Development of an ontology for the representation of firefighters' data requirements during building fire emergencies

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Abstract. Firefighters require accurate and timely information regarding a building and its environment to perform their duty safely and effectively during a fire emergency. However, due to the chaotic nature of building fires, firefighters often receive erroneous, conflicting, or delayed information that can affect the outcome of a hazard. In this paper, we propose a solution in the form of an ontology that defines building and environmental data needed by firefighters during a building fire emergency. The ontology can be a basis for developing intelligent tools and systems that collect building and environmental data from different data sources and provide comprehensive information to firefighters. It can also facilitate the data exchange process between the different personnel involved in emergency response. The ontology was developed by following the METHONTOLOGY method, and it was implemented using the web ontology language (OWL) in Protégé 5.5.0.

1. Introduction

Firefighters employ different strategies to safeguard occupants, reduce property damage, and protect themselves during building fires. They devise their strategy based on the best available information they have at any given time (OSHA, 2015). Hence, the availability and quality of information play a vital role in the outcome of an emergency. Additionally, Firefighters should be made aware of any hazards or obstacles they may come across outside or inside the affected building ahead of time. At the same time, overloading firefighters with excess information should be avoided since it can cause difficulty and confusion in data collection and interpretation (Li et al., 2014). The success of a firefighting strategy relies on providing the correct information and resources to the right people at the right time (Xu and Zlatanova, 2007).

However, acquiring and communicating accurate and timely information during a fire emergency is challenging. Occupational safety and health administration (OSHA, 2015) provides insight into the difficulties firefighters face when acquiring information at an incident site. According to OSHA (2015), firefighters have a frequently changing workplace which is an emergency site. Hence, it is unlikely for them to know their next workplace ahead of time. Furthermore, they operate in a mentally stressful environment while performing physically exhausting work that makes collecting, interpreting, and communicating information challenging. Moreover, they may need to operate during the night or in harsh weather conditions. These conditions, possibly combined with smoke from the fire, will reduce visibility. In such conditions, firefighters find it difficult to fully comprehend their environment and gather information from different signs that are used to communicate valuable information to the firefighters. The challenges are further magnified in complex building structures such as high-rise buildings and underground structures. Any delay caused by these issues might adversely affect the subsequent operation and the overall outcome of the incident. Mishaps such as poorly located fire hydrants, unclear fire alarm information, or inaccessible equipment can result in a delay during which the fire likely grows and becomes more hazardous to occupants' and firefighters' lives (OSHA, 2015).

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Solution for the problems discussed in the previous paragraph can be provided through intelligent tools and systems that collect required data about an affected building and its surrounding from different data sources and provide comprehensive information to firefighters. Such intelligent tools and systems can assist firefighters in conducting their tasks with the utmost safety and effectiveness (Balding, 2020). However, before designing such systems, we need to have a well-defined understanding of firefighters' data requirements. Ontologies can be used to establish such understanding. They enable us to develop machine-understandable definitions of different concepts in a given domain along with their relationships (Noy and McGuinness, 2001). Through ontologies, a shared understanding of a domain between people and systems can be established (Neto et al., 2021).

In this research paper, we present an ontology that models firefighters' data requirements. The ontology will represent the data firefighters require regarding different elements and features inside an affected building and its surrounding. The ontology can then be used to design systems that gather and integrate data from different data sources and provide comprehensive information to firefighters during building fires. Having a well-defined data requirement will also facilitate the data exchange process through various mediums between the different personnel involved in the emergency response (Jones et al., 2005). Understanding how first responders interact with building features can also assist building designers in designing structures that ensure firefighters' safety and provide necessary firefighting features (OSHA, 2015). The paper is structured as follows. Section 2 discusses existing ontologies related to building fire emergencies. Section 3 presents the method we employed to develop our ontology. Section 4 provides a detailed discussion of the firefighters' data requirement ontology we developed. Discussions and conclusions are provided in Sections 5 and 6, respectively.

2. Related Works

A study conducted by Li et al. (2014) has shown first responder's heavy reliance on peoples' experience, memory, and observation to gather information during fire emergencies. This reliance could bring negative consequences. A fire emergency site may become chaotic and confusing (Li et al., 2014). Under such circumstances, firefighters may find it hard to describe and communicate information accurately. Additionally, memory and experience differ from personnel to personnel. Moreover, as noted by Li et al. (2014), human memory might introduce human errors. Hence, Li et al. (2014) concluded that advanced tools and technologies that assist first responders in overcoming these limitations are necessary.

Adapting new tools and technologies for firefighting should be done with great care since firefighting is a potentially dangerous work (Balding, 2020). Therefore, having a well-defined understanding of firefighters' data requirements is essential to developing tools that ensure safety and effectiveness. Ontologies are one method of creating such understanding. Ontologies can establish a shared understanding of a domain between people and systems (Neto et al., 2021). We can define a set of data and their structure through ontologies, which can then be used by different problem-solving tools, applications, and systems (Noy and McGuinness, 2001).

Some ontologies we identified, such as the *DoRES* ontology (Burel et al., 2017), focused on the general representation of concepts related to wide-ranging crisis events. Other ontologies, such as *SEMA4A* ontology (Malizia et al., 2010), focused on communicating information to affected people during emergencies. In some ontologies, the focus was put on the emergency providers, including firefighters. However, in these ontologies, the emergency was not mainly focused on building fires. Fan and Zlatanova (2011) proposed an ontology that relates the different organizational units involved in emergency response with the data they require and the processes they take part in. spatial data was the focus of the ontology. Their proposal requires emergency responders, including fire brigades, to have their own ontology representing their geospatial data requirement. Saad et al. (2018) developed and implemented an ontology that established a common vocabulary between team members (human and robots) during urban search and rescue efforts. Gang Liu et al. (2011) developed an ontology that focused on community-based fire management. However, it only represents high-level concepts that are aimed towards the affected community rather than firefighters.

We have also identified a group of ontologies that are explicitly focused on emergency scenarios in buildings. Nuo et al. (2016) developed an ontology to generate a semantic graph of a building in times of fire emergency. The graph could then be used to obtain smoke spread information and escape routes. The ontology aimed to support rescuers and victims during the rescue process. Bitencourt et al. (2018) developed the *EmergencyFire* ontology to support standardization and sharing of building fire response protocols. The ontology models the procedures and actions taken during a fire emergency, and it provides terms that can help describe the emergency. It also captures knowledge regarding the involved organizations, the resources they can deploy, and the form of communication they use. However, a detailed representation of knowledge regarding building features and building surroundings that are important for firefighters' operation was absent since it was outside the scope of the ontology. Neto et al. (2021) presented an ontology to assist the information exchange between the different parties involved in the building evacuation process during fire emergencies. The authors believe the ontology helps to understand the building evacuation domain and contributes to the development of applications and systems that can be used during building evacuation. Finally, we have the *Smart Building Evacuation Ontology (SBEO)* that represents knowledge regarding buildings and their occupants that can be useful for the safe evacuation of people during emergencies (Khalid, 2021).

Overall, several ontologies with concepts that can apply to building fire have been developed in the past. Some provided only a general representation by focusing on top-level disaster management. Other ontologies explicitly made their focus on building fire emergencies. They described concepts related to hazard description, firefighters' actions, and building evacuation. However, the representation of data needed by firefighters regarding building features and the building's surroundings were minimal and outside the scope of those ontologies. Therefore, we propose an ontology that can fill the gap. The ontology we present in this paper provides a detailed and comprehensive representation of the data firefighters need about several features and components of an affected building and its surroundings. Based on this new ontology, intelligent systems and technologies that collect and provide essential data to firefighters can be developed. The ontology can also be used to facilitate the data exchange between the different personnel involved in building fire emergency response.

3. Research Approach

To develop our ontology, we followed the METHONTOLOGY method proposed by Fernandez et al. (1997). METHONTOLOGY is a well-structured method to develop ontologies from scratch. The consecutive phases of the method we followed are specification, conceptualization, and Implementation**.** While going through the three development phases, knowledge acquisition was also conducted simultaneously. METHONTOLOGY includes two additional phases, which are integration and evaluation. These phases are outside of the scope of this paper.

Knowledge Acquisition: The knowledge captured in the ontology was gathered from the analysis of scientific papers, a manual, and two international codes. The scientific papers include a study conducted by Li et al. (2014) with 29 first responder participants to evaluate firefighters' information need during a building fire emergency response; A study by Isikdag et al. (2008) where data requirements for a successful fire response management operation were identified; a workshop conducted by the National Institute of Standards and Technology (NIST) with 25 participants on the information need of first responders (Jones et al., 2005) and multiple studies regarding environmental factors that influence the spread of fire (Ghodrat et al., 2021)(Santarpia et al., 2019)(Heron et al., 2003). A manual published by OSHA that provided detailed information regarding firefighters' typical interaction with building features and fire protection systems during fires hazards was another source of knowledge (OSHA, 2015). The international building code (International Code Council (ICC), 2018a) and the international fire code (ICC, 2018b) were also used.

Specification: In this phase of the ontology development, a specification document is prepared. The document specified the purpose and scope of the ontology and its intended use (see Table 1). A glossary of terms that should be included in the ontology was also prepared. This action continued with the subsequent phases as more knowledge was acquired. The glossary of terms allowed tracking of terms that needed to be modelled and ensured they were not missed (Fernandez, Gómez-Pérez and Juristo, 1997). It was also helpful to filter out synonyms or irrelevant terms.

Table 1: Ontology specification document.

Requirements	Descriptions
Domain	Building fire emergency
Purpose	Building an ontology to represent data regarding several features and components of a building and its surroundings that firefighters need when responding to building fires.
Scope	The focus is on data about an affected building, its different components, and its surrounding.
Intended use	The ontology can be a basis for developing tools and systems that gather essential data about a building and its surroundings and provide the collected data to firefighters in an integrated form. It can also facilitate the data exchange process between different personnel involved in emergency response.
knowledge source	Scientific papers: (Li et al., 2014), (Isikdag, Underwood and Aouad, 2008), (Jones et al., 2005), (Ghodrat et al., 2021), (Santarpia et al., 2019), and (Heron et al., 2003). Manual: (OSHA, 2015). International codes: (ICC, 2018a), and (ICC, 2018b).

Conceptualization: In this phase of ontology development, knowledge is structured in a conceptual model (Fernandez, Gómez-Pérez and Juristo, 1997). First, the glossary of terms that were created in the specification phase was completed. These terms represented different concepts and their properties acquired through knowledge acquisition. A middle-out approach was used to identify the terms. As pointed out by Fernandez et al. (1997), this approach first identifies primary concepts that need to be represented in the ontology. Then, based on necessity, the concepts could be specialized or generalized. International codes were used whenever possible to generate concise and consistent terms that others can reuse in the future (see Table 1). The terms in the glossary were grouped into classes, properties, and instances. Finally, relationships were established between the terms.

Implementation: The next phase in the ontology development was implementing the ontology in a formal language. The web ontology language (OWL) was used to implement the ontology. OWL can represent the meaning of terms and the relationship between terms in a machine-interpretable language. Protégé 5.5.0, an open-source application, was used as the development environment to create the OWL file. The following section will describe the ontological model that we named *Firefighters' Data Requirement Ontology*.

4. Firefighters' Data Requirement Ontology

The firefighters' data Requirement ontology represents concepts regarding the data firefighters need about an affected building, the building's features, and the building's surroundings. In protégé, several classes were created to represent different concepts. OWL provides the *ObjectProperty* feature to represent the relationship between two classes and the *DatatypeProperty* feature to represent the relationship from a class to a data value (McGuinness and van Harmelen, 2004). We have used both features extensively in the ontology.

In this section, the ontology is described with the help of figures (Figure 1 – 3). In the first two figures, the following convention is used. The red box emphasizes a class, and the yellow boxes represent all other classes related to the class in the red box. Different lines are used to represent different relationships. Solid lines with a black 'is a' text indicate subclass relationship. Solid lines with a blue text indicate *ObjectProperty* relationship between classes, and broken lines with a green text indicate *DatatypeProperty* relationship from a class to a data value. Lastly, the deep purple blocks indicate instances of a class. Sometimes a thick black arrow is extended from a class to indicate the existence of more information that is not shown in the figure. And a yellow box with three dots is used to indicate the existence of more subclasses.

The ontology uses *IncidentSite* class to represent the site where the building with fire hazard is located. This class is shown in a red box in Figure 1. The class is related to *IncidentBuilding, SurroundingTerrain, SurroundingStructure,, FireCommandCenter* and *WeatherCondition* classes. The *IncidentBuilding* class represents the building where the fire hazard occurred. The classes *SurroundingTerrain* and *SurroundingStructure* represent the terrain and structures surrounding the incident building, respectively. A fire command center is a dedicated location where the status of fire protection systems, alarms, and other emergency systems can be monitored and controlled (ICC, 2018b). The *FireCommandCenter* class is related to the *ControlPanel* class, which represents the different control panels firefighters would want to locate and use to control several building systems and utilities. The *IncidentSite* class is also related to the *WeatherCondition* class, which represents weather-related information firefighters may want to know, such as wind speed, temperature, and precipitation. The *IncidentSite* class is also related to the *Address* class, which captures several types of addresses required during a building emergency.

The *SurroundingStructure* class represents all artificial and natural structures surrounding the incident building. The subclass of *SurroundingStructure* represents powerlines, pipelines, hazardous materials, and obstructions such as fences. Information about these environmental elements is essential because they could obstruct firefighting operations or even cause severe injuries to the firefighters (OSHA, 2015). Fire can spread from the incident building to its surrounding through vegetation. Hence, vegetation surrounding an incident building is represented using the *Vegetation* class. A fire lane is an access road designated for the passage of fire apparatus (ICC, 2018b). This class is also a subclass of the *Road* class. In addition to the fire lane, the *Road* class represents the road that leads to the incident site (*RoadToIncident*).

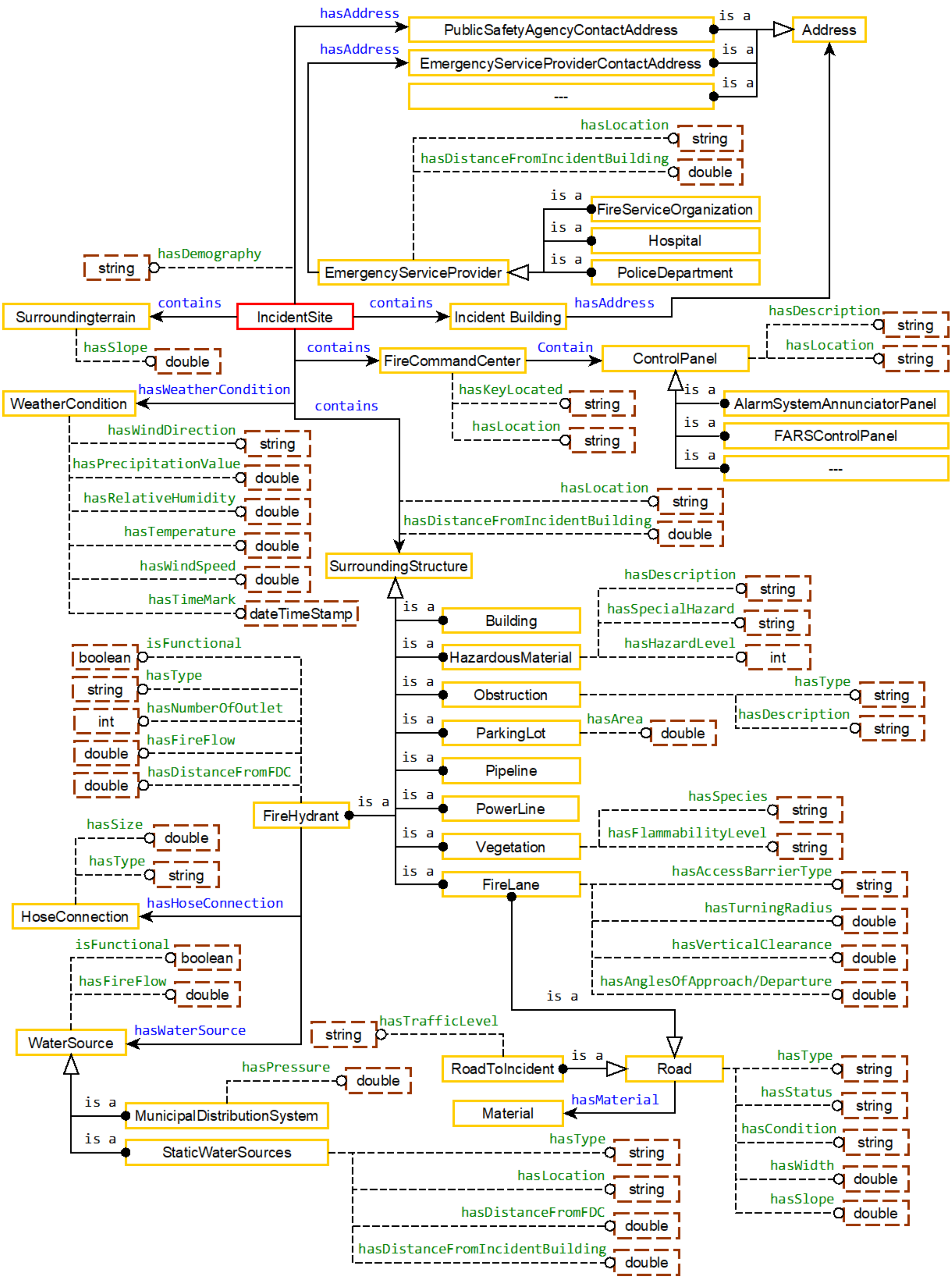


Figure 1: The *IncidentSite* class, its properties, and its relationship with other classes.

Fire hydrants are essential for most fire suppression operations since they provide access to a water supply system. We modelled information that should be provided to firefighters in advance to locate and connect to a fire hydrant rapidly. The *FireHydrant* class is related to two classes representing water sources and hose connections. An adequate water supply is essential for firefighting since most fire suppression systems and operations are water-based (OSHA, 2015). Accurate information about hose connection type and size should be provided to firefighters because incompatible hose connections can create severe problems during firefighting operations (OSHA, 2015). We also connected all other concepts in our ontology related to some form of hose connection to *HoseConnection* class.

Several information requirements about the incident building are modelled as properties of the *IncidentBuilding* class. A complete list of the requirements can be seen in Figure 2. The figure also shows the relationship between *IncidentBuilding* and other classes. These classes include the *BuildingOccupancy* class, which represents a building's occupancy based on the international building code (ICC, 2018a), the *BuildingComponent* class, which represents information about the different components of the building, and the *constructiontype* class with its five possible alternatives (ICC, 2018a).

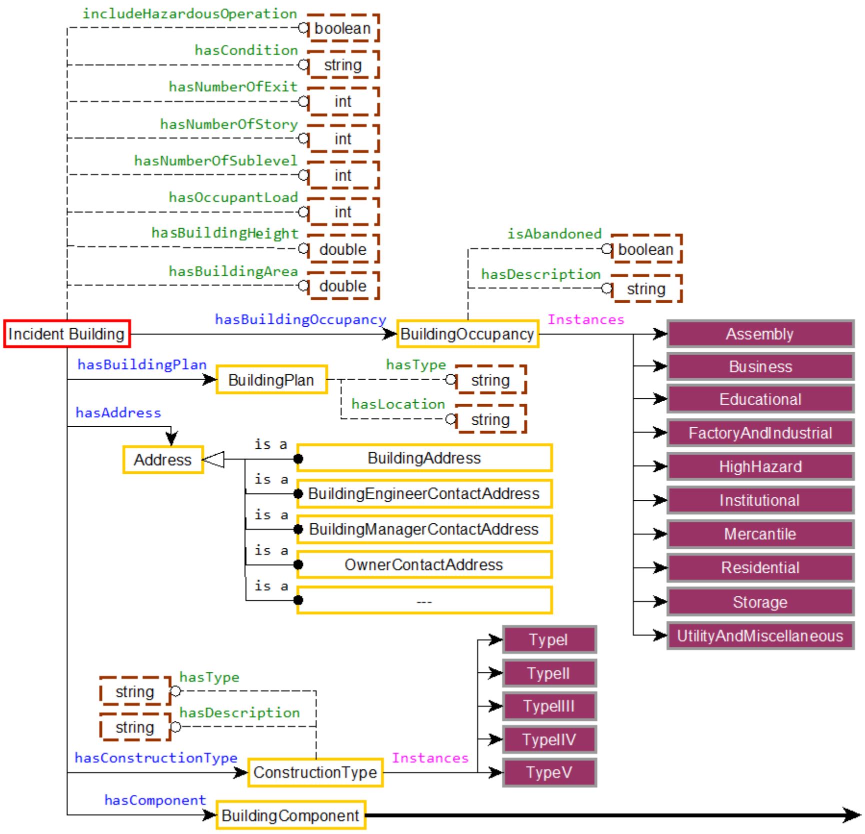
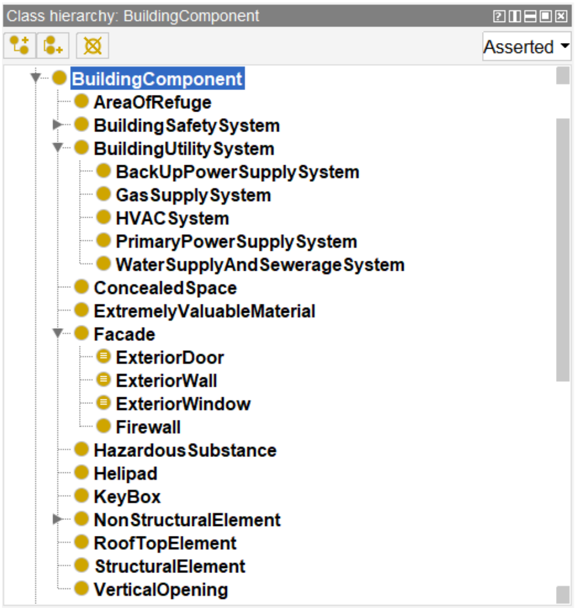


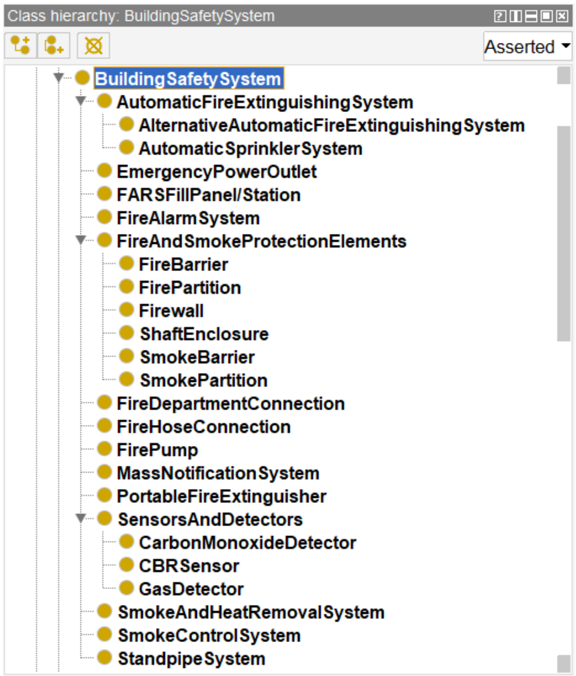
Figure 2: The *IncidentBuilding* class, its properties, and its relationship with other classes.

The *BuildingComponent* class has several subclasses representing different building elements and systems firefighters interact with during their operations (see Figure 3(A)). *BuildingSafetySystem* is the largest subclass of *BuildingComponent*. Several subclasses are defined for *BuildingSafetySystem* that capture information about the different fire safety systems found inside buildings. The complete list is shown in Figure 3(B). An automatic fire extinguishing system refers to sprinkler systems or another automatic fire extinguisher system installed in a building. In most buildings, a sprinkler system is separated into coverage zones

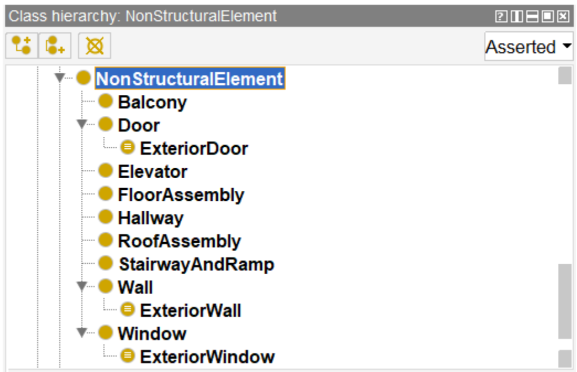
(OSHA, 2015). This information is valuable to firefighters because the fire can be located based on the active sprinkler zone. The Fire alarm system and other sensors and detectors are also divided into different zones. A standpipe system is a system of pipes in a building that provides water for manual firefighting and, in some cases, to sprinkler systems (OSHA, 2015). A fire department connection (FDC) is an inlet through which firefighters feed water into the standpipe system. In contrast, fire hose connections (FHC) are outlets of the standpipe system inside the building where firefighters can connect their fire hoses (OSHA, 2015).



(A)



(B)



(C)

Figure 3: Subclasses of (A) *BuildingComponent* class, (B) *BuildingSafetySystem* class, and (C) *NonStructuralElement* class.

In addition to safety systems, other building components firefighters may interact with are also captured in the ontology. This includes several building utilities that usually need to be shut down or at least controlled during fire emergencies (OSHA, 2015). Firefighters should also be informed of the location and type of any hazardous material they may come across in the building. Information regarding the façade of an incident building is essential for firefighters. It could be used to predict the spread of fire to the surrounding buildings or other structures. Some rooftop elements could be helpful in some firefighting operations, but they can also cause hazards. For instance, skylights can be used to ventilate a building, but they can also cause firefighters to fall through (OSHA, 2015).

Limited information about structural and nonstructural building elements is modelled in the ontology to not overload firefighters with excess information. OSHA (2015) describes how building elements could assist firefighters or sometimes cause a hazard. Doors, hallways, stairways, and in some cases, elevators are essential during egress. Meanwhile, floor and roof assemblies made with lightweight construction members could collapse and injure firefighters. The complete list of the nonstructural elements (subclasses of *NonStructuralElement*) is given in Figure 3(C).

5. Discussion and Future Activities

The last two phases of the METHONTOLOGY method are evaluation and documentation. The documentation phase refers to documenting each step of the development process, which we have done so far. According to Fernandez et al. (1997), evaluation covers verification and validation of the ontology. The authors defined *verification* as the technical process that confirms the correctness of an ontology. Then, they defined *validation* as the process that confirms whether an ontology corresponds to the concepts it was modelled to represent. We plan to conduct verification and validation in our future work. For that purpose, we plan to reach out to fire departments, firefighter associations, and other related organizations to find firefighters. Then, by consulting with the firefighters, we will validate the ontology. We plan to develop a prototype based on the ontology to facilitate the discussion with the firefighters. The prototype will use the concepts established in the ontology to provide a platform that provides essential information to firefighters.

After verifying and validating our ontology, we will explore possible data sources that can provide the data identified by our ontology. Examples of possible data sources include Building information models (BIM), city models and asset management systems. We will study these and other possible data sources and how they can provide necessary data that can assist firefighters in conducting their life-saving activity safely and successfully.

6. Conclusion

In this research work, we introduced the firefighters' data requirement ontology. The ontology models relevant data regarding a building, its features, and its surroundings that is essential for firefighters' operation during building fires. The ontology was built using the METHONTOLOGY method of ontology development. The ontology can be the basis for developing systems that collect building and environmental data from various data sources and provide comprehensive information to firefighters. Such systems can support firefighters during building fire emergencies to make decisions that safeguard occupants, protect the firefighters themselves and reduce property damage. The ontology can also facilitate the data exchange process between the different personnel involved in emergency response. Our future objective is to verify and validate the ontology through discussion with experts and to develop a prototype tool based on the ontology. Additionally, we will explore potential data sources that can meet firefighters' data requirements established in the ontology.

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