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ORIGINAL PAPER

A geo-ontology-based approach to decision-making in emergency management of meteorological disasters

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Abstract Ontology as a kind of method for knowledge representation is able to provide semantic integration for decision support in emergency management activities of meteorological disasters. We examine a meteorological disaster system as composed of four components: disastrous meteorological events, hazard-inducing environments, hazard-bearing bodies, and emergency management. The geospatial characteristics of these components can be represented with geographical ontology (geo-ontology). In this paper, we propose an ontology representation of domain knowledge of a meteorological disaster system descending from an adapted geospatial foundation ontology, designed to formally conceptualize the domain terms and establish relationships between those concepts. The class hierarchy and relationships of the proposed ontology are implemented finally at top level, domain level/task level, and application level. The potential application of the ontology is illustrated with a case study of prediction of secondary disasters and evacuation decision of a typhoon event. The multi-level ontology model can provide semantic support for before-, during-, after-event emergency management activities such as risk assessment, resource preparedness, and emergency response where the formed concepts and their relationships can be incorporated into reasoning sentences of these decision processes. Furthermore, the ontology model is realized with a universally used intermediate language OWL, which enables it to be used in popular environments. This work will underlie the semantic integration among human beings, between heterogeneous systems and between human beings and systems, enable spatial semantic reasoning, and will be useful in guiding advanced decision support in emergency management of meteorological disasters.

Keywords Geo-ontology · Meteorological disaster · Emergency response

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1 Introduction

Meteorological disasters refer to those disasters triggered by atmospheric activities and causing loss of life and property directly or indirectly. Meteorological disasters are among the most severe natural disasters for many countries worldwide. The analysis of disaster statistics compiled for the period 1967–1991 indicates a rising trend in the numbers of people affected by natural disasters. Statistics also indicate that extreme meteorological and hydrological events account for 62% of all events recorded as natural disasters. If those associated with weather events are included, the percentage rises to 85%. Over the same period, about 3.5 million people were killed by meteorological and hydrological events, while about 2.8 billion were affected by them (Obasi 1994). United Nations reported, in total, 739,930 people died from meteorological disasters directly during 1947–1980 (Yang and Zhao 2007). China is one of the few countries in the world most severely affected by meteorological disasters because of its large population and rapid economic growth. China has suffered enormous loss of life and property due to such events as rainstorms, typhoons, and snowstorms in the past decades. China's major meteorological disasters affect about 400 million people, and economic losses resulting from the disasters account for roughly about 1–3% of the gross domestic product. In the recent half century, hundreds of millions of people suffered from major meteorological disasters in China, and the direct economic loss was as much as several hundred billion (Liu and Yan 2011). Global climate change is anticipated to bring about increasingly frequent weather anomalies all over the world, and these aggravate the risk of meteorological disasters. In January 2008, a long-lasting low-temperature and freezing condition in the southern part of China resulted in unprecedented damages, with 129 people dead and the total economic loss about 151.65 billion Chinese Yuan (Sun and Zhao 2010).

Many researchers argue that a disaster system is composed of hazard factors, hazard-bearing bodies (HBBs) and hazard-inducing environments (HIEs), or the like (Shi 1996, 2005, 2009; Wang et al. 2012). Shi proposed a widely accepted theory framework in natural disaster domain. Disastrous meteorological (weather or climate) events (DMEs) are thought of as the hazard factors of meteorological disasters. These events are different from meteorological activities such as rainfall, temperature increase/decrease, and air motion. Only when these kinds of meteorological activities are significantly different from a normal level will they trigger DMEs. Hazard-bearing bodies are factors that includes humans, things, and systems (coherently formed from humans or things manually or naturally). HIEs are referred to as some macroscopic natural or social determinants of meteorological disasters. Some other researchers also propose an additional component generally called emergency management (EM), which represents human intervention to the above components (Fan et al. 2009). The meteorological disaster system, as a subset of the disaster system, can be delineated through these theoretical frameworks. In this paper, we present a framework of a meteorological disaster system based on that of a public safety proposed by Fan et al. (2009) with an additional component: HIEs.

Figure 1 shows the structure and interaction of the proposed meteorological disaster system. From the viewpoint of system dynamics, the individual components are inter-connected with one another. As far as meteorological disasters are concerned, hazard factors are derived from those common meteorological factors such as precipitation (including rain, snow, hail), wind, and temperature. When they significantly exceed a normal level in such conditions as quantity, extent, or rate, hazards appear. HBBs include all kinds of natural and man-made objects vulnerable to DMEs such as agricultural fields, buildings,

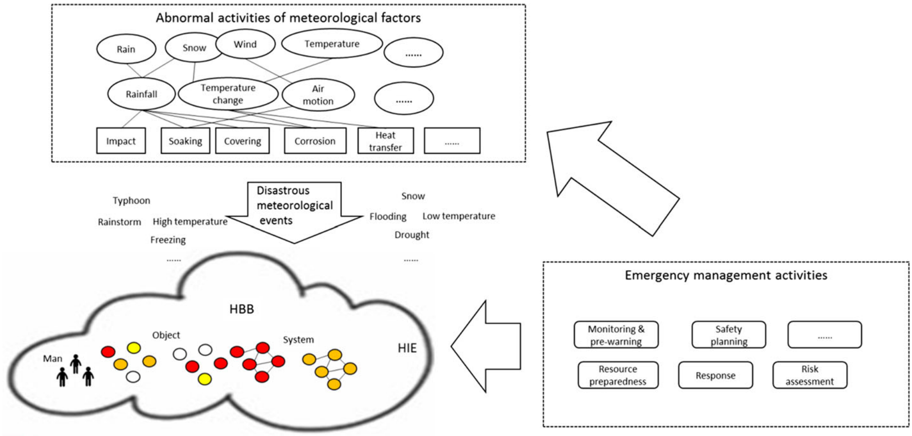

Fig. 1 Components of meteorological disaster system and relationships between them

forests, grassland, manufacturers, and facilities. The HIEs of meteorological disasters include geology, terrain, climate, and urban environments.

The symbiotic process of typical disasters can be treated as the mutual competing process of material flow, energy flow, and information flow among the "four elements" (DMEs, HBBs, HIEs, EM) in the meteorological disaster system. Although there are various categories of meteorological disasters (e.g., typhoons, rainstorms, snowstorms, extreme temperature), it is feasible to map these disasters to some universal effects such as impact, soaking, covering, corrosion, heat transfer (Zhang et al. 2016).

In order to strengthen the emergency management of meteorological disasters and increase the capability of preparedness, mitigation, response, and recovery for meteorological disasters, risk assessment and emergency response decisions have been paid much attention by worldwide researchers and emergency staff. The former provides goals and references for emergency resource planning and allocation, specialist training, and compilation of emergency plans, while the latter provides support for scientific and effective action on occurrent disasters. Some researchers have investigated risk assessment methods for specific kinds of meteorological disasters, such as hurricanes, drought, rainstorms, and heat waves (Emanuel et al. 2006; Vandentorren et al. 2006; Shahid and Behrawan 2008; Yin et al. 2011; Falter et al. 2015; Lai et al. 2015; Papathoma-Koehle et al. 2016). The response to meteorological disasters in recent years has demonstrated great progress due to improved capabilities in weather forecasting and climate prediction, as well as governmental efforts in emergency management. Some emergency plans are established in advance in consideration of potential disaster scenarios, available emergency resources, and organizational structure (Perry and Lindell 2003; Bernard and McGeehin 2004). This work is helpful for first response following emergency resource planning and well-prepared procedures in emergency plans the moment the disasters for which they are prepared occur. However, these pre-disaster plans are generally inappropriate to use without adjustments in a specific disaster, since they are composed before the disaster, and in situ conditions of disasters can be completely unanticipated.

In current studies of risk assessment and emergency response decision-making in meteorological disasters, domain knowledge is seldom systematically modeled and considered. On the other hand, more researchers recognize the importance of incorporating semantic information in modeling and analysis for support of emergency management activities such as safety planning, risk assessment, and emergency response decisions across multiple agents. The heterogeneity of the information is a problem that limits most of these activities that use them. In such emergency management activities, the collection of emergency information such as fundamental geographic data, risk sources, protection objects, real-time disaster situations, and emergency resources is essential for us to make proper decisions. With advances in geospatial data acquisition techniques (for example, Geographic Information System, Global Positioning System, remote sensing, and the sensor web), the capability of gathering emergency information has shown great improvements. Furthermore, some semantic or logic relationships among those components comprising meteorological disasters play no less a role in emergency analysis and decision-making. These semantic relationships include topology, hierarchy, direction, ordering. How to model, represent, and retrieve these kinds of semantic relationships is currently being paid much attention by academic researchers.

The remaining parts of this paper are organized as follows. Section 2 reviews some related work from ontology modeling, geo-ontology, and ontology in disasters (especially meteorological disasters). In Sects. 3 and 4, an effort is made to construct a descending ontology model of the proposed meteorological disaster system taking an adapted geospatial foundation ontology as upper ontology, following analysis of geographical characteristics, hierarchical conceptualization, and logical abstraction of the meteorological disaster system. Section 5 describes a decision-making framework, which is the core of a decision support system for meteorological disasters. In Sect. 6, the potential application of the ontology is illustrated with a case study of prediction of secondary disasters and evacuation decision of a typhoon event. Lastly, we present our conclusions and discuss further work.

2 Related work

Ontology as a kind of method for knowledge representation is able to provide semantic integration among human beings, between heterogeneous systems, and between human beings and systems. In many ontology applications, ontology modeling is utilized to identify concepts, categories, relations, and rules, thereby defining and conceptualizing the knowledge in a specific domain to make it easier to build a model, which can facilitate other tasks such as knowledge engineering, database design, information modeling, and information inquiry (Guarino 1998; Agarwal 2005). Ontology has been widely used in emergency management to provide logic semantic rules for decision analysis. Hung et al. (2004) developed a plan ontology that can capture the knowledge found in the domain of military planning organizations, tasks, and relations, such as task assignment. Wang et al. (2005, 2006, 2009) used an ontology of emergency knowledge to formalize the logic and semantics of an emergency plan and emergency response process, in which ontology is used to provide an effective means to implement semantic level integration. Sotoodeh (2007) constructed an emergency management ontology model and defined relationships among some critical ontology concepts, including emergency, infrastructure, region/population, and collaboration. Galton and Worboys (2011) described some work on the ontology of information that can contribute to a solution of the integration problem, so that the Common Operating Picture can provide the unified view required of it truly and effectively.

Meanwhile, some researchers have explored geo-ontology from the geographic information science domain, and this focus has increasingly drawn interest and continues to grow. Geo-ontology is a more complex, intricate concept. Geo-ontology mainly refers to studying geographic objects, concepts, categories, and relations, extending ontology to a geographic context (space–time context). Agarwal (2005) expounded on a comprehensive and critical review of ontological considerations in GIScience, which helps in identifying the significant issues and directing the follow-up research agenda in GIScience. Kolas (2006) suggested types of ontologies that could support a geospatial semantic system, whose work provides general reference for establishing a rich, dynamic, and flexible geospatial knowledge base in a specific domain. Henriksson et al. (2008) examined a set of core geographical concepts of the Finnish geo-ontology (Suomalainen paikkaontologia, SUO). Those concepts are associated either with discrete geographic objects with well defined boundaries or with continuous fields over space. In their paper, some classes that describe the spatial aspects of places (e.g., locations), regional geography (e.g., administrative regions), patterns based on human interaction with nature (e.g., land use), and aspects related solely to the physical environment (e.g., landforms) were defined for geographically referenced data discovery and retrieval on the Web. Li et al. (2009) introduced the conception of a geo-object ontology, which is a shared formalization and display specification of a conceptual knowledge system in the field of concrete application of spatial information science. They articulated that the biggest difference between ecumenical information ontology and geo-ontology is that the latter has spatial characteristics, and explained how the proposed geo-object ontology serves ultimately geographic information retrieval service. Jung et al. (2013) proposed an ontology-enabled framework for a geospatial problem-solving environment allowing collaboration among Web service providers, domain experts, and solution seekers to semantically discover and use geographic information services to solve a target class of geospatial problems. In their study, GIS Data Theme ontologies, GIS ontologies, and GIS Function Theme ontologies are designed to structure the classification of GIS datasets, geospatial features, and GIS functions, respectively. Among some specific applications, Hu et al. (2013) introduced an ontology design pattern for semantic trajectories, discussed the formalization of the pattern using the Web Ontology Language (OWL) and applied the pattern to two different scenarios, personal travel and wildlife monitoring.

To reuse structured knowledge through core ontologies, modeling of a disaster system drew the attention of the formal ontology community. Following a formed foundation of standardized geospatial ontologies (geo-ontologies) proposed by Kolas et al. (2005), many more specific geospatial ontologies have been built into disaster management. Fan et al. (2009) were faced with two major challenges: (1) the integration and extraction of the heterogeneous spatial data, and (2) their transmission to emergency management actors in an emergency response. They discussed the possibility of applying the ontology to resolve semantic heterogeneity in emergency response and proposed a concept for a solution to the semantic interoperability problem in emergency management using an ontology. Jung et al. (2013) validated the applicability of the proposed framework in their study through a prototype implemented using an earthquake as an example. Xu et al. (2014) put forward a conceptual model of knowledge for earthquake disaster emergency response (EDER), where geo-ontology serves to represent geospatial characteristics of the EDER knowledge and addresses a need for semantic interoperability in the modeling process. In their study, 3-layer modeling primitives, considered a top-level ontology, are proposed, to provide the foundation of the EDER knowledge representation. In recent years, situation detection is enhanced with development of numerous ICT applications, thereby provide better support for disaster management (DM). In view of the lack of well-founded structural and temporal constructs of traditional design techniques, Moreira et al. (2015) applied ontology-driven conceptual modeling to situation-aware (SA) DM and demonstrated the prominent role played by DM core ontology in the development of SA applications.

Some research has been carried out in ontology-enabled problem-solving foundations of meteorological disasters. To solve the classification and identification of the disaster level caused by severe weather, He et al. (2012) proposed an ontology representation of severe weather based on the W3C standard to support promulgating the definition and identification of warning of meteorological disasters among trades. Gui et al. (2010) proposed meteorological disasters' ontology knowledge representation in the guidance of frame theory. Chou et al. (2011) put forward the method of tracking a meteorological disaster via Internet ontology. Zhang et al. (2015, 2016) provided a definition of a meteorological disaster system and proposed a model called meteorological disaster ontology (MDO) to formally describe domain knowledge of a meteorological disaster system.

In summary, currently existing approaches to ontology modeling of disaster management (including meteorological disasters) lack systematical analysis of disaster systems and general representation of them. For meteorological disasters, Zhang et al. (2015, 2016) seldom considered geospatial factors. However, a meteorological disaster system is a typical kind of structure and process inherently bound to space and time. DMEs happen in a certain location (or area) and time (or a period of time), HBBs are some spatial existence and usually have to be referenced in a space–time context, and HIEs generally refer to geographic (or geographically referenced) backgrounds. As a result, it is essential to consider geographic location specific semantic relationships between concepts of the meteorological disaster domain. In this paper, we first extend analysis of the meteorological disaster system by emphasizing on the spatial and temporal characteristics of the components of it. Then, we proposed a geospatial foundation ontology based on existing geo-ontologies to meet the expressivity of spatial and temporal characteristics of the meteorological disaster system. Finally, we built a descending ontology model from the geospatial foundation ontology, which adds geospatial dimensions to meet universal requirements of decision support of emergency management of meteorological disasters.

3 Toward geo-ontology

3.1 Different kinds of ontologies

3.1.1 Ontology classification

Guarino (1998) defined several levels of generality that give rise to different types of ontology: top-level ontology, domain ontology and task ontology, and application ontology (Fig. 2).

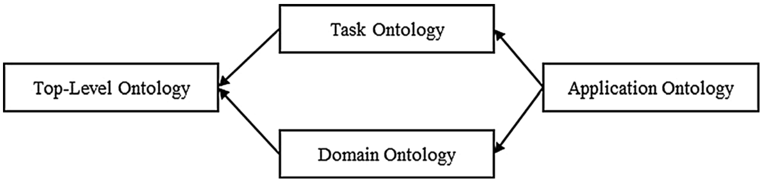

Fig. 2 Graphic representation of the different kinds of ontology proposed by Guarino (1998)

Top-level ontology They contain reusable generic terms that are common across all domains. Top-level ontology is most properly conceived as a series of perspectives on reality. The currently existing top-level ontologies include BFO, CYC, DOLCE, which can be selected as the top-level part of the lower ontology (task ontology and domain ontology).

Domain ontology and task ontology They contain terms that are specific in a particular domain (e.g., meteorology or hydrology) or specific task (e.g., planning). These terms are usually defined as specializations of existing concepts in top-level ontologies.

Application ontology It contains all necessary terms to model a particular application. These ontologies are often specializations of domain ontologies or task ontologies.

From a point of view of mathematics, ontology can be defined as

$$\mathbf{O} = \{\mathbf{C},\mathbf{R},\mathbf{H_c},\mathbf{rel},\mathbf{A}\}, \tag{1}$$

where $\mathbf{C}$ is a finite set of concepts, R is a finite set of relationships, $\mathbf{H_c}$ is the concept hierarchy or taxonomy, **rel** is non-taxonomic relationships between concepts (e.g., $\mathbf{rel}(\mathbf{R_1}) = (C_1, C_2)$ specifies that C_1 and C_2 have the relation R_1), and $\mathbf{A}$ is a set of axioms.

Concepts are some key terms from a domain. Specifically, some nouns can be selected as concepts of ontology. The ontology can be defined based on two types of concepts, "terminal" and "non-terminal," and two types of relations, "has" and "is_a" (Torres et al. 2005). Axioms refer to assertions (including rules) in a logical form that together comprises the overall theory that the ontology describes in its domain of application.

Formally conceptualizing the domain terms and establishing the class hierarchy are the first steps in building up ontology. This is generally accomplished with object-oriented (OO) analysis and modeling techniques, by which the concepts are mapped to classes. The relationships between concepts are implemented through properties. There are two types of properties: object property and data property. Object property defines the relations between two classes, and it works as a bridge linking two individuals from different parts of the class hierarchy. Data property acts more like the innate attribute of an object and it describes relations between individuals and data values.

3.1.2 Conceived ontology hierarchy

According to the above classification idea of ontology, we conceived the ontology hierarchy of a disaster system. As shown in Fig. 3, meteorological disaster ontologies should include all levels of ontologies, with domain ontology, task ontology, and application ontology as the core. As popular kinds of knowledge engineering techniques, domain ontology, task ontology, and application ontology are required to be built in view of the domain-specific business, while the top-level ontology is common for all domains. The ontologies drive the reasoning and analysis process related to specific activities of the emergency management of meteorological disasters. To describe geospatial characteristics of the meteorological disaster system fully, we first proposed geospatial foundation ontology based on some existing studies on geo-ontology. The geospatial foundation ontology inherits from selected top-level ontology and combines some existing geospatial ontologies (e.g., GeoXG reported by W3C Geospatial Incubator Group W3C geospatial ontologies, https://www.w3.org/2005/Incubator/geo/XGR-geo-ont-20071023/). Then, the adapted ontology (called as geospatial foundation ontology or geographic modeling primitives hereafter) is taken as root in the hierarchy of meteorological ontology. Domain

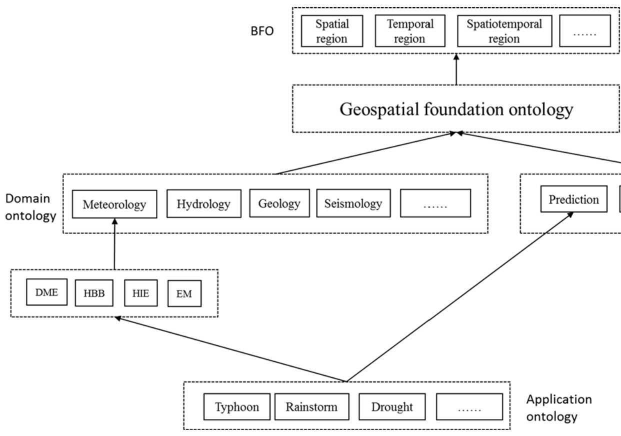

Fig. 3 Hierarchy of the ontology with geospatial characteristics derived from the geographic modeling primitives

ontologies, task ontologies, and application ontologies are inherited from their upper ontologies, which are further explained as follows.

Top-level ontology In this study, basic foundation ontology (BFO) is selected as the superclasses of the descending ontology. BFO are divided into two varieties: continuant (or snapshot) entities, such as three-dimensional enduring objects, and occurrent entities, such as processes conceived as unfolding in successive phases through time. These spatial and temporal concepts provide foundational support for presentation of geospatial context in meteorological domain. Concretely, those corresponding entities (or classes) will superclass the derived classes in domain ontology and the task ontology.

Domain ontology Domain ontology describes concepts in a meteorological disaster system and relationships between these concepts. Here, the four components of the meteorological disaster system (DMEs, HBBs, HIEs, and EM) inherently linked with geographical characteristics should be modeled with geo-ontology properly. In fact, these ontologies can be implemented through inheriting the corresponding classes (concepts) from the geospatial foundation ontology.

Task ontology Task ontology is constructed to provide semantic support for some activities in emergency management of meteorological disasters. Task ontology aims to represent disaster-general knowledge. This is knowledge commonly usable for various meteorological disasters. In turn, some general procedures and rules should be represented in this level of ontology.

Application ontology Application ontology models disaster-specific knowledge. This knowledge differs from one disaster to another. Generally, application ontology is derived from relevant domain ontology and task ontology according to specific procedures, behaviors, rules, and goals. For example, when faced with the prediction of potential secondary disasters of a typhoon, we need to launch a typhoon track analysis model to analyze the scope affected by the typhoon and an evacuation analysis model to determine evacuation strategy. Neither domain ontology nor task ontology can provide these kinds of disaster-specific knowledge.

3.2 Geospatial foundation ontology

There are many existing geographical ontologies such as GeoXG mentioned above, Geospatial Ontology from http://www.geoinformatics.cc, GeoNames Ontology, Geo-ontology for INSPIRE data themes, Geospatial Semantics and Ontology from USGS. Taking the GeoXG as references and combining some existing studies (e.g., Agarwal 2005; Kolas et al. 2005; Henriksson et al. 2008; Jung et al. 2013; Xu et al. 2014), we propose a geospatial foundation ontology to create geospatial items and geospatial relationships between items, which constitute the geospatial characteristics needed to represent meteorological disaster knowledge. So here we extend the meteorological disaster ontology to a geo-ontology-based representation into which several typical kinds of spatial relationships are incorporated to accurately grasp the temporal-spatial feature. '*Time Relationship*' is used to describe the sequential relations of two objects. '*Measure Relationship*,' '*Direction Relationship*,' and '*Topology Relationship*' is also implemented as three sub-properties of '*Spatial Relationship*,' and they depict how two objects correlate with each other in distance, location, and topology, respectively. In '*Direction Relationship*,' quantitative cardinal directions are used to describe accurate direction relationship; on the other hand, some qualitative relations are included to support rough reasoning. In addition to '*front*,' '*behind,*' '*left*,' and '*right*' for directions on a plane, '*Above*' and '*Below*' is used to better illustrate a three-dimensional scene. In '*Topology Relationship,*' semantics of spatial topological invariants between objects are expressed with three kinds of overlap cases: intersect, contain, and disjoin. Some theoretical models can be utilized to model these binary topological relationships (Egenhofer and Herring 1994). Those entities related to boundary in BFO (with suffix_boundary) are used as upper ontology in the adapted geospatial foundation ontology. Figure 4 shows the adapted geospatial foundation ontologies in our study, which are next used to derive the domain ontology and task ontology of the meteorological disaster system.

4 A descending ontology model

Taking the entities in the geospatial foundation ontology shown in Fig. 4 as superclasses, a descending ontology (including domain ontology and task ontology, as explained above) is derived to model the domain knowledge of the meteorological disaster system. The

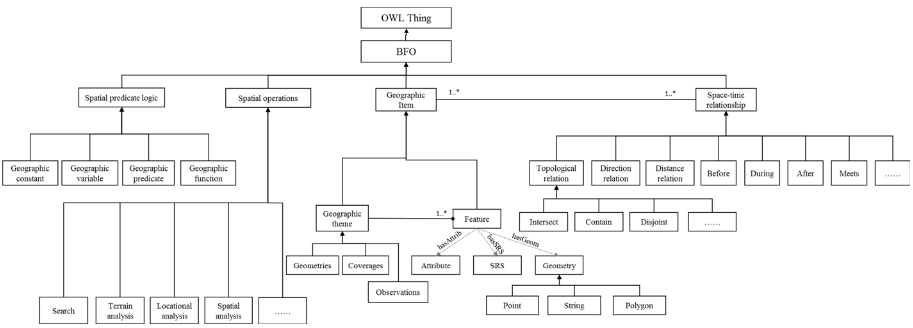

Fig. 4 Adapted geospatial foundation ontology model

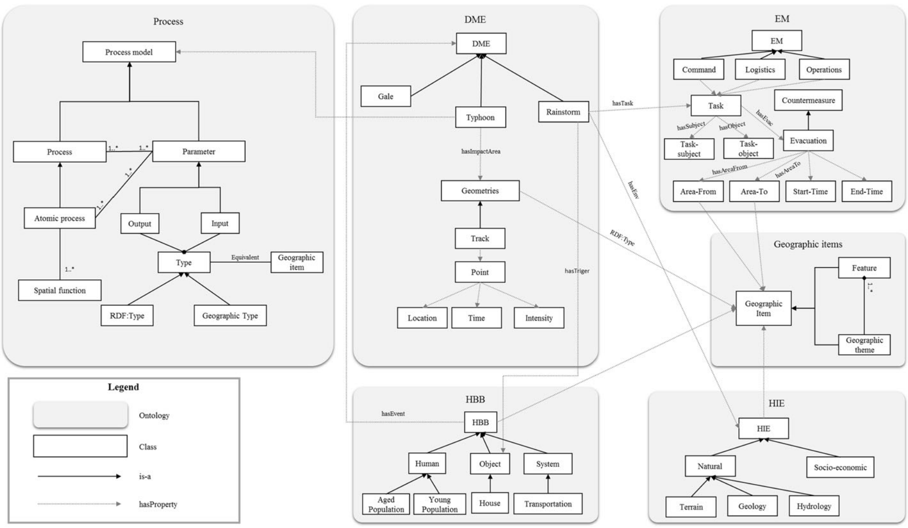

Fig. 5 Structure of the descending ontology for the meteorological disaster system (only the main classes and properties are depicted). Typhoon and evacuation is expanded as a disaster and task-specific example

descending ontology considers disaster-general aspects and is supposed to lay a foundation for problem-solving of a specific meteorological disaster (e.g., typhoon).

Corresponding to the four components of the meteorological disaster system, four ontologies are built to represent the relationships and definitions of the components of it. In these ontologies, some classes are correlated with other two ontologies: geographic item and process. Examples such as typhoon in DME and evacuation in EM and the main classes and properties are presented in Fig. 5.

The basic meteorological factors including rain, snow, wind, and temperature are the origins of various disastrous meteorological events such as drought, flood, freezing, severe storms, tropical cyclones, and winter storms. The mapping between those factors and disasters is investigated according to a so-called meta-action notion (Zhang et al. 2016) where 11 common effects produced from activities of meteorological factors (e.g., rainfall, temperature change, and atmosphere motion shown in Fig. 1) are summarized. Here also a glossary of meteorology is referred to develop the ontology. In Fig. 5, typhoon class is fully expanded to illustrate the structure of DME ontology and its relationships with other ontologies including HBB, EM, HIE, process ontology, and geographic item.

4.1 DME ontology

The DME ontology specifies the classification of disastrous meteorological events and their potential secondary events. We adapted the hierarchical classification established by the State Council of China, which contains 19 subcategories of disastrous meteorological events. Each of these events is built as a class to cover its definition. These definitions will be heterogeneous from domain to domain, or nation to nation. For example, typhoon is referred to as tropical cyclone in China, while it is called hurricane in the USA. Utilization of the ontology will assist in solving this kind of heterogeneity. Specifically, the built-in predicate of *equivalence class* in ontology language or editor (e.g., protégé) can be used to realize this goal. Some other relations are also specified in the DME ontology, which links

Table 1 Some typical original meteorological disasters, affected objects (or triggers), and potential secondary disasters

Original disasters	Hazard-bearing bodies and triggers	Secondary disasters
Drought	Forest, grassland, crop, desertification risk area, people and livestock	Forest fire, grassland fire, plant diseases and insect pests, desertification
Extreme rainfall	Plant, geo-hazard risk zone, river basin, village, crop, building, people and livestock, road, communication facility, channel, catchment area, coastal beach	Plant diseases and insect pests, landslide, debris flow, collapse, inundation, waterlogging, surge, communication outage
Tropical cyclone	–	Gale, rainstorm
Cold wave	–	Gale, sleet, freezing
freezing	Plant, electric power system, communication facility, road, crop, people and livestock, coastal beach	Plant diseases, water pollution, desertification
Gale	Construction site, electric power system, transportation	Falldown, blackout, short circuit, traffic accident, traffic jam

these events to the classes of other ontologies. For example, the relations between events and risk sources are delineated through the *hasTrigger* property and those between events and hazard-bearing bodies through the *hasImpactObject* property. In order to direct the DME ontology construction, in addition to referring to the classification of disastrous meteorological events, we prepared a comprehensive mapping table of disaster cascading rules (Table 1) to support reasoning for potential risk of secondary disasters, i.e., what secondary disasters may be triggered by the original disaster.

4.2 EM ontology

The EM ontology revolves around activities of four general phases of emergency management in meteorological disasters: preparedness, mitigation, response, and recovery. These activities are generally organized as a set of tasks. Every task includes subjects, objects, and restrictions or conditions. Subjects are the performers of the task, objects are the action objects of the task, and restrictions or conditions express the operational restrictions or conditions of the task. Temporal characteristics are substantial attributes of a task. Some of those classes defined for EM ontology are imperative to inherit from space–time objects of the geospatial foundation ontology and space–time relationships between those classes and relevant classes from other ontologies can be inherited from the space–time predicates of the geographic predicates. In order to evaluate time-dependent decision-making, generally, the temporal relationships of disaster evolution and countermeasure need to be identified. In our study, the temporal concepts proposed in the OWL-Time ontology by OGC (Hobbs and Pan 2006) are referred to and integrated into the space–time relationship classes of the geospatial foundation ontology. The temporal concepts in the OWL-Time ontology are shown in Fig. 6.

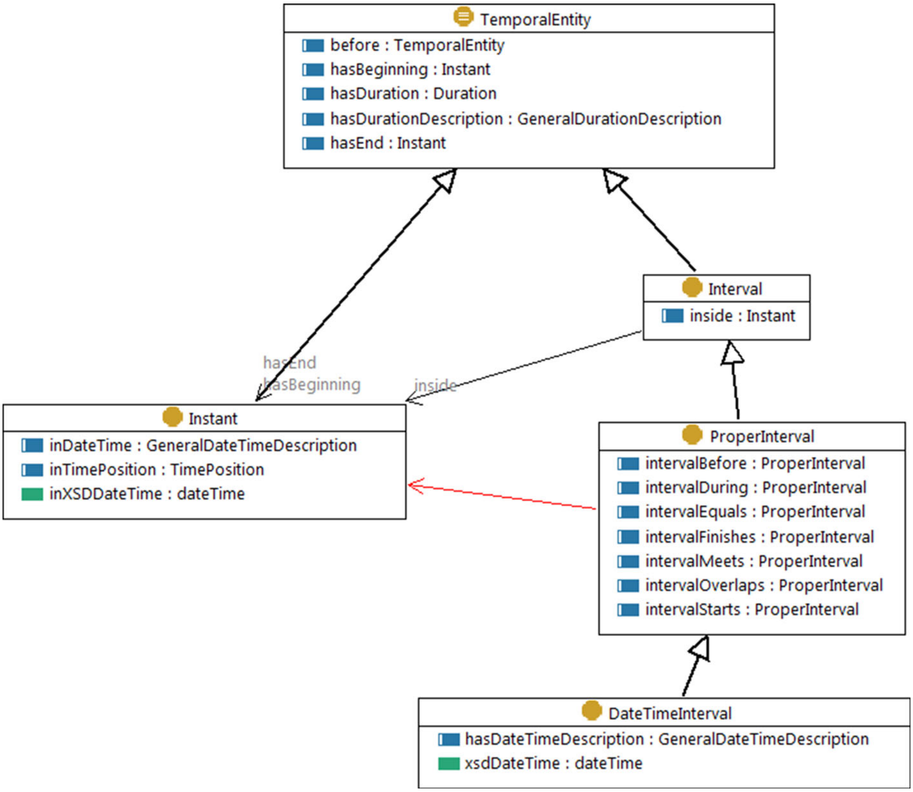

Fig. 6 Core model of temporal entities proposed in the OWL-time ontology (Hobbs and Pan 2006)

4.3 HIE ontology

The HIE ontology is intended to delineate the macroscopic background where disastrous meteorological events happen. In the DME ontology, *hasHIE* property links an event to its inducing and occurrence background. These macroscopic backgrounds can be classified into natural and socioeconomic ones, according to their features. For example, the natural backgrounds include geological, geomorphic, and topological ones. The *hasCoverage* property is set for HIE ontology to specify its geospatial data, generally modeled as continuous surface implemented through a field model in GIS. Raster data structure is a kind of suitable approach toward representing a field. Furthermore, there are other models able to store a field, such as regular grid, triangular irregular network, and contour.

4.4 HBB ontology

The HBB ontology describes the hierarchical classification of objects to be affected by different disastrous meteorological events and its relationships with DME ontology and geographic items. As recognized, different types of disastrous meteorological events will affect certain types of objects, which are determined by disaster cascading rules as listed in Table 1. These rules are able to be directly implemented with an ontology editor tool (e.g., protégé). Substantially this modeling capability depends on the underlying ontology

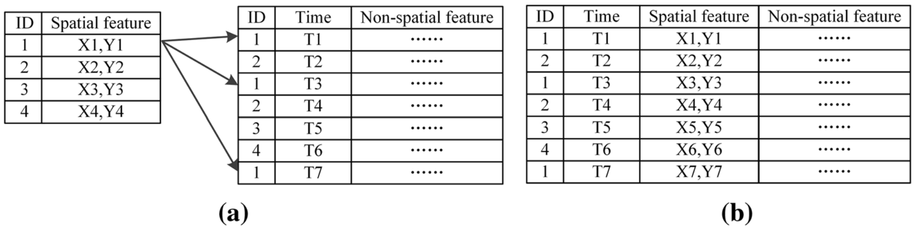

Fig. 7 Spatiotemporal data model for spatial entities with variable location and geometry

description language (e.g., OWL for protégé). On the other hand, whether natural or socioeconomic objects, they are all geographically referenced, depicted through an object property *hasGeom*. It is useful here to note that geospatial attributes (e.g., location or shape) of some types of HBBs (e.g., human, farmland) change with time. Thus, a space–time geometry in GIS is useful to provide expressivity for these HBBs' geometrical features. Figure 7 shows a kind of spatiotemporal data model for spatial entities with variable location and geometry.

4.5 Process ontology

Process ontology delineates the relationships and definitions of an analysis process, intended to define the standard classes (e.g., atomic process, input, and output) and properties (e.g., *hasInput*, *hasOutput*, *hasPrecondition*, and *hasResult*) describing how an analysis process involving geospatial data and GIS functions works, such as their inputs, outputs, and results. The process ontology is designed according to the OWL Web service (OWL-S) (Martin et al. 2004). The parameters of an analysis process include geospatial and non-spatial. The former can be specified through classes from geographic items and the latter through some primitive types in some computer description language such as xml:double and xml:string in XML. The link between geospatial parameters (including input and output) of process and geographic items in the geospatial foundation ontology is built with *hasInput* and *hasOutput* properties. With regard to those non-spatial parameters, xml data types can be referred to by the *RDF:Type* property for them. The preconditions and results of an analysis process as specified in the OWL-S ontology can also be annotated through the *hasPrecondition* and *hasResult* properties using specific expressions (Janowicz et al. 2010) in the process ontology. Given that the focus of our study is methodological demonstration, however, we only pay attention to inputs and outputs of the process.

5 The application framework

Once the meteorological disaster ontology is well constructed, it can provide decision semantic information for emergency management of meteorological disasters including routine and urgent activities, such as resource planning, prediction of secondary disasters, and countermeasure compilation. Meteorological disaster ontology itself provides domain knowledge representation of meteorological disasters, formalizing associated knowledge at different levels. As a result, the needs for analysis and reasoning in different decision goals of various tasks of emergency management are addressed. Thanks to the complement of geographical items in the ontology model, the complex process that occurs in a geospatial environment can be described more fully. Thus, decision-making of emergency management is expected to attract more interest.

In the course of these activities, some judgment and decision analysis need to be made based on ontological representation of domain knowledge including implicit knowledge (one of the most important advantages why we construct an ontology model) coupled with some supplementary rules formalized by SWRL (Semantic Web Rule Language, http://www.w3.org/Submission/SWRL/)). Given that the ontology model (corresponding to OWL language) is not able to express all relations (e.g., triggering conditions of the secondary disasters), expressivity of OWL can be extended by adding SWRL rules to an ontology. SWRL rules are DATALOG rules with unary predicates for describing classes and data types, binary predicates for properties, and some special built-in n-ary predicates. Protégé OWL editor supports SWRL rules, and several well-known reasoners such as Pellet and Hermit used in protégé also support SWRL rules.

As shown in Fig. 8, three types of main participants operate the ontology based system collaboratively to make it function. Domain experts are responsible for inspection and management of domain knowledge; they define and revise formal semantics in ontologies using an ontology editor such as protégé by revising classifications in the ontologies, delineating the SWRL rules, and establishing OWL-DL restrictions (e.g., a feature must have at least one geometry, spatial reference system (SRS), and attribute). Decision makers and external systems represent two categories of end users: human beings and systems, respectively. Whichever the end users are, the application will formalize the problems with rules first to facilitate the ontology engine, interpreting them and inferring in the ontology. During the reasoning, the ontologies mainly offer built-in rules (explicit or implicit) generally as *is-a* or *hasProperty*, which will be embedded into SWRL rules. Then they are interpreted by the reasoner, and the reasoning results are output to provide decision-making for emergency management activities. Some data and processing services (in the geospatial context, they are geo-data and geo-processing services, respectively, such as impact area analysis of disasters) may be required during the reasoning. The relevant data and processing service can be registered to the ontologies according to OWL-S and, as a result, they can work well together with the reasoner. Relevant geo-data and geo-processing services can be published resorting to some geospatial tools. For example, the geodatabase of ArcGIS is a fundamental infrastructure where those essential data such as HBB data, rescue resources, HIE data are organized and stored. They can be published through map

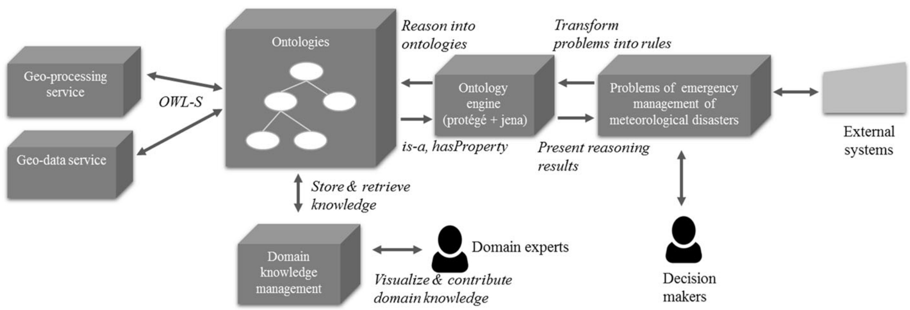

Fig. 8 Application framework of the meteorological disaster ontology in emergency management of meteorological disasters including routine and urgent activities

services of ArcGIS Server (http://www.esri.com/en/arcgis/products/arcgis-enterprise/Overview). ArcGIS Server can also publish geo-processing services easily.

For example, if we wish to predict potential secondary disasters of an original disaster (say, a typhoon), a typhoon track prediction model is employed to forecast the possible track in a coming period of time. With the affection scope and risk sources (triggers) as input and combined with the disaster cascading rules and domain knowledge implied in meteorological disaster ontology, the resulting distribution of possible secondary disasters can be produced.

6 Case study of disaster chain analysis of typhoons

6.1 Disaster chain

A disaster is often followed by some secondary disasters. If not prevented or controlled effectively and efficiently, the consequence caused by these resultant disasters will probably lead to more serious loss. This kind of cascading effect of disasters is called a disaster chain. Figure 9 illustrates a typhoon disaster chain. As seen, the original typhoon disaster will induce rainstorms and gales. The rainstorms will further cause torrents and inundations. The gale will cause storm surges and billows. The torrents will cause mud-rock slides and landslides.

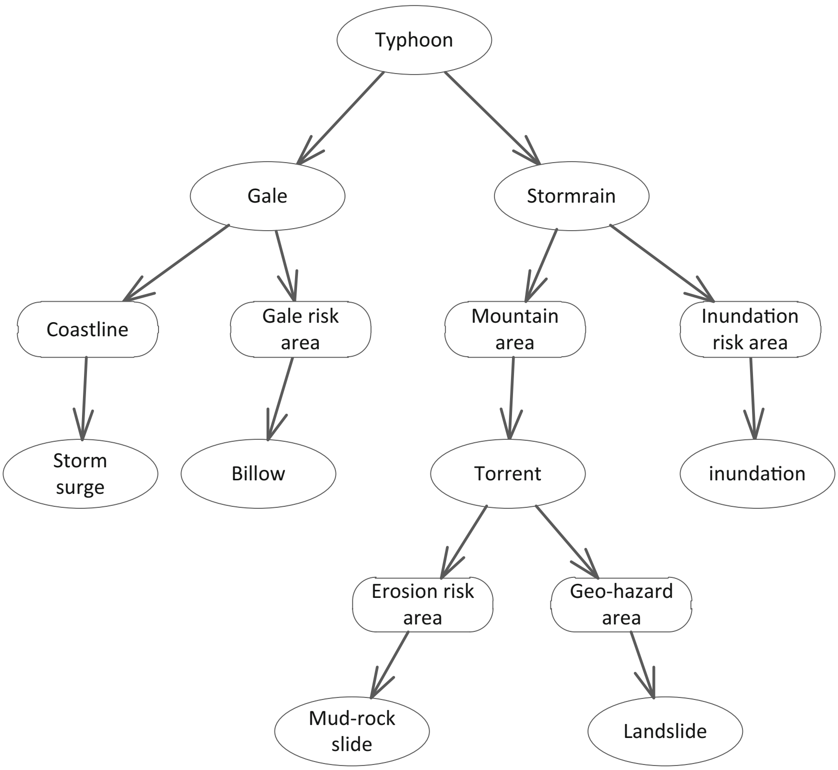

Fig. 9 Example of disaster chains of typhoons

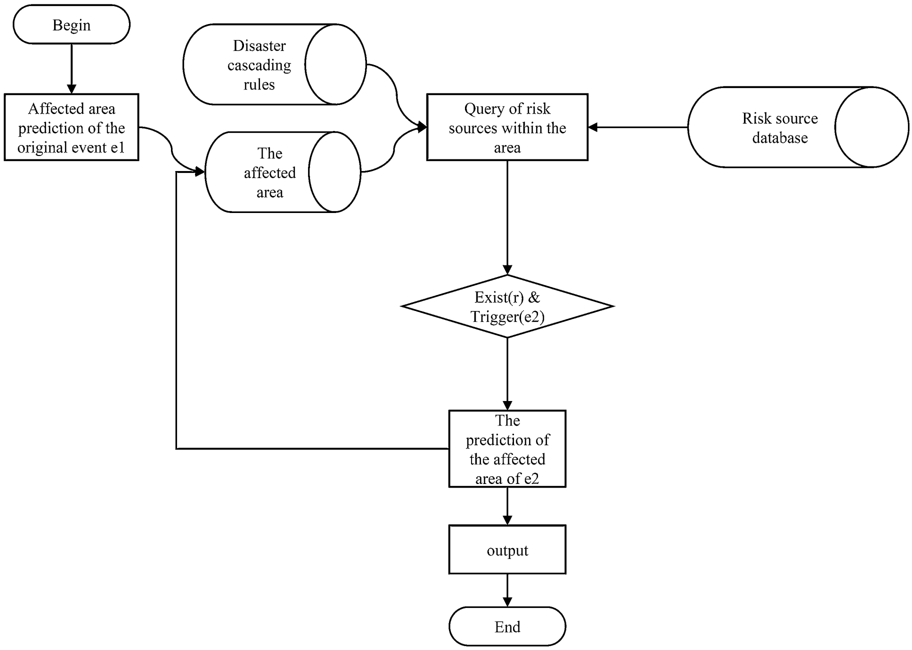

Fig. 10 Prediction workflow of potential secondary disasters for an original disaster

In a geographic area, secondary disasters can be predicted according to the disaster chain coupled with risk sources (triggers) distributed over the area. After the original event occurs, ones can predict the affected area caused by the event with corresponding models (e.g., Gaussian plume model for chemical material leakage, typhoon path prediction model for typhoons). In view of the affected area, risk sources contained in the area and vulnerable to the original disaster are identified with GIS topology analysis and target filtering under the support of prebuilt risk source database. These risk sources will be affected by the original event and release material, energy or information that is called disaster factors by Fan et al. (2009). Those disaster factors further cause secondary disasters. We can further analyze possible second-order secondary disasters taking the identified secondary disasters as new original events. Figure 10 shows the flowchart of prediction of secondary disasters of a typhoon.

This analysis process includes some geospatial data and processing that can be supported by several geospatial analysis functions from GIS. Table 2 lists the used GIS functions in terms of the steps involved in the workflow.

6.2 Evacuation

In a typhoon case, evacuation, as a kind of effective countermeasure, is performed frequently. The key to successful evacuations is timely transfer of the affected crowd to a safe area before the typhoon arrives, such that the available shortest evacuation time (ASET) is greater than the required shortest evacuation time (RSET). We can estimate the ASET according to the predicted time of arrival of the typhoon and the RSET can be estimated by the preparation time plus transfer time of the crowd (depending on transfer means and routes). For simplicity, we think it is safe if the wind ring of the typhoon (a space–time

Table 2 Some geospatial functions incorporated in the reasoning process

Step#	Operation	Geospatial data	Geospatial functions
1	Calculate the affected area by an event	[in] track (point sequence); [out] impact area (polygon)	Buffer, overlap
2	Pick out the objects in the affected area whose categories are *triggers* in cascading rule table (Table 1)	[in] objects (point collection), [out] filtered objects (points collection)	Feature query
3	Clip the secondary events according to the safety states of the selected objects	[in] objects, [out] clipped secondary events	Attribute query
4	Calculate the affected area by the secondary events respectively	[in] disaster dynamic process (space–time feature (point, line or polygon)); [out] impact area (polygon)	Buffer, overlap
5	Go to step 2 and execute the analysis recursively	–	–
6	Summarize the loss caused by the event and its secondary events considering space–time relationships	[in] impact area (polygons), [out] human casualty and property loss	Zonal statistics

entity) has a temporal relationship of *Disjoin* with the evacuation source area (at the beginning of the evacuation) and evacuation destination area (at the end of the evacuation).

6.3 Rule implementing

SWRL is used to define additional rules that cannot be expressed in the OWL. SWRL rules can use other predicates than just class or property names. A SWRL reasoning rule includes two parts, *antecedent* and *consequent*. It can be described as *antecedent* → *consequent*. The *antecedent* expresses some integrated premises before the reasoning process and the *consequent* shows the result that can be acquired after this process is fulfilled. Furthermore, *atom* is the basic component which appears in an integrated *antecedent*. In SWRL, properties and individuals defined in the OWL are applied in *atom* clause as the attribute and the parameter of the *atom*, respectively. There are many sorts of *atom*s, but in our work two common *atom*s in SWRL syntax are used in the reasoning phase of problem-solving:

$C(?x)$: If x is an instance of the class C or the value of its data property, then $C(?x)$ holds;

$P(?x, ?y)$: If x is related to y via property P, then $P(?x, ?y)$ holds. Here P is the property defined in the existing ontology, x and y can be variables, individuals or the data value. In SWRL syntax, a rule can be described in a form like this: $a_1 \wedge a_2 \wedge a_3 \wedge a_4 \wedge \ldots\ldots \wedge a_{i-} \ldots\ldots \wedge a_n \rightarrow b_1$. *Atoms* a_i and b_i can be either $C(?x)$ or $P(?x, ?y)$. There are also built-in functions in the SWRL syntax that are capable of describing the logical comparison relationship.

6.4 Rule sentences

We have written all rules for some typical activities of emergency management of meteorological disasters such as safety planning, integrated risk assessment, prediction of disaster chain, and emergency response. As the length limit, we only demonstrate some key rule sentences that are used in reasoning for analysis of secondary disasters of an original event (here, only the first-order secondary disasters are concerned) and evacuation decision explained above (Table 3).

6.5 Results and discussion

We demonstrate the analysis results of two interrelated tasks: disaster chain (affected objects) and evaluation of an evacuation strategy. The process is as follows. The first step is building the hierarchy and relationships of the concepts relevant to the meteorological disaster system. In this step, we have chosen the Protégé tool (http://protege.stanford.edu/) to build different ontologies to represent this knowledge, according to the Figs. 3, 4, 5 and Table 3.

According to the model proposed in the previous sections, three different levels of ontologies: geospatial foundation ontology, domain ontology, and application ontology are designed. Among them, application ontology is to represent disaster-specific knowledge which is depicted with some classes derived from the corresponding classes in the domain ontology. More specifically, the BFO ontology file with OWL format is imported into the protégé tool, which is taken as top-level ontology. Two classes: *continuant* and *occurrent* from BFO are taken as geospatial foundation ontology. They depict spatial and temporal concepts from which the descending ontology (including domain ontology, task ontology and application ontology) is inherited. HBB is divided into three classes firstly: *human*, *object*, and *system* as explained in Fig. 1. The subclasses for each of them are elaborated as shown in Fig. 11. EM knowledge is represented by three classes: *operations*, *logistics*, and *command*, plus their corresponding properties and subclasses, and relationships with the classes of other ontologies. For example, the *Evacuation* has the properties: *hasAreaFrom*, *hasAreaTo*. It is a subclass of *Task* that is a subclass of *Operations*. The parameters of the two properties are related to the ontology *Geographic_item*. DME ontology is realized according to a proposed disaster classification standard (the National Standard of Incident Classification, proposed by the State Council of China). *Process* ontology is realized consulting the W3C proposal. Furthermore, those relationships as shown in Fig. 5 are defined through Object Property in protégé tool. In order to specify the space–time relationships, e.g., the space–time impact analysis of typhoon, a *Typhoon_impact* process is subclassed from the *Process_model* class. The *Execute* method of *Typhoon_impact* inherited from the parent class is realized to obtain the dynamic (time-dependent) impact area in terms of the track and real-time attributes (e.g., pressure, wind, etc.) of the typhoon. Again, for example, the *Typhoon_evacuation* class is concretized with *Evacuation* class in the DM ontology to specify some different behaviors and properties for the typhoon. These properties and class hierarchy relationships and ontology relationships will drive the reasoning process according to the rule sentences realized by SWRL, which is related to task-specific decision-making in emergency management of meteorological disasters. We built and stored the rules in the Protégé tool. As seen in Table 3, Rules 1, 2, and 3 are compiled to reason the resultant disaster chain, and Rules 4, 5 are compiled to evaluate the evacuation tactics.

Based on the realized ontology representation and the formalized rule description of decision task, the problem-solving process can be executed as follows: parsing the OWL ontology file, realizing operations, and presenting reasoning results. Java API package Apache Jena (http://jena.apache.org/index.html) is used to parse the ontology file. Ontology individuals are automatically created through calling Jena API. Test data such as risk

Table 3 Rule sentences for analysis of disaster chain

Rule ID	Rule sentence	Comment
Rule 1	*(Typhoon(?e1)∧Gale(?e2))∨(Typhoon(?e1)∧Rainstorm(?e2))∨(Rainstorm(?e1)∧Geo-risk_area(?t)∧Landslide(?e2))∨…* *→ TriggerNext(e1, e2)*	*Delineate the cascading effect of disasters*
Rule 2	*TriggerNext(e1, e2)∧Geo-risk_area(?t)∧Contain(?area, ?t)* *∧Polygon(?area)∧hasImpactArea(?e1, ?area)* *→ hasSecondaryDisaster(?e1, ?e2)*	*Judge what secondary disasters will actually happen*
Rule 3	*Feature(?data1)∧Feature(?data2)∧SRS(?srs1)∧SRS(?srs2)∧hasSRS(?data1, ?srs1)∧hasSRS(?data2, ?srs2)∧sameAs (?srs1, ?srs2)∧differentFrom (?data1, ?data2)* *→ hasTheSameSRS (?data1, ?data2)*	*Verify whether two data have the same spatial reference system or not*
Rule 4	*Task(?task)∧Subject(?subject)∧hasSubject(?task, ?subject)∧Object(?obj)∧hasObject(?task, ?obj)∧hasEvac(?task, ?evacuation)∧hasAreaFrom(?evacuation, ?area-from)∧hasAreaTo(?evacuation, ?area-to)∧* *hasImpactArea(?e, ?area)∧* *Safety(?evacuation, ?area)* *→ Evacuation(?evacuation)*	*Articulate the involved predicates of the evacuation question*
Rule 5	*Route(?route) ∧ Track(?track) ∧ Disjoint(?route, ?track)* *→ Safety(?route, ?track)*	*Express a condition in which both the evacuation route and the typhoon track are disjoint (Here route and track are space–time objects and Disjoint means a space–time topological relationship)*

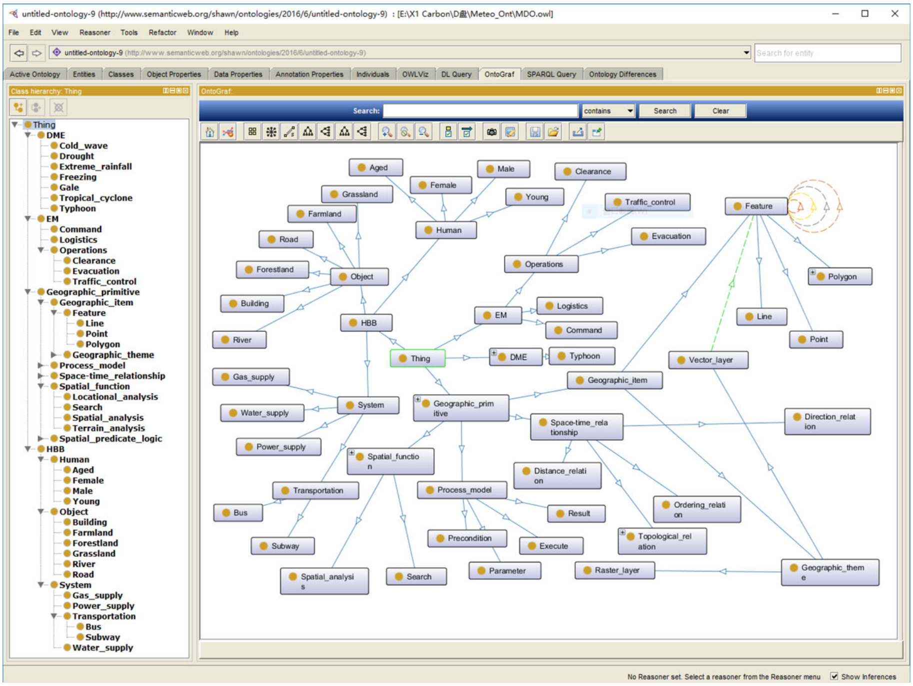

Fig. 11 Screenshot of the constructed class hierarchy of the proposed meteorological disaster ontology with protégé editor. These ontology classes have been depicted in details afore

resources, affected area, typhoon path and intensity are saved with geospatial database. Test program reads data from the geospatial database and instantiates ontology individuals according to the ontology classes. ArcGIS Server is used to provide support for geospatial services such as geo-data services and geo-processing services, which can easily publish geospatial data into standard geo-data services such as WMS (Web Map Service) and WFS (Web Feature Service). And it can also create web service compatible geo-processing services. Several used operations such as buffer, overlap, zonal statistics, disjoint are also realized with ArcGIS Server. For the geo-processing service calls, the REST protocol and JSON format is used for input and output parameters. We walk through the process step by step manually. The reasoning results are organized and demonstrated in Fig. 12.

We took typhoon Dujuan (landing at 8:50 am, Sept. 29, 2015, in Xiuyu District, Putian City, Fujian Province, China) as a disaster scene for the risk analysis and response. Before the typhoon landed, China Meteorological Administration predicted the most likely path and influence of the typhoon in the next 24 h through a prediction model of typhoon paths. According to the forecast results, a track probability map of the typhoon path as shown in Fig. 12 was obtained. We present this typhoon track probability map as a subclass of Feature of the Geographical_item. In particular, it is a trajectory object consisting of a sequence of points having position, time, intensity, influence radius, etc., attributes. The Buffer attribute of the subclass is used to calculate the range of influence of the typhoon at a particular time, i.e., the circular area based on the radius of the wind.

The rules of the disaster chain presented in Table 1 are formalized through the DME class and the HBB class (and their subclasses), and the object properties between them.

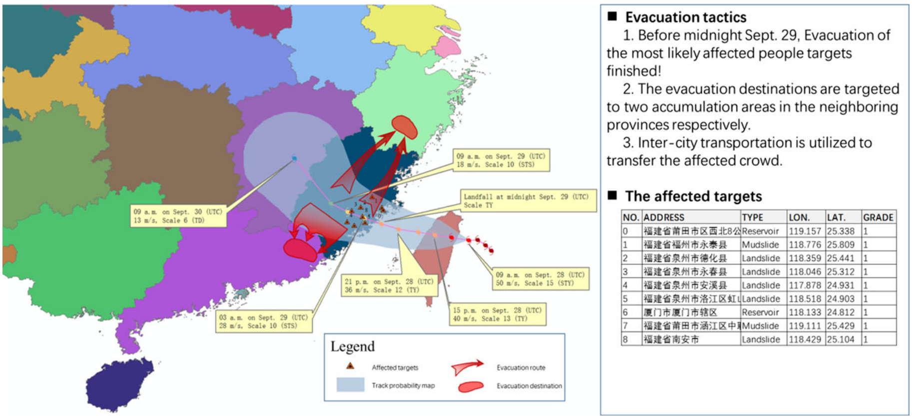

Fig. 12 Illustration of the analysis of secondary disasters of a typhoon (Dujuan) and the evacuation decision based on the proposed geo-ontology based meteorological disaster ontology

Rule 1 indicates that if events *e1* and *e2*, and hazard-bearing body *t* are the instances of corresponding entities (They are subclasses of DME and HBB classes) in Table 1, then the disaster chain relationship is established (e.g., a typhoon disaster can cause gales and rainstorms, and further cause landslides in the geo-hazard risk areas as shown in Table 1).

We implement the disaster chain rules in the way of ontology relationships, and it was combined with the predicted typhoon affected area to see what secondary disasters will actually happen under the rainstorm brought by the typhoon. This rule is specified as Rule 2. According to Rule 1 and Rule 2, disaster *e1* may actually cause secondary disaster *e2* if disaster *e1* and *e2* meet the triggering conditions and when *e1* occurs there is a relevant HBB (triggering element) within its influence area.

We loaded the HBB information within the typhoon affected area from the prebuilt risk source database, and instantiated the corresponding HBB (such as the geo-hazard risk area, the road, the house, the farm) subclasses according to the type and location of them. In the process of instantiation, the spatial attributes of these HBBs are stored through instances of the point class. The basic information of the typhoon disaster Dujuan and the HBBs is inserted into the reasoning rules, and the risk analysis results (The secondary disasters possibly caused by the typhoon Dujuan, and their type, spatial position, etc.) were output. Similarly, based on Rule 4 and Rule 5 listed in Table 3, the evacuation measures can be reasoned (including the evacuation areas, the number of population, the evacuation time requirements, the evacuation destination requirements).

Figure 12 presents illustrative results of analysis of secondary disasters of a typhoon and evacuation decisions. As shown in Fig. 12, some potential affected targets are identified according to a reasoning process given in Fig. 10. An evacuation plan is evaluated according to rules 4, 5 given in Table 3. From the rules, a disjoint topological operation is used to judge whether the plan is safe or not. Based on these results, emergency staff can take corresponding measures to response the typhoon. Some countermeasures for mitigating and avoiding the risk can be carried out (e.g., consolidate the affected dam beforehand, and organize the affected mass to evacuate in time). Here, it is worth noting that the evacuation route and the typhoon track are space–time objects (polygons). So the *disjoint* is a space–time topological operator. After evaluated, the feasible evacuation plan is presented in the interactive interface.

7 Conclusions and future work

Emergency decisions play an important role in augmenting resilience before a meteorological disaster happens and reducing loss of life and property after a meteorological disaster happens. The development of artificial intelligence brings opportunities to provide a computer-aided problem-solving approach, which enables scientific countermeasures and rapid response for some activities (including routine and urgent) involved in the emergency management of meteorological disasters. With the aid of formalized domain knowledge, computers can retrieve and utilize them automatically. In addition, when faced with each of these activities, some heterogeneous systems and multiple agents have to share and exchange information among each another. Semantic integration is essential in order that they collaborate smoothly.

We have presented a preliminary exploration of the application of ontology in modeling a meteorological disaster system. In view of this system's inherent geographic characteristics, this paper has proposed a geo-ontology based approach. The geo-ontology extends ontology to a space–time context and then it can describe some concepts associated with the geospatial environment. Correspondingly, spatial relationships specifically appearing in a space–time context are considered in the geo-ontology. After investigating the meteorological disaster system, we analyzed concepts and relationships between components of a meteorological disaster system and gave the preliminary framework of the geo-ontology of the meteorological disaster system. As a result, the potential application of the proposed geo-ontology has been illustrated with an explanation of predictions of secondary disasters and evacuation decisions of a typhoon event. For general modeling, the ontology can provide semantic support for disaster-general and task-general decision-making in emergency management of meteorological disasters. More specifically, the ontology model can provide support for before-, during-, after-event emergency management activities such as risk assessment, resource preparedness, emergency response where the formed concepts and their relationships can be incorporated into reasoning sentences of these decision processes. This approach is significantly different from some classic disaster dependent methods. It is flexible and extensible for meteorological disasters. Compared to the classic expert system, the ontology model is augmented in expressivity and maintainability. It is easy to extend the hierarchy and relationships through a standardized language OWL. With the support of ontology API (e.g., Jena), we can integrate the knowledge into commonly used enterprise information system framework such as J2EE and.Net framework. Furthermore, semantic heterogeneity is also solved easily in view of power exchange ability of ontology in heterogeneous information including structure heterogeneity and semantic heterogeneity (Fan and Zlatanova 2011a, b). Thus, the proposed perspective provides an approach to semantic integration among human beings, between human beings and heterogeneous systems, and among heterogeneous systems. The multi-level ontological model provides a universal foundation for knowledge representation of emergency management of meteorological disasters.

In our future work, we intend to further improve and elaborate on the model. We look forward to using the model in various emergency management information systems, such as forecast and a pre-warning publishing platform of meteorological disasters. Moreover, a GIS-based automatic instantiation of ontology and integration of geographical analysis with reasoning will be deeply studied. We think it is quite necessary to fully exploit the standardized support of geo-data and geo-processing services that provide Web service interfaces. Besides, the core of the next work is to construct a decision support system capable of providing support for risk analysis and emergency response of emergency management of meteorological disasters based on the proposed ontology. An on-going project “National Incident Pre-warning Publishing System” in China is planning to use our research to support forecast of meteorological disasters such as prediction of secondary disasters, response measures proposal, etc. (http://www.weather.com.cn/zt/qxfwzt/2518418.shtml). This work will underlie semantic integration in these systems and will enable advanced emergency decisions.

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