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Exploring ontologies for semantic interoperability of data in emergency response

Zhengjie Fan · Sisi Zlatanova

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Abstract Emergency response is a complex activity involving many actors and heterogeneous spatial data. Two of the major challenges are the integration and extraction of these data and their transmission to emergency management actors. Although significant progress has been made regarding the systemic and syntactic heterogeneity of data in this context, semantic heterogeneity remains insufficiently addressed. Here, we discuss the possibility of applying the ontology to resolve semantic heterogeneity in emergency response. We propose a concept for a solution to the semantic interoperability problem in emergency management using an ontology by presenting a case study.

Keywords Semantic interoperability · Ontology · Spatial data · Emergency management

Introduction

Natural and manmade disasters have occurred regularly throughout human history. Recent large disasters (*e.g.*, the Haiti Earthquake, Hurricane Katrina, the China Earthquake, and South Asia Tsunami) have involved increased management complexity during these emergencies. On the one hand, population density in cities has been growing at a much greater rate than in times past. Consequently, there are more people affected when a disaster occurs. On the other hand, climate change and technological developments may cause unexpected anomalies and industrial failures such as heavy rain, oil spills, landslides, nuclear waste leaks, and disease outbreaks. This increasing management complexity requires new approaches and tools to facilitate decision making in the face of disasters. How to alert, respond to and recover from disasters are major human challenges.

Information from various disciplines is used in emergency management, among which spatial data play an important role (Snoeren et al. 2007). Spatial data facilitate the identification of the geographic locations of disasters, affected buildings, rescue teams, victims and shelters. These data help to clarify the landscape of the affected area or the level of damage to buildings, roads and bridges or the depth of inundated areas. Thus, spatial information helps to increase situational awareness (Zlatanova and Fabbri 2009).

To enable the use of these data, emergency responders require fast and efficient access to them to allow for timely action. In large disasters, countless numbers of people are involved, but normally, emergencies are managed by four response units, i.e., the fire brigade, police department, medical services and the municipality (Xu and Zlatanova 2007). Although they are dealing with the same incident or disaster, the information needed by different response units may be very different. For example, in case of a large forest fire, the fire brigade needs access to all roads (paved and unpaved) leading into the area, whereas the police and ambulance would only need access to the paved roads. The municipality should have a clear understanding of the locations of buildings and the numbers of people inside to

Z. Fan (✉)
Web Information Systems, EWI, Delft University of Technology,
Mekelweg 4,
2628 CD Delft, The Netherlands
e-mail: zjfanster@gmail.com

S. Zlatanova
Section GIS-technology, OTB, Delft University of Technology,
Jaffalaan 9,
2628 BX Delft, The Netherlands
e-mail: s.zlatanova@tudelft.nl

prepare evacuations. All of this information should be extracted and processed from spatial data sets and distributed to different response units accurately and quickly. Therefore, data interoperability in emergency response is highly necessary.

The Spatial Information Infrastructure (SII) is designed to help access and find spatial data in an emergency response (Scholten et al. 2008). However, SII only solves certain problems of data interoperability, namely, systemic (*e.g.*, differences in hardware and operating systems), syntactic and structural interoperabilities (Sheth 1998; van Harmelen 2008). Semantic interoperability, that is, differences in the meaning of data with respect to language, code, message or any other form of representation, is not addressed by the SII (Sheth 1998). Semantic heterogeneity of the spatial data remains one of the biggest challenges in emergency response.

Emergency response personnel in different domains are generally not experts in spatial data and SII. Therefore, the emergency responders are not familiar with the technological aspects of the system. They may request information in their own words or based on their understanding, which is usually not the domain vocabulary that can be 'used' by certain software. For example, a fire brigade may use 'house' for the same real-world feature that is usually indicated as a 'building' on the topographic map. This complicates the work of emergency responders, who must usually train in advance to learn the large amount of domain vocabulary required to locate the desired information. Thus, a way to provide emergency responders with the necessary information is a challenging problem in emergency response (Visser et al. 2002; van Harmelen 2008).

To support this task, there should be a common definition of concepts and relationships for emergency responders to refer to when they use spatial data. Having a common understanding of the concepts will permit the automation of information searches and queries. The software will be able to 'understand' the meaning of the spatial data and quickly deliver the needed data to the correct responders. This unified definition is called a standard terminology (Sheth 1998). Many researchers have suggested applying the concept of ontology to represent the standard terminology and therefore solve the semantic interoperability problem in the work of emergency managers (Neches et al. 1991).

Here, we discuss the potential of using ontology construction to resolve semantic heterogeneity in the emergency response. The paper is organised as follows. "Related work" section presents related work on applying semantic-related technology and ontology for spatial data and emergency responses. "Semantic interoperability in emergency management" section theoretically analyses the possibility of applying an ontology to emergency management. "Ontology" section introduces the basic definition of ontology and discusses the main steps of ontology modelling. "Ontology modeling for emergency management" section introduces a case study illustrating how to build an ontology for emergency management. Finally, we conclude the article in "Conclusions and future work" section.

Related work

Related work on the semantic technology in spatial data

Many previous works have discussed why semantic-related technology is needed to solve pending problems in geographical information systems (GIS) (Cohn 1997; Guarino 1998; Smith 1995; Frank 1998). Cohn (1997), in a review of the literature on qualitative spatial representation and reasoning, states that the human-computer interaction in GIS should be more concise and accurate than it is currently. However, it is unlikely that a single and powerful spatial representation language that is suitable for all applications can be constructed. Facing the challenge of combining several spatial representation languages and reasoning systems requires solving the problem of semantic interoperability in the human computer interaction (Cohn 1997). Guarino (1998) analysed the usefulness of the ontological concept in information systems such as GIS by showing how an ontology can help increase user application knowledge in a domain and can assist users in querying domain information. However, this author only proposed a possible ontology structure for applications and did not attempt an implementation to demonstrate the power of the ontology.

Apart from Guarino (1998), Smith (1995) and Frank (1998) also discussed the possible ways of constructing ontologies for GIS data. Frank (1998) suggested building the ontology into five tiers that describe this data from not only from the viewpoint of human-independent reality but also that of subjective knowledge. The application of ontologies in GIS has also been discussed regarding human-computer interactions (Lemmens et al. 2006; Aasman 2008; Fonseca et al. 2002; Métral et al. 2009). Métral et al. (2009) proposed an ontology structure in demonstrating how to integrate different 3D models. Aasman (2008) conducted research on querying spatial data, but this system could only query simple spatial data. Fonseca et al. (2002) designed a special ontology-based geographical system. Specifically, the system was an ontology-based system called ODGIS that could classify different types of images in GIS. However, the system only integrated images in GIS; it did not consider other types of spatial information.

There have also been other works in which the authors attempted to define spatial relationships with logic, using such concepts as 'overlapping' and 'touching', which help the ontology to process the spatial relationships (Bedel et al. 2008; Kong et al. 2003; Haarslev et al. 2001; Bennett 2001). Others have utilised such logic-based spatial relationships to retrieve geographical data (Haarslev et al. 2001; Bedel et al. 2008).

In summary, none of the recent theoretical works that applied semantic technology to spatial data attempted implementation to demonstrate their feasibility. Related works including implementation only built ontologies for small amounts of spatial data. To date, there have been no semantic-based systems that can both integrate spatial data models across different information communities and also provide flexible querying and reasoning functions.

Related work on ontologies in emergency management

Although many studies have applied semantic-related technology to spatial data, few have applied the ontology to emergency management, and most of these works only provided conceptual structures (Chatterjee and Matsuno 2005; Li et al. 2009; Ru-zhi et al. 2009). An ontology-based emergency response system remains to be built. Chatterjee and Matsuno (2005) discussed the necessity of using the ontology to solve the linguistic differences between disaster scenario descriptions and rescue robot capability descriptions and to set the standards in both respects. Li et al. (2009) proposed an ontology-based architecture for geo-objects in disaster systems. Ru-zhi et al. (2009) also suggested building an ontology-based emergency response plan.

Several works have constructed emergency response systems for specific applications (Li et al. 2008; Scott and Rogova 2004; Araujo et al. 2008; Ekelhart et al. 2006). Li et al. (2008) created an emergency response ontology for emergency response workflow. Zlatanova et al. (2010) presented an ontology-based query system but only for two data sets. Scott and Rogova (2004) built a task model of crisis management with an ontology for detecting the occurrence of the crisis. Araujo et al. (2008) used the ontology to construct simulations for training procedures in emergency response. Ekelhart et al. (2006) also used the ontology for emergency simulations.

Thus, a mature ontology-based emergency response system is required that can both integrate spatial data models across different information communities and provide flexible querying and reasoning functions.

Semantic interoperability in emergency management

Currently, spatial data are stored in a large array of models that are not specifically intended for emergency responses. Emergency managers require access to critical spatial data from these models for making decisions. However, emergency responders have their own domain knowledge, which may use different words than the spatial data models to describe the same thing. Thus, mappings between the models of the emergency managers and those of the emergency responders should be constructed whenever either part of the mapped pairs is changed or a new model is needed. As an ontology can include uniform definitions of model data, it is expected that its implementation will reduce the time and complexity of model mapping and data integration in emergency response. This implementation would thus support the more efficient extraction of information for each emergency responder.

A large amount of semantic information can be accessed more easily using ontology-based methods rather than traditional spatial methods (Pundt 2008), if the semantic meanings are well defined. For example, the fire brigade may want to know the shortest path from its station to the disaster area. This query requires path searching within the geographical data on the map. The 'shortest path' can be computed with the help of the road network. However, before determining the shortest path, the meaning of 'road network' must be defined. Thus, an agreement on the meaning of such spatial concepts is important and necessary, as the responder's understanding of a certain feature may differ from the way this feature is represented or modelled in a particular model. In this example, different data models may have different network structures. Thus, an ontological model is needed to define the semantic meanings of such spatial data for further data processing (Pundt 2008).

Furthermore, if the spatial data in emergencies are related in ontologies, context-related data for emergency actors can be efficiently extracted. In the context of the ontology, querying and reasoning functions could be used to demonstrate the relevance of the data. If the data are not relevant to the context, then they are not the target information for the responder in that situation, regardless of the availability of the data in the data set. For example, after a disaster occurs, maps of the area where the disaster occurred are useful for the emergency management actors. If these maps were defined with accompanying semantic information (*e.g.*, coverage area and boundaries) in the ontology, it would be easier to determine whether a given map is the required one. It could be determined by ontological reasoning whether or not a map has semantic relationships with the given context. By defining rules delineating the relationships between emergency responders, a procedure for selecting the correct target information in certain contexts could be realised. Thus, by querying and reasoning based on the ontology, it would be possible for the emergency responder to compute the explicit relationships between objects in a spatial data situation (Pundt 2008).

Ontology

Ontology is a term defined in philosophy as ‘the philosophical study of the nature of being, existence or reality in general, as well as of the basic categories of being and their relations’. Researchers in computer science imported this word and gave it a new definition. In information theory, an ontology is defined as ‘an explicit and formal specification of a conceptualisation’ (Gruber 1993). There are two important aspects of this definition:

1. Explicit: The meaning of each concept is clearly and uniquely defined.
2. Formal: The concepts in the ontology are defined in a formal language that is easily understood by machines.

There are many hierarchical and nonhierarchical relationships in an ontology that link different concepts together into a large conceptual network (Antoniou and van Harmelen 2004). Hierarchical relations demonstrate the generalisation of relationships between similar concepts. Nonhierarchical relationships demonstrate other relationships between concepts such as aggregation. In other words, an ontology is a network of concepts and relationships that provides specifications of the knowledge in a domain within which people communicate (Uschold and Grüninger 1996). As a key technology in the field of semantics, an ontology is a unified structure that is a shared conceptualisation. It is a standard explanation of concepts and relationships used by the application field (Agarwal 2005; Visser et al. 2002; Bittner et al. 2005). Moreover, querying and reasoning using an ontology can help elucidate the implicit or contradicting concepts and relationships that may not be readily apparent.

Ontology modelling

Given the definition of an ontology, in this section, we illustrate how to construct an ontology. There are three main steps in building an ontology: ontology capture, ontology coding and ontology mapping (Uschold and Grüninger 1996).

In general, various types of ontologies can be constructed (Agarwal 2005):

1. A Knowledge Representation Ontology defines the representational primitives in formal language.
2. A General Ontology defines the vocabulary concerning things, events, time, space, and other factors in a general application scenario.
3. A Domain Ontology defines the concepts and relationships of a particular application domain.
4. A Reference Ontology defines top-level concepts and relationships for negotiating meanings across different domains.
5. A Linguistic Ontology defines grammatical concepts in natural language to link philosophical ontology with engineering ontology.

Usually, the type of ontology used is decided by the modelling aim. For example, if the ontology is intended to provide an interpretative vocabulary for several application fields, it is best to choose the reference ontology. If the ontology will link oral words with abstract concepts, perhaps a linguistic ontology is needed.

Ontology capture

In this step, key concepts and relationships in the knowledge field are selected. The definition of concepts and relationships should be specified as well.

Ontology coding

In this step, the ontology is written in the formal language. According to the definitions of concepts and relationships specified in the ontology capture step, the ontology is constructed as a knowledge network. The commonly used ontology languages are the resource description framework (RDF[1]) and the web ontology language (OWL[2]). The commonly used ontology editors are Protégé[3] and KAON2[4].

There are three types of ontology architectures: global, peer-to-peer and hybrid (Wache et al. 2001).

1. Global ontology architecture: Here, there is only one large ontology for the application field. All concepts and relationships are well defined by the ontology without referring to other ontologies. This architecture is suitable for the situation in which all parties of this application domain have a common understanding and agreement on concepts and relationships within the application domain.
2. Peer-to-peer ontology architecture: In this architecture, several ontologies are built simultaneously. Furthermore, there are mappings between them. Ontology designers should separate the corresponding concepts or relationships of one ontology from those of another ontology to interlink them. Finally, these ontologies can also form a concept and relationship network similar to that in the global ontology architecture. However, it can before seen that many redundant data may exist in this architecture because it has less constraints on the agreement of parties regarding the concepts and relationships of the different ontologies. This architecture is chosen when many parties

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[1] http://www.w3.org/TR/rdf-primer/

[2] http://www.w3.org/TR/owl-features/

[3] http://protege.stanford.edu/

[4] http://kaon2.semanticweb.org/

in the application domain wish to build their ontologies according to their application needs.

3. Hybrid ontology architecture: This architecture is a combined structure of the two aforementioned architectures. In this architecture, a general ontology is constructed for the shared vocabulary of each individual ontology. Commonly accepted definitions and constraints of shared vocabulary are defined in the general ontology. Apart from this general ontology, several ontologies may be built. Each small ontology can be mapped onto the general ontology, and a large ontology is formed by interlinking.

Usually, the hybrid architecture is preferred for ontology coding. This structure can both contain all the abstract information of the application domain and include as much domain details as possible.

The ontology can be edited manually with the ontology editor. However, it is tiresome and time-consuming work for the ontology designer. In general, it is impossible to manually edit every model with an ontology editor. Currently, the data models are represented mostly in UML, as there are some methods of converting the UML class graphs into OWL files (Leinhos 2006). The Ontology Definition Metamodel (ODM) introduces common features corresponding to both UML and OWL. Eclipse designed an implemented solution[5] for transformation from UML to OWL according to this correspondence. Leinhos (2006) used the transformation language XSLT[6] to convert the UML class graphs into OWL files.

However, it is not sufficient to only transfer data schema in UML to the ontology language. The data should also be transformed to the ontology language. Several authors have addressed this problem (Bizer 2003; Barrasa et al. 2004). Bizer (2003) and Barrasa et al. (2004) both created new mapping languages to transfer records in the database to existing OWL files. Specifically, Barrasa et al. (2004) created R_2O, an extensible and declarative language, to describe the mapping from the relational database schema to the ontology. Thus, R_2O also facilitates the transfer records of in the relational database to existing OWL files. Bizer (2003) presented another declarative mapping language, D2R MAP, to describe the mapping between the relational data schema and the OWL ontology.

Ontology mapping

In many application domains, more than one ontology usually exists; therefore, this section discusses the mapping between different ontologies for information sharing. Methods of ontology mapping originate from various research areas. Briefly, there are four main mapping methods: the linguistic, statistical, structural and logical methods (van Harmelen 2008). The linguistic method builds the mapping by locating similarities in the attached labels of mapped concepts. The statistical method builds the mapping by comparing the instances of concepts. The structural method determines the mapping relationship between two concepts according to their hierarchical locations in their ontologies. The logical method builds the mapping by computing the logic relationships between mapped elements. Euzenat and Shvaiko (2007) also developed a classification of ontology mapping with a classification scheme nearly identical to those described above, although they used different names. For example, the logical method belongs to the semantic-based techniques in Euzenat and Shvaiko (2007). Extensional techniques use the same definitions as the statistical method. The linguistic method has definitions similar to those of the terminological techniques described in Euzenat and Shvaiko (2007).

There are many ontology mapping systems. COMA++[7] is a matching system that matches OWL ontology as well as relational and XML schema. This system realises the matching process at the schema level. COMA++ allows the ontology user to give feedback on the matching result and refine it, and it applies all matching techniques excluding the semantic-based technique; this results in a set of correspondences (Euzenat and Shvaiko 2007). MapOnto[8] is another matching system that also matches relational schema, XML schema and OWL ontology. This system uses both statistical and structural methods to match different data sources. The outputs are a set of mapping relationships that can be chosen by users (Euzenat and Shvaiko 2007).

Ontology storage and querying

After the ontology is constructed, there should be a system to store and query the ontology. Sesame (Broekstra et al. 2002), Jena[9] and KAON[10] (Oberle et al. 2004) are three early developed ontology management tools. Sesame is a system for storing the ontology in RDF or RDF schema that can be queried with RDF query language (RDQL). Jena is also a tool that can be used to store RDF ontologies, also supporting RDQL. KAON is an infrastructure that supports ontology in OWL-DL and F-Logic in addition to RDFS; its querying language is SPARQL[11].

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[5] http://www.eclipse.org/m2m/atl/usecases/ODMImplementation/

[6] http://www.w3.org/TR/xslt

[7] http://dbs.uni-leipzig.de/Research/coma.html

[8] http://www.cs.toronto.edu/semanticweb/maponto/index.html

[9] http://jena.sourceforge.net/index.html

[10] http://kaon2.semanticweb.org/

[11] http://www.w3.org/TR/rdf-sparql-query/

Currently, there is a trend for storing the ontology in relational databases. Oracle has developed its own semantic technologies that fit in the DBMS. First, Oracle semantic technology stores the ontology in OWL and RDF. Second, it supports querying semantic information and the ontology-assisted querying of enterprise data, which means that querying is executed on semantics rather than on syntax. Furthermore, Oracle semantic technology also provides flexible reference functions. It can reason in OWL and RDF as well as according to user-defined rules. That is, the user may define rules to guide the reasoning process for the desired results.

Rules

After the ontology is successfully constructed, the ontology user can retrieve and extract information from it. When the emergency responder sends his or her query to the ontology-based emergency response system, the system should use the reasoning features of the ontology to help the user locate the needed information. The rule has the form

$$A_1, \ldots, A_n \rightarrow B \qquad (1)$$

which can be explained as 'IF the conditions $A1, \ldots, An$ are satisfied, THEN carry out the action B' or 'IF $A1, \ldots, An$ are true, THEN B is true' (Antoniou and van Harmelen 2004). The ontology languages RDF and OWL do not have the ability to describe complex rules (Antoniou and van Harmelen 2004). Thus, several tools have been proposed to merge rules with the ontology. SWI-Prolog[12] is a system that can import RDF ontologies into its rule system and realise the reasoning function. Oracle 11g also provides functions for defining user-defined rules in addition to RDF or OWL ontology (Eiter et al. 2008). The semantic web rules language (SWRL[13]) is designed to add a rule layer upon the ontology language OWL. As an extension of OWL, SWRL is supported by several powerful reasoners, such as Pellet[14] and RacerPro[15] (Eiter et al. 2008).

Ontology modeling for emergency management

A emergency response case

Emergencies can vary greatly. Each type of emergency management requires different data sets and procedures to manage it. Here, we concentrate on one case to illustrate how to build ontologies for emergency management.

Imagine there is a large fire in an urban area. The fire starts in an industrial establishment near the city and spreads to several industrial buildings. Because of the fire, a large cloud with dangerous substances has been released. In this case, the first emergency management actors are the fire brigade, local paramedics, police, municipality and the advisor for dangerous substances (ADS). The tasks and the roles are clearly defined: the fire brigade trucks should go to the locations where they can fight the fire, the medical personnel should care for citizens with medical complains, the municipality should monitor the situation and decide whether evacuation from the affected area should take place, and the ADS should assist in taking samples from different locations in the affected area and computing the plume.

Currently, many systems for command and control (C&C) can provide all of the data needed by these actors, such as Eagle (Fig. 1) and MultiTeam in the Netherlands. However, most of the current systems do not filter the data but access and display all available data. This has two consequences: 1) the information may be too much to perceive and analyse and 2) some of the displayed data might not be understandable for some actors because they are from different domain. The semantic heterogeneity is very high.

There are in total two types of data in the emergency response: static data and dynamic data. Static data, such as topographic data (CityGML, TOP10), cadastre data (Cadaster), and hydrographic data, are stored in the data set before the disaster occurs. Dynamic data are the data obtained after the disaster occurs, such as the population suffering from the disaster and the area of the poisonous gas plume. Figure 2 shows an example of the information sharing between emergency management actors (here, the municipality, police officers, fire brigade and medical centre) and both static and dynamic data sources in the C&C system. However, the system cannot provide the right information to the right actors due to two main problems.

First, the computer cannot distinguish the concept groups 'river, lake, and water area', 'suburban area, urban area, blocks, buildings, abstract buildings, high buildings, low buildings, farms, and neighbourhood' and 'road, street, highway, and transportation'. The actors use their own concepts to describe the disaster and submit them to the C&C system, whereas the data source uses domain concepts to describe the spatial data and other disaster-related information. Thus, although the meanings of the concepts from both sides are similar, the computer cannot understand the meanings or integrate them.

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[12] http://www.swi-prolog.org/

[13] http://www.w3.org/Submission/SWRL/

[14] http://pellet.owldl.com/

[15] http://www.racer-systems.com/

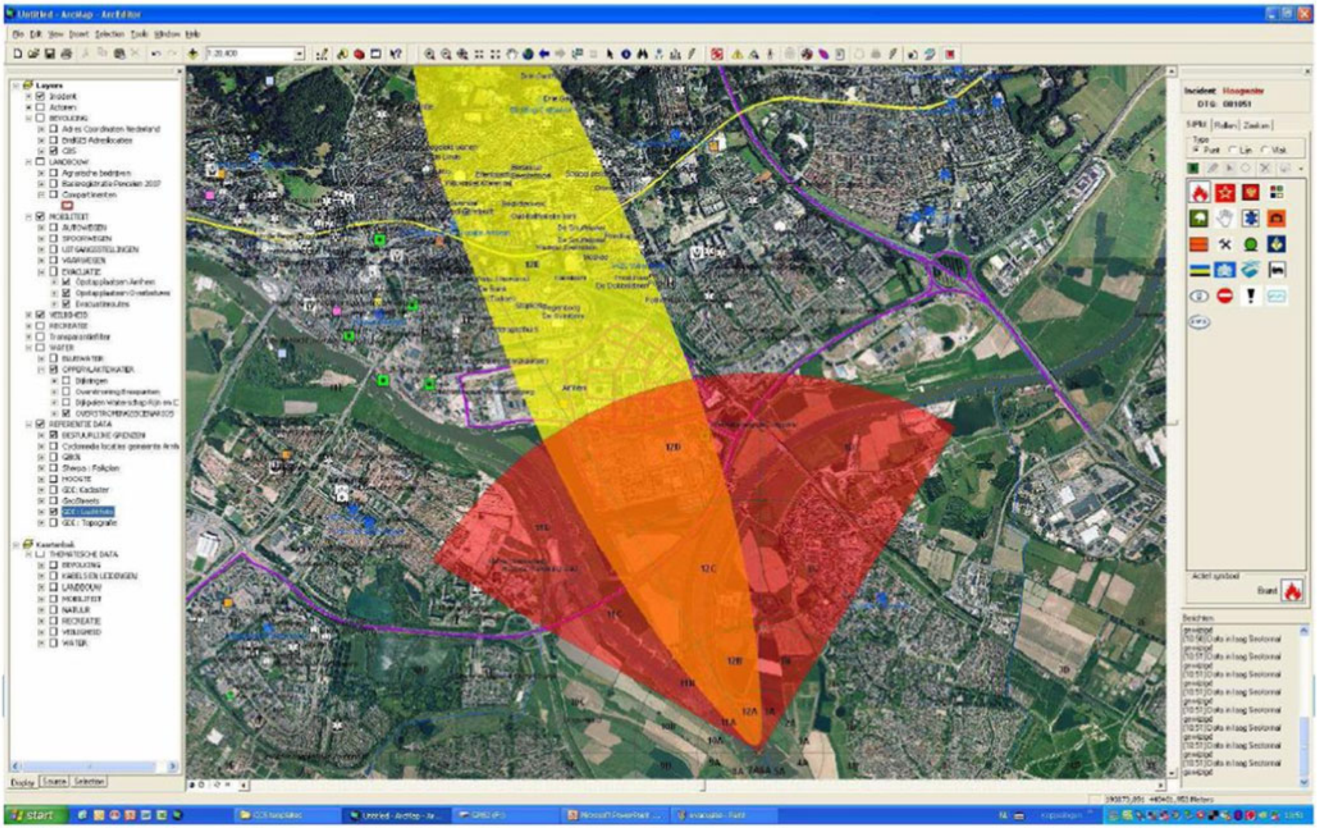


Fig. 1 Eagle One (GEodan, ESRI, Microsoft)

Second, the C&C system displays the information available on the screen as shown in Fig. 2, which may confuse the responders. Specific information in an emergency response should be extracted for each target person. There are many predefined processes for emergency management. For example, in the Netherlands, each process consists of several tasks to be fulfilled by the responders (Zlatanova 2010; Xu et al. 2008). The

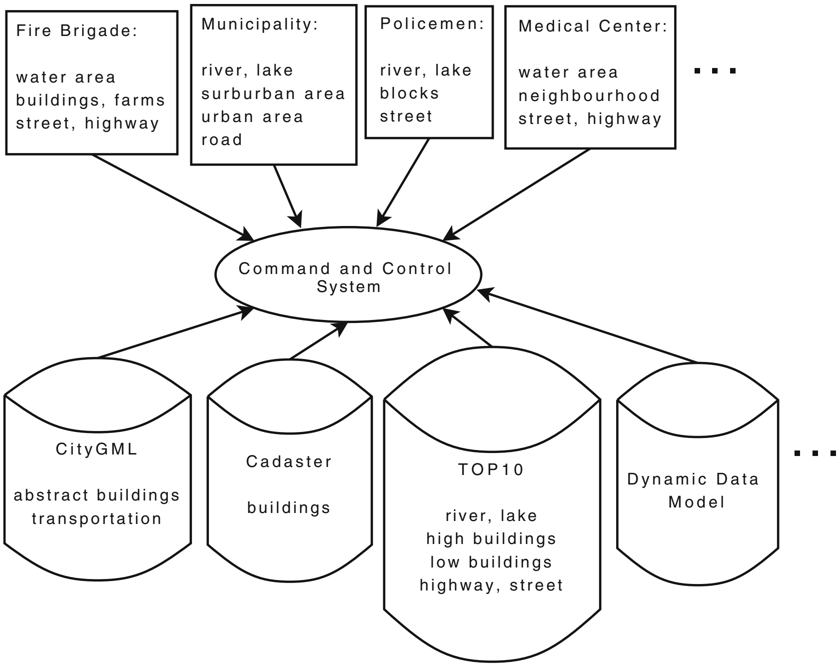


Fig. 2 Information sharing in C&C system

relationships between processes, responders, tasks and data can be modelled in UML (Zlatanova 2010). For different tasks, the responders may need different information. Thus, some rules should be defined to guide the querying procedure, which has the form of 'IF… THEN…'. For example, if John is a fireman and his task is to explore a building on fire (*e.g.*, the building of the Architecture faculty in Delft burned down on 13 May, 2008) as a part of the process 'fire fighting', he must obtain a set of data: the digital floor plans of the first to seventh floors and information about the resistance of the elevator section, which is on fire. If Steven is an on-duty officer and his task is to coordinate the fire trucks to be used in the process 'fire fighting', then he needs another set of data: detailed maps of the area around the building, the best arrival times for two specialised fire trucks from the nearby harbour (*e.g.*, Rotterdam) and all fire hydrants in the area. With the help of these rules, the information-extracting process can be guided to deliver task-related information to the responders.

Ontology modelling stages

The emergency response ontology prototype can be constructed in the following stages:

1. Phase One

   In this phase, we build ontologies for the actors, static and dynamic data models, processes and tasks and evaluate them.

   (a) Ontology coding for actor and data models

   For each actor in the emergency management and data models, certain commonly used words are collected along with their domain-related definitions.

   For example, in Fig. 2, 'road' in the vocabulary of a municipality could be defined as 'any kind of path that vehicles and pedestrians can pass', 'highway' in TOP10 could be defined as 'a kind of path that only permits vehicles to pass', and 'street' in TOP10 could be defined as 'a kind of path that vehicles and pedestrians can pass and usually has a certain speed limit'. Based on these definitions, the computer could distinguish the 'meanings' of these three concepts and find the relationships between them. Specifically, both 'street' and 'highway' are a type of 'road', but 'street' is different from 'highway'. The computer can then acknowledge the differences in these concepts and extract actor-needed information in TOP10. After building the concept network, the ontology could be manually built with the ontology editor. However, as there are usually many concepts in a domain, it would be a time-consuming task to edit each concept manually. In such situations, UML class graphs of the concept network could be drawn first. Next, UML files could be transferred into OWL files with the methods described in "Ontology coding" section. Afterward, the records of these models in the database are mapped to the OWL files. Apart from building the ontology for emergency actors and static data, a dynamic data model should also be transferred to the ontology. Here, we use the dynamic emergency management model written in Zlatanova and Dilo (2010). Dynamic data are those data obtained after the disaster occurs that originated from the region server in the disaster area and not from a database compiled before the disaster. Figure 3 shows the dynamic data model in the UML of Emergency Management (Zlatanova and Dilo 2010). In the figure, only the main classes and their associations are shown. Dashed lines indicate dependencies, meaning that the existence of the source data depends on the target data.

   Damage to buildings and mobile properties and injuries to people and animals are contained in the classes 'DamagedBuilding', 'DamagedCar' and 'DamagePA', respectively. Then, complaints from people from the affected area (*e.g.*, breathing problems) are collected in the class 'Complaint'. In an emergency, several of the processes are activated to rescue victims and deal with the disaster so as to reduce property damage and loss of life, which are contained in the class 'Process'. The class 'EventObject' contains the event information that occurs in the disaster field. Four main classes, 'Department', 'DMSUser', 'Vehicle' and 'Team', describe the emergency response sector. 'DMSUser' and 'Team' are both dedicated to measuring the information arising from the incident if it involves dangerous substances. In such cases, 'Sectormal' and 'Gasmal' contain the information on the affected area and gas plume, respectively. The ontology file of the dynamic data model can be built by first transferring the UML class graph to the OWL file. The records in the database are then mapped in the OWL file. We used the transferring method of Leinhos (2006). The OWL file is shown in Protégé in Fig. 4.

   (b) Process and task ontologies

   There are many predefined processes for emergency management. Each process consists of several tasks to be fulfilled by actors. For example, in the generic dynamic data model, 'DMSUsers'

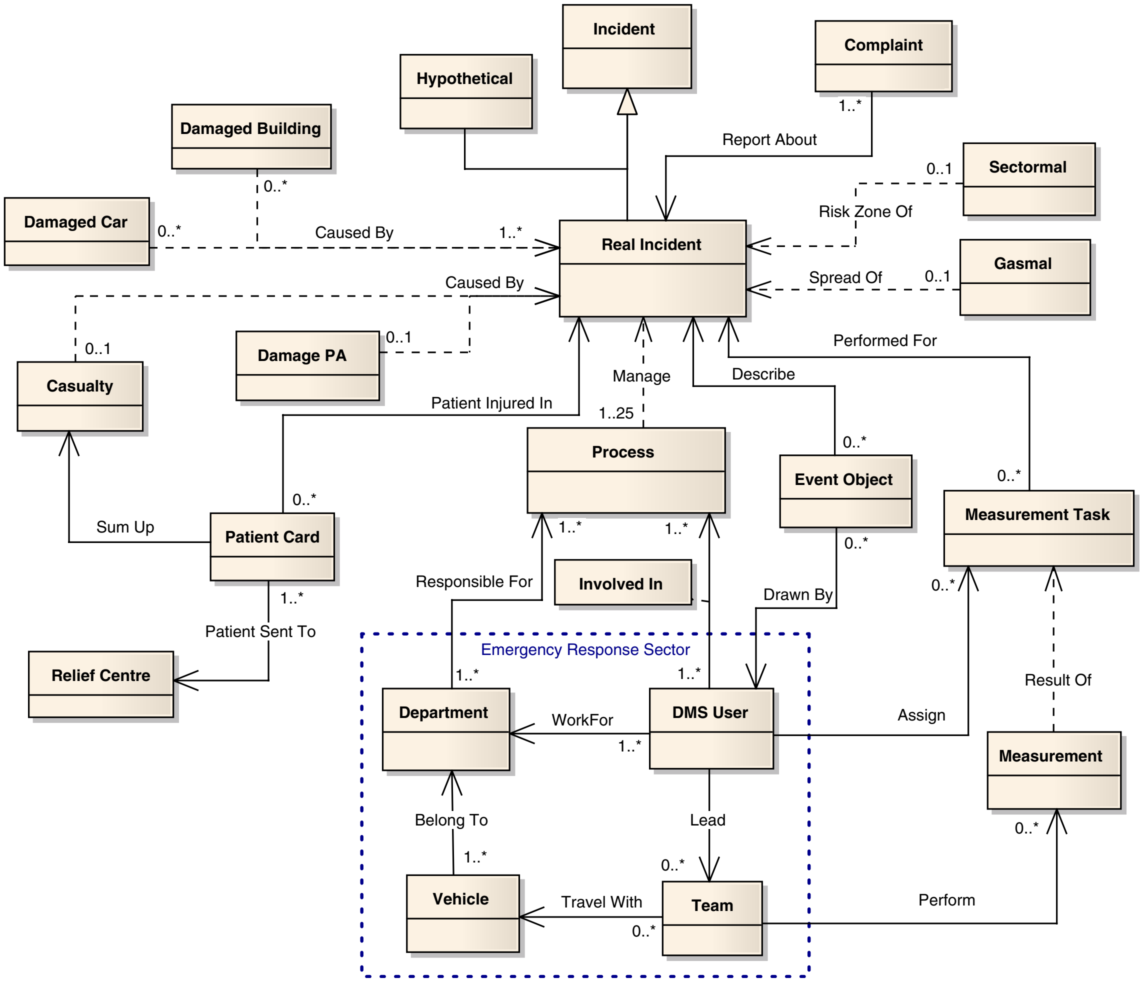


Fig. 3 Conceptual model of dynamic data for emergency response

are involved in 'Process'. However, in detail, the fire brigade is only involved in processes Nos.1~7, and the police department is only involved in process Nos.11~17. Thus, this process-dependent information should be linked together. The links can be defined by object properties in the ontology or by rules. Using the process 'observation and measurement', introduced in Xu et al. (2008), as an example, two rules can be defined as follows:

$$process(x) \wedge task(y) \wedge actor(z) \wedge team(p) \rightarrow$$
$$sending(information(q), actor(z))$$
$$process(x) \wedge task(y) \rightarrow$$
$$producing(information(o))$$

The first equation means that if actor z is involved in process x, task y and team p, information q should be sent to him. The second equation means that information o will be produced if task y in the process x is completed.

(c) Ontology evaluation and storing

After each ontology is built, it should be evaluated to decide whether its structure can correctly express the semantic information in emergency management. Furthermore, it is better to store the constructed ontologies in suitable software that can sustain a large ontology, such as Oracle 11g.

2. Phase Two

In this phase, we match several constructed ontologies together. Finally, we attempt to extract actor-required information by querying or reasoning in the ontology. In this phase, ontology updating is also considered.

(a) Ontology matching

In this step, the constructed and evaluated ontologies are matched with each other. In other words, the emergency management ontology is formed by linking these ontologies together. The method of linking involves finding the semantic

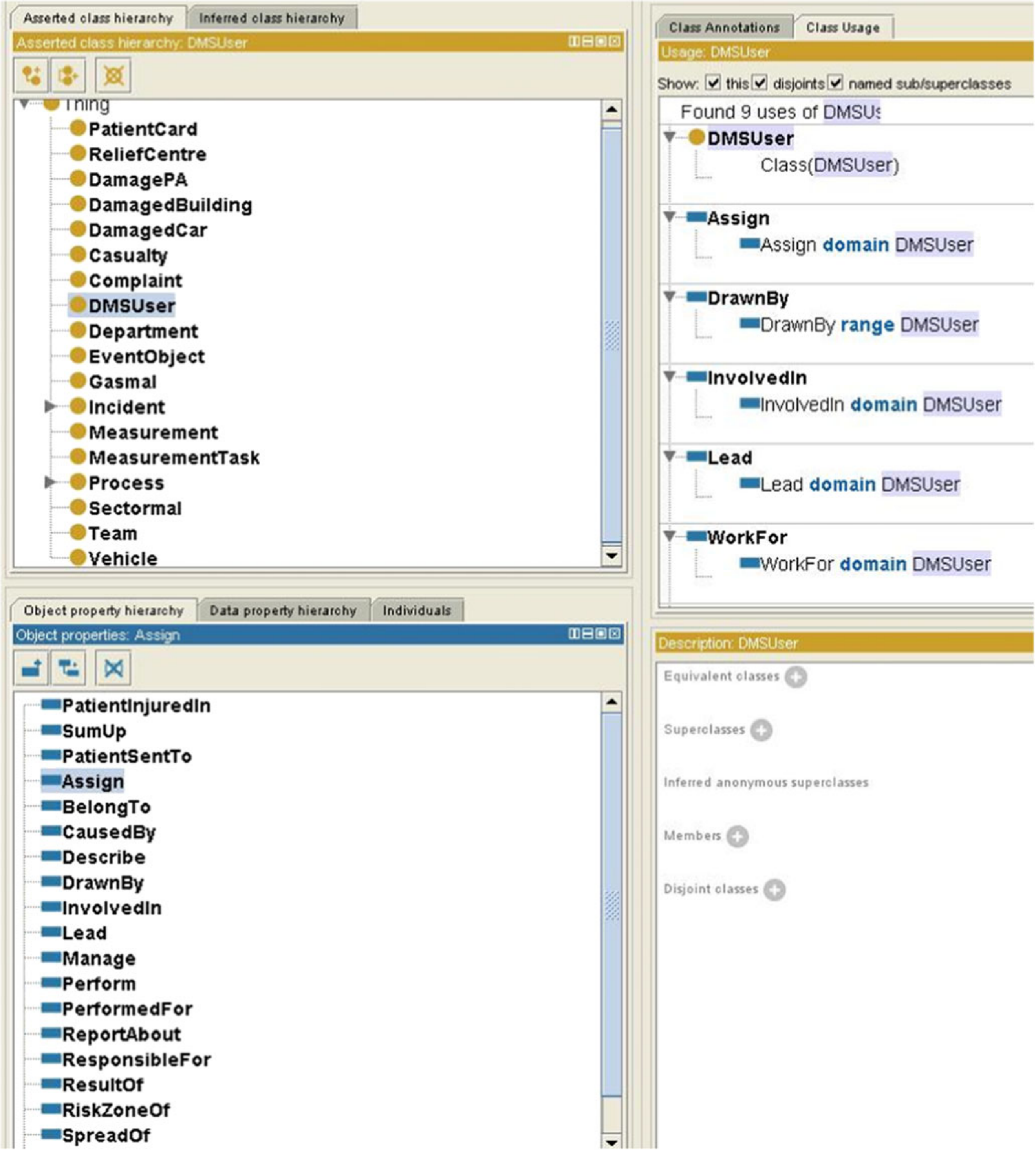


Fig. 4 Ontology of the dynamic data model

relationships among them. As explained above, this process may require different types of mapping methods to be performed. For example, when mapping the ontology of the police officers with that of TOP10, the linguistic method may be used to map the concepts ‘river’ and ‘lake’ in both ontologies. The statistical method may be used to match the concept ‘road’ in the ontology of the municipality with the concepts ‘street’ and ‘highway’ in the ontology of TOP10. The concept 'road' will certainly contain the instances of 'street' and 'highway'. Therefore, the latter are subclasses of 'road'. The structural method could be also used when mapping 'road' in the ontology of the municipality with 'street' and 'highway' in the ontology of TOP10. In the ontology of the municipality, 'road' is a part of 'urban area'. In contrast, in the ontology of the Medical Centre, the concepts 'street' and 'highway' are also included in 'neighbourhood'. Moreover, 'neighbourhood' is a subclass of 'urban area'. Then, 'road', 'street' and 'highway' must have certain generalisation relationships. The logical method could be used to map the concepts 'transportation' and 'road'. 'Road' is 'transportation' on land. That is to say, 'road' is defined by attaching a restriction to the definition of 'transportation'. Then, logically speaking, the concept 'transportation' subsumes the concept 'road'. Therefore, 'road' is a superclass of 'street'. The concept network after mapping the ontologies is shown in Fig. 5. The unlabelled arrows represent the generalisations between concepts. The arrows labelled 'composition' represent aggregations between concepts.

(b) Extracting context-oriented information

Context-oriented information can be obtained by querying the ontology with query language or reasoning using the previously defined rules and a powerful reasoner.

(c) Ontology updating

As a disaster is a dynamically changing event, new information will continue to enter the emergency management area. It is best to periodically update the emergency response ontology with new records from data models.

There remain several open questions to be discussed for the emergency response ontology prototype. First, in the ontology modelling step, it is plausible to build the emergency management ontology into the hybrid architecture. In particular, we could build a generic ontology to define the meanings of the data in the dynamic data model. Usually, an ontology of dynamic data requires several domain ontologies for reference from which to obtain the exact definitions of data in certain application domains. For example, when 'Measurement Task' defines the task for measuring poisonous gas plumes, a gas dispersion and meteorology ontology is needed. When 'MeasurementTask' defines the task for measuring the flood, a hydrology ontology is needed.

Therefore, is a time ontology needed as well? As time is very critical for emergency management, information obtained from the affected field may have time relevance. For example, the area affected by the incident may change over time. The GRIP level and scale of the incident also may change over time. Currently, time is modelled as a property or attribute of the corresponding object. However, it might be worth investigating whether a time ontology should be constructed to define the clear boundary of time states, *e.g.*, before, after, and during. In time A, the affected area is computed. The emergency level is defined (*e.g.*, GRIP 2 in the Netherlands, Xu et al. 2008). The corresponding processes of the GRIP level are then activated along with the tasks of the actors (Zlatanova 2010). At time B, the affected area may be enlarged, requiring a higher GRIP level and more actors. Such information could be linked by the same time class in the time ontology to keep time consistent in the disaster information. Moreover, the durations for integrating C&C information, updating them and distributing them to target actors could be assigned maximum time limits by referring

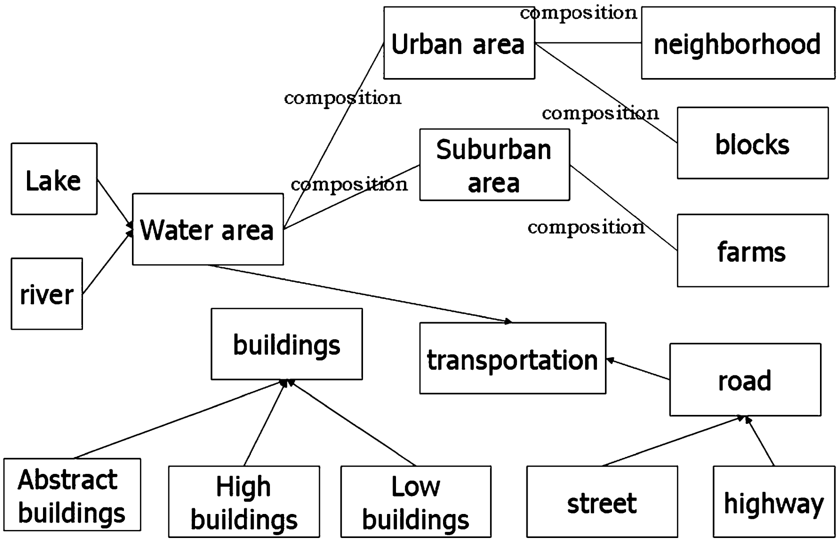


Fig. 5 Concept network after ontology mapping

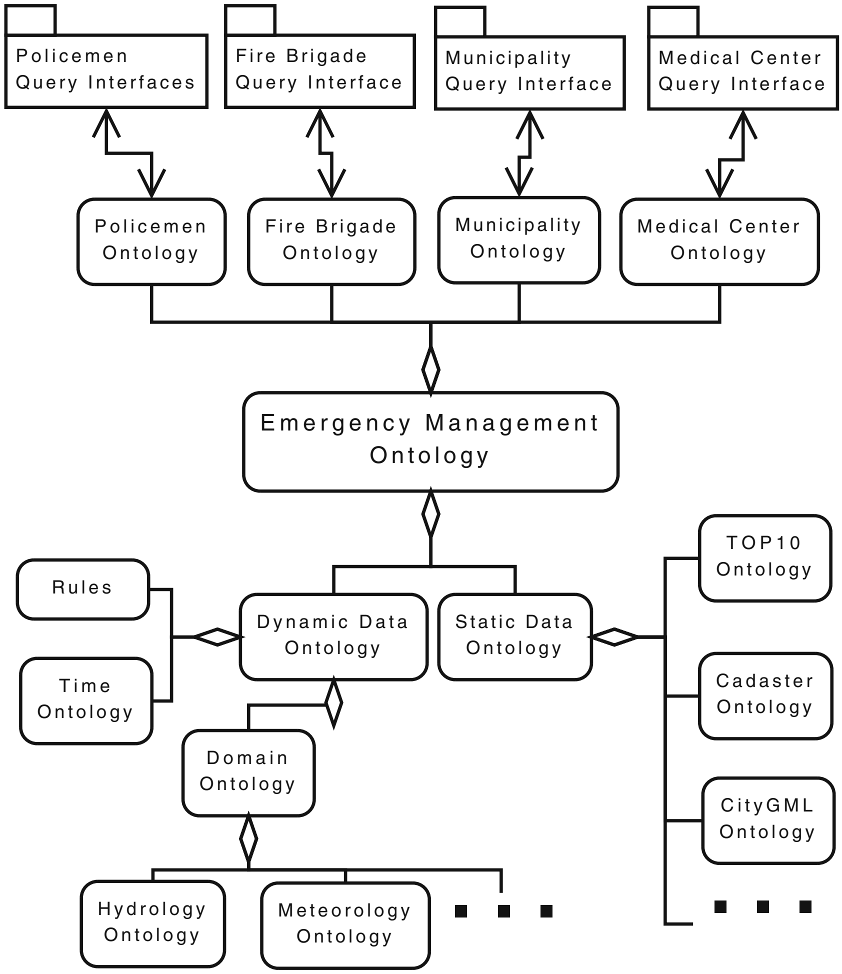
to the time ontology. Thus, it might be easier and faster to control the dynamic data flow between different classes.

Therefore, the emergency management ontology should contain two main parts: a dynamic data ontology and a static data ontology. As different disasters may require different dynamic data models, a dynamic data ontology may need to be linked to corresponding disaster ontologies. A static data ontology is composed of various types of ontologies that can assist responders in decision making. In addition, responders have their own domain ontologies that define the vocabulary of their daily work. Corresponding to these ontologies, there are several query interfaces connecting with emergency management ontology via linkages with the ontologies of the actors. These interfaces accept queries from the actors, search the target data from emergency management ontology, and then send the results back to the actors.

Furthermore, the dynamic data and static data ontologies must be linked because the emergency responders need information from both. In the processes of ontology linking, it is possible to combine the semantic mapping method with the nonsemantic mapping method. For example, it is common to match the vocabulary of concepts first and then to compute whether they have logic (spatial) relationships with each other. The main structure of the emergency management ontology is shown in Fig. 6.

In conclusion, the use of ontologies may help to represent semantic information in emergency management in two respects. First, ontologies could provide uniform definitions for the data used in emergency management. On the one hand, actors in emergency management are not technical experts, thus they cannot understand the words used by technical experts who are responsible for the maintenance of different models. On the other hand, different application domains, such as hydrology and meteorology, specify different meanings for the same concept. It is thus difficult to integrate the information in these domains. Ontology assigns a uniform explanation of the concepts that are agreed upon by both experts and actors in different domains. This type of explanation can act as a bridge for understanding between experts and actors and between different application domains. Second, if the concepts and relationships are clearly defined, context-related information could be correctly distributed to the

Fig. 6 Emergency Management Ontology



actors. For example, if the data in emergency management are labelled with explicit definitions regarding their contexts, it is unlikely that the data will be delivered to unrelated actors. Therefore, using an emergency management ontology, emergency responders could query the information from their query interfaces and obtain the data needed to save people affected by the disaster.

Conclusions and future work

In this study, we analysed the possibility of applying ontologies to resolve the semantic interoperability inherent in emergency management. Although there are many related works on using ontologies to solve the spatial data-related problems in emergency response, the research has generally been theoretical. No mature prototypes or software currently exist that can be used in real disaster scenarios to help emergency actors. To illustrate the problems and analyse the applicably of using ontologies in emergency management, a simple scenario is introduced. We believe ontologies may be useful when integrating data models with user models, performing semantic-related operations on spatial data, and helping actors extract context-related information. We elaborated an emergency management ontology by using a dynamic data model and several existing data sets that have been identified as important for emergency response. Although the presented work is at a very early stage, the completed investigation allows us to continue the work according to the main stages listed in the paper.

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