Challenges in Semantic Interoperability in Emergency Management

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Abstract. Disaster management increasingly depends on various information systems. Interoperability among these systems is necessary, especially during disaster response. Despite extensive efforts on semantic interoperability, there exist serious challenges in exchange of critical information in this domain. This research highlights some of these challenges and explores various paths to advance the existing approaches.

Keywords: Disaster management, semantic interoperability, conceptual modeling, ontology, ontology reconciliation.

1 Introduction

Disaster management increasingly depends on various information systems to improve the exchange of critical information and to support better decision making. Communication and coordination is at the core of disaster operations, and interoperability among the information systems is an important part of it. Interoperability comes in different levels [1] that semantic interoperability is the focus of this paper. Despite an extensive effort on semantic interoperability, that we will discuss some of them in Section 2, interoperability is still a source of controversy in comprehensive emergency management. On the one hand, the domain is so diverse and the industry is still exploring various needs of different sectors of the society. On the other hand, there are scattered solutions that are not integrated under a cohesive framework or are difficult to be adopted by industry. The approaches can be categorized into two groups: (1) bottom-up approaches that try to provide interoperability through various data standards with the support of various automation tools, (2) top-down approaches that try to facilitate interoperability by providing an overarching conceptual model for the domain. The next section will discuss some of these approaches in more details. In Section 3, we will discuss our research questions, research findings and future work.

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2 Related Work

2.1 Interoperability Data standards

There are various geospatial standards such as Geography Markup Language (GML) [2] for the exchange of geographical information. People Finder Interchange Format (PFIF) [3] encodes information about missing or displaced people in disasters. ISO/IEC 11179 [4] is an international standard for metadata registry. It provides a guideline for definition and representation of data elements in a hierarchal schema. Among the frameworks using ISO/IEC 11179, the notable ones in the domain of disaster management are Universal Data Element Framework (UDEF) [5] by The Open Group consortium and National Information Exchange Model (NIEM) [6] by U.S. Department of Justice and the Department of Homeland Security.

UDEF categorizes objects in an enterprise into high-level concepts such as entity, asset, document, enterprise, etc. It also classifies attributes of these objects, such as amount, graphic, picture, date, etc., in a separate hierarchy. It then assigns a number or alpha character to the nodes of both hierarchies and uses this structure to generate identifiers for uniquely labeling data elements in an enterprise. The identifiers are derived by concatenation of the assigned numbers or alpha characters.

NIEM is a framework for sharing critical information across all levels of US government. Again the center of this exchange framework is its metadata repository. The core concepts include person, address, organization, etc. They define the high-level artifacts that are universally shared across all subject matter domains. The domain data elements, on the other hand, extend the universal data elements or add new data elements according to the specific needs of the given domain. One notable difference between NIEM and UDEF is that UDEF separates the definitions of the attributes from the objects. In this way it can provide more variability in mapping between the domain concepts and UDEF high-level concepts.

The Organization for the Advancement of Structured Information Standards (OASIS) [7] also has a set of standards mainly for transporting and routing emergency messages: Common Alerting Protocol (CAP) (a data interchange standard for alerting and event notification), Emergency Data Exchange Language (EDXL) (for routing messages including requesting or deploying resources or communicating their status), and Customer Information Quality (CIQ) (a set of specifications for parties (person/organization) and their relationships). They can be used as a payload for the standards discussed above. All the standards mentioned in this section use XML as an enabling technology.

2.2 Ontologies[2]

Upper and domain ontologies both have applications in disaster management. The two upper ontologies used in this domain are Descriptive Ontology for Linguistic and

[2] For further information on ontologies please see Uschold, M. and M. Gruninger, Ontologies and Semantics for Seamless Connectivity. ACM SIGMOD Record, 2004. 33(4)

Cognitive Engineering (DOLCE) and Basic Formal Ontology (BFO). The conceptual difference between DOLCE and BFO is that DOLCE is based on linguistic and cognitive science and biased towards human perception [8], however BFO assumes there is an objective reality out there and claims provision of a transparent description of real world [9]. Little and Rogova [9], for example, have used BFO ontology to provide situational awareness in a disaster by detailed modeling of entities and attributes, relationships, events and processes.

There are numerous applications of domain ontologies as well. Liu & Fang [10] use ontologies to organize the tasks involved in an emergency response to debris flow. They use the lexical categorization of the concepts and formed the high-level concepts into generic verb, generic noun, generic adjective, generic adverb, and other generic constraints. Araujo et al. [11] define five different domain ontologies for their training simulation systems: Emergency ontology contains information, such as the cause, severity, or characteristics, about the incident. Person ontology contains information about the users of the system or the participants in the simulation scenario. Object ontology contains information about the objects or any rescue equipment taking part in an emergency response. Tactic ontology contains information about the rules and routines the response team follows. Finally infrastructure ontology contains information about the environment the incidents happen. Mathus et al. [12] and Kruchten et al. [13] take a different approach and use OO modeling methodology to conceptualize the core concepts of the ontology. Matheus et al. design an ontology for situational awareness. A situation in their model consists of objects, relationships, and a goal. The model is designed to capture evolutions of the objects and relations over time. Kruchten et al. design an ontology for investigating the interdependencies among infrastructures, such as power system or water system, during a disaster. The interdependencies among infrastructures are modeled at both physical and social levels. Physical elements of infrastructures are modeled as a network of interconnected elements. Interactions at social level are modeled by the agents that communicate and coordinate the operations during disaster response. The city that the infrastructures serve is modeled as a set of blocks named cells. Depending on the nature of things occupying the cells, they can be residential, economic or government.

2.3 Ontology reconciliation

There is a large body of research on semantic integration in the database and ontology disciplines. Database research deals with schema matching and answering queries using multiple sources of data [14]. Ontology research, on the other hand, deals with semantic heterogeneity in structured data [15]. In order to exchange information and knowledge between diverse ontologies, we need to be able to reconcile them. The most common approaches to reconciliation are ontology merging and ontology alignment [16]. In merging, a common ontology is created by unifying all information from all source ontologies. On the other hand, in aligning, the source ontologies are made consistent and coherent with one another but kept separately. Interoperability is enabled by a set of alignment statements which specify the relations between the ontologies.

3 Research problem

In Section 2 we discussed some of the related work on conceptual modeling and semantic interoperability in disaster management domain. Briefly bottom-up approaches usually use ad-hoc methods for modeling. This causes difficulties for the information systems that are developed based on these models and need to exchange critical information in disasters. The standards mainly work at data specification level. Some of them use classification schemas that are formed from common data artifacts across enterprises, and therefore they don’t capture the context in which those data are used. Moreover there is a patchwork of these standards that need to be integrated in order to be suitable for the users. Upper ontologies, on the other hand, provide domain-independent constructs to articulate phenomena in a domain, and are proposed to facilitate interoperability among domain ontologies. However aside from the fact that there is no unique way to conceptualizing the world, their constructs are abstract and mapping them to domain concepts is not trivial. They need special expertise and their enabling technologies are not readily available to industry.

This research explores different paths to improving semantic interoperability among disaster information systems through (1) finding methods to enhance the conceptual models developed for such systems (for the purpose of interoperability), (2) proposing modeling solutions for common scenarios in the domain, and (3) developing matrices to assess suitability of the interoperability standards for the application systems in the domain.

We started off by looking into some upper ontologies and system theories to see if we can find some practical rules and principles for design and evaluation of domain conceptual models. We particularly turned to an adaptation of Bunge upper ontology, named Bunge-Wand-Weber (BWW) [17], that comparing to other upper ontologies, such as Dolce and BFO, has fewer constructs, close correlation with system theory, and been extensively used for information systems concepts. We initially used it in an exercise for modeling interdependent infrastructures in disasters (Figure 2 in [18]). However we did not find it much of guidance in modeling of our problem domain. Looking at the literature on BWW [19], it has mainly used for evaluation of meta-modeling languages such as Entity-Relationship or UML. We found BWW and UML aligned in fundamental concepts, although BWW’s formality sheds light on some constrains of UML. We also found BWW less expressive, comparing to other ontologies, in conceptual modeling of application domains.

Wand and Weber [20] also proposed ontological completeness and clarity for ontological evaluation of conceptual models. Ontological completeness refers to the ability to represent all the phenomena in the problem domain. Ontological clarity determines whether the constructs of the model exhibit the following deficiencies: overload (one construct modeling several concepts from the domain), redundant (several constructs modeling the same concepts in the domain), excess (the construct does not correspond to any concepts in the domain), or deficit (lack of a construct to represent a concept in the domain). We did an exercise of this evaluation method on another model we developed for interdependent infrastructure in disasters using UML [13]. What we experienced was that since the application models use different abstraction and simplification methods to meet the requirements and constrains imposed by their problem domain, using such methods to assess the soundness of the models may not be not enough because they have to be assessed within the context they are developed, however this method can help to surface the trade-offs made in the modeling process and can be used as a basis for comparison across several models. As mentioned above, this method has been more appropriately used for evaluation of meta-modeling languages.

Another theory that we studied was Living System Theory (LST). We were interested to learn about other theories that can provide different perspectives to modeling structural or functional aspects of this complex domain. We would like to know whether they can augment the existing methods to better capture and represent the semantic of the domain. LST identifies main functions and processes that are common among all living systems. It categorizes living systems to 8 levels from cells to supranational organizations and identifies 20 common processes (or sub-systems) necessary for their functions. Eight of these sub-subsystems process matter-energy (for metabolic purpose), ten of them process information (for coordination and control), and two of them process both matter-energy and information. Examples for information processes are 'input transducer', which communicates with the environment and brings information across the system boundary, and 'channel and net', which transmits information to other parts of the system. The corresponding matter-energy processes are 'ingestor', which brings matter-energy into the system, and 'distributor', which transports matter-energy to other parts of the system [21]. LST has a functional view rather than a structural view to systems, and it is different than (and complement to) an ontological view that discusses the nature of being and their relations. One application of this theory in disaster management could be for classification of various roles and services, but we need a structure in place (in another word an ontology) in order to be able to apply some of those constructs. Again similar to upper ontologies, we found the constructs of this theory very abstract. There were no rules or procedures to facilitate their mapping to real world applications and we found very limited work with an attempt to do so [22, 23].

In addition to the top-down approaches discussed above, we have also explored some bottom-up approaches. We believe one way to exploit and systematically capture common modeling issues in the domain is to find some common scenarios and develop solutions for them in form of patterns[3]. We closely work with a W3C incubator group called Emergency Information Interoperability Framework (EIIF) [24]. The goal of the group is to identify current issues in semantic interoperability among information systems in emergency management and propose an

[3] For further information on design patterns please see Rising, L., Patterns: A Way to Reuse Expertise. IEEE Communications Magazine, 1999. 37(4).

interoperability framework for these systems. The group consists of IT experts from academia and industry who have also experience in emergency management.

One of early tasks within the group was developing a use-case, 'Who is Doing What Where", as part of an exercise to surface the issues in one of important use-cases of the domain, where the interoperability is mandatory. The author created a prototype model for this use-case using UML. It was originally created from the database schemas of two emergency information systems, and then refined in iterations through the feedback from the group. Some issues that were brought up by the members during this process were: proper modeling of various roles in emergency situations, separation of the state of an entity from the definition of that entity, proper level of abstraction for a conceptual model, proper naming of the concepts or attributes for which an international standard exists.

We proposed to the group an interoperability framework that incorporates a spectrum of approaches from weak to strong semantic to address diverse needs of the stakeholders and application systems in the domain and to allow users to choose solutions according to the requirements and constraints in their problem domain without excluding other approaches. Of course the implementation of such a framework largely depends on the availability of resources and the scope the group will set for its future work. Nevertheless the section that defines the scope of the framework includes a classification of necessary functions and features for emergency information systems and a set of critical uses-cases that define the domain context for such systems and can inform development of their critical functions and the data standards for disaster management. Currently a set of new use-cases have been proposed by the members and upon approval of the group's proposal, the work on them will continue.

We also need to further investigate in what ways a catalogue of patterns that address common use-cases and modeling issues in the domain can benefit the information system designers. Some related work to these patterns in software engineering are [25] and [26], that provide a collection of meta-data patterns for organizations using UML and Entity-Relationship modeling languages respectively. Another related work on design patterns is done by Gangemi [27]. These patterns provide solutions for common conceptual problems across various domains using upper ontologies. They define generic use-cases for these common problems and provide ontological models for them in form of patterns. An example for the patterns of this kind is "participation of an object in an event".

Another activity we are pursuing is mapping the existing data standards for disaster management to the data models of a number of disaster information systems, and in the process of doing so, we plan to identify some concrete issues in the design of such schemas. We are interested to develop matrices for assessment of such data standards to help users choose suitable schemas for their application systems and help designers to develop better data standards. The standard that we are currently investigating is the NIEM framework.

4 Conclusion

We discussed some of the challenges in interoperability among information systems in disaster management and enumerated some top-down and bottom-up approaches for them. Interoperability has always been the holy grail for software systems, and the diversity and criticality of disaster management add to that complexity. It looks like the ultimate solutions lie between two worlds: modeling methods that are informed by formal theories but yet are flexible enough to allow users to adapt them to their particular problems and technologies that enable and facilitate the adoption of those methods.

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