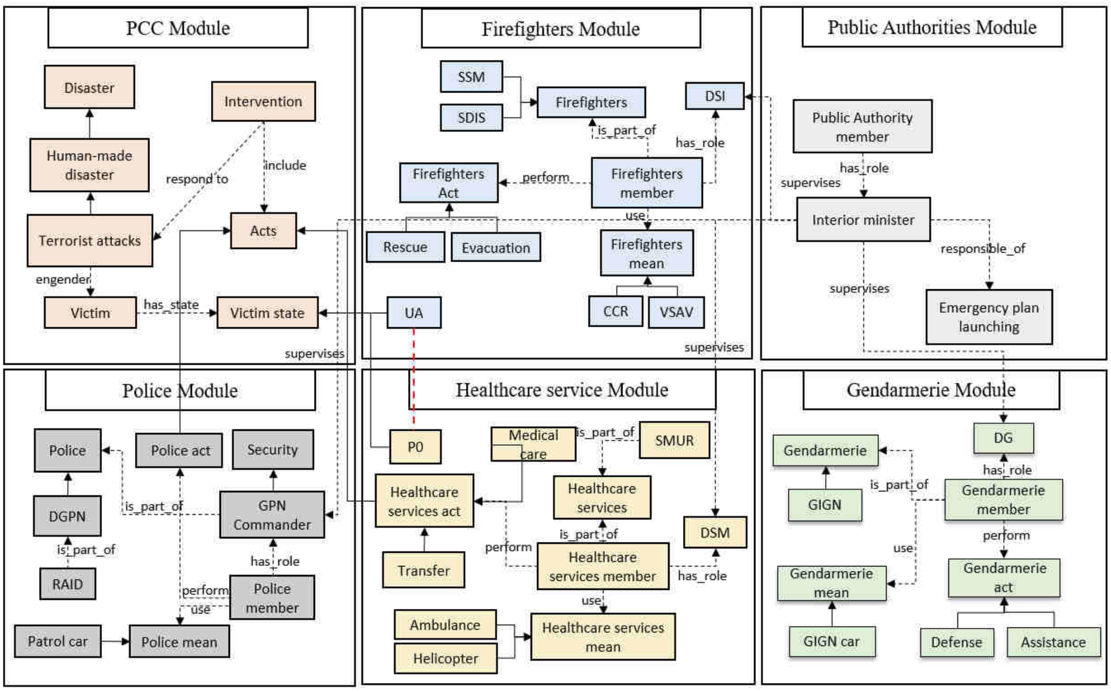

Figure 3. Partial view of stakeholders' modules

Concerning the message module, it is related to the PCC module and subsequently to the stakeholders 'modules. To defined it, we reused classes from PS/EM Communication Ontology (Chan et al., 2017). Authors were based on EDXL-RM (Emergency Data Exchange Language-Resource Messaging) standards. Figure 4 shows a partial view of the proposed module. The reused classes are marked with the prefix EDXL. We defined a *message* as an *information bearing artifact*. There are three different types of messages that could be exchanged among ERs; *informative message* (*information message*, *alert message*, *report message,* etc.), request message (*backup message*, etc.) and *response message (*a response message "is_about" a request message). In addition, a message is characterized by a state (*treated*, *untreated* or *ongoing*), a confidentiality (*public*, *private* or *limited*) and a degree of criticality of the information to be exchanged (*extreme*, *moderated* or *secondary*). Moreover, a message is identified by an *ID* and the same for *sender* and *receiver* which are defined as an *agent*.

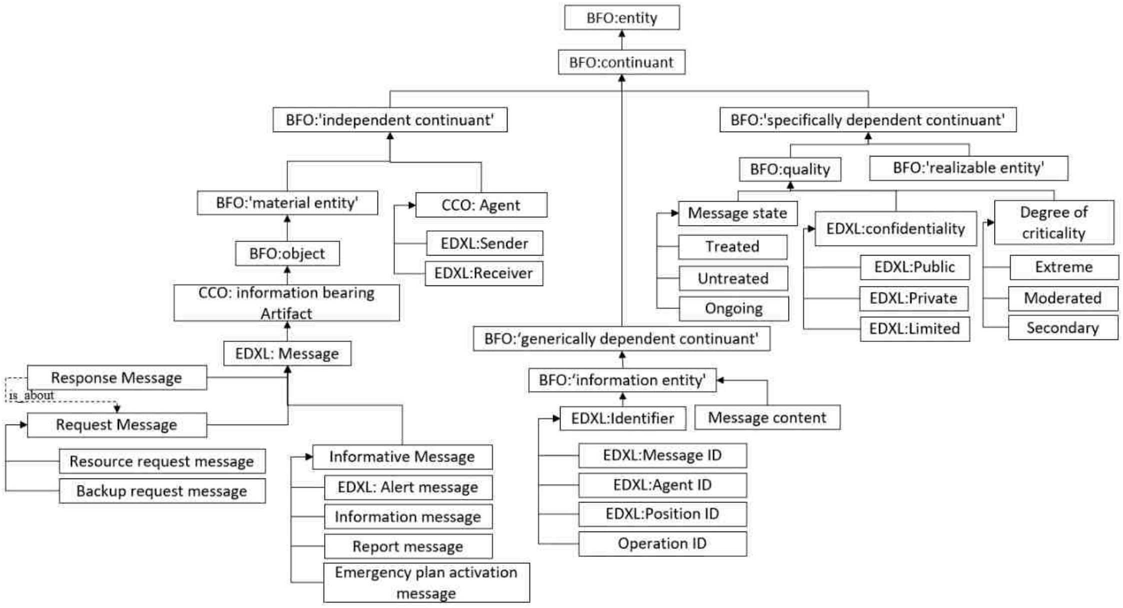

Figure 4. Message module

Implementation

The proposed formalization models are encoded in the ontology implementation language OWL and implemented using Protégé. It is an open source ontology editor and framework that propose a set of tools to construct ontologies. It facilitates the definition of classes, properties, and rules, visualization and reasoning. First, we reused BFO and CCO to build the PCC and message modules by utilizing the "owl: import" feature of OWL2. Second, we imported PCC to construct the stakeholders' modules. Then the different modules are merged together and integrated into one ontology "POLARISCO". Table 2 presents the classes and relations of the global ontology.

Table 2. Classes and relations of POLARISCO

Ontology	Number of Classes	Number of Relations
Developed ontology		
POLARISCO	447	25
Imported ontology		
BFO	27	-
CCO	195	152
Total	669	177

Evaluation

To evaluate the proposed ontology, from one hand, the consistency of POLARISCO modules was checked using the reasoner HermiT, which is an OWL2 reasoner included in Protégé. The aim is to ensure that the constructed ontology don't contain logical incoherencies or modeling issues such as contradictory relations between classes. On the other hand, to check if the ontology responds to the fixed specifications, we translate the CQs into SPARQL (Simple Protocol and RDF Query Language) language so as to query the ontology. To do so, the ontology was instantiated using feedbacks and documents of "Richter-65". It is an exercise of simulation of an earthquake in France which involves all the ERs.

One of the examples of the obtained results are presented in figure 5 to answer the following CQ: "Who are the operational commanders of the involved ERs in "Richter-65"?"

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX po: <http://www.semanticweb.org/linda/ontologies/2017/10/POLARISC1#>

SELECT    ?Rôle_de_commandememnt    (?Membre_des_pompiers as ?Membre)
WHERE {   po:Richter_65    po:commanded_by    ?Membre_des_pompiers.
          ?Membre_des_pompiers    po:has_role    ?Rôle_de_commandememnt.
          }
```

Rôle_de_commandememnt	Membre
COS	Jacquin
DSM	Durand
Directeur_GPN	MORVAN
DG	Lizurey

Figure 5. SPARQL query and result of the CQ

To summarize, we proposed POLARISCO, a modular ontology that define ERs knowledge and the needed information to ensure a semantically interoperable information exchange among stakeholders. It concerns firefighters, health care services, police gendarmerie and also public authorities. The modular conceptualization of the ontology enables its reuse as separate modules. One strength point of the development of the ontology is the fact that the process of collecting information, testing and evaluating the ontology was made referring to stakeholders. In addition, the designed ontology is validated by the emergency experts. POLARISCO will be used in English or French, we are working on labelling each class of the ontology in the two languages. The global modular ontology described in this paper is available in OWL format on GitHub: https://github.com/LindaElmhadhbi/POLARISC-Ontology.

CONCLUSION AND FUTURE WORK

In operational disaster response, there are various ERs from different EROs that potentially must work together towards a successful resolution of the disaster. However, communication is still ineffective since each ER uses his own technical vocabulary without realizing that they can be referring to different concepts. As a result, a different interpretation of data may happen that handicap the response process and cause slower decision making. To resolve semantic heterogeneity among ERs, there is an ample need to define the complex knowledge of the different stakeholders. Therefore, the purpose of this work is to come up with a common shared vocabulary in order to ensure semantically interoperability between ERs. So, we proposed POLARISCO, a modular ontology that enables semantically interoperable communication among stakeholders a comprehensive operational picture of the field. As future works, the proposed ontology can be extended to be used in the field of smart cities once it is aligned with existing standards and well-known models for smart city data. In addition, the ontology will be tested by means of a concrete use case to show how a communication act can be improved across different ERs and practitioner's feedbacks will be presented.

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