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Route Planning for Fire Rescue Operations in Long-Term Care Facilities Using Ontology and Building Information Models

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Abstract: As our society ages, more and more elderly or disabled people live in long-term care (LTC) facilities, which are vulnerable to fires and may result in heavy casualties. Because of the low mobility of LTC residents, firefighters often need to enter the facility to save people. In addition, due to LTC facility management needs, many doors or windows on the passages for a fire rescue operation may be blocked. Thus, firefighters have to employ forcible entry tools such as disk cutters for passing through, which may lengthen the rescue time if an incorrect route or tool is utilized. As new information technologies such as ontology and building information modeling (BIM) have matured, this research aims at proposing a BIM-based ontology model to help firefighters determine better rescue routes instead of using rules of thumb. Factors such as the path length, building components and materials encountered, and forcible entry tools carried are considered in the model. Real LTC fire investigation reports are used for the comparisons between the original routes and the ones generated by the proposed model, and seven experts joined the evaluation workshop to provide further insights. The experts agreed that using the proposed approach can lead to better fire rescue route planning. The proposed BIM-based ontology model could be extended to accommodate additional needs for hospital fire scenes, in the hopes of enhancing the efficiency and effectiveness of firefighters' rescue operations in such important facilities.

Keywords: building information modeling (BIM); shortest path; ontology; semantic web rule language (SWRL); search and rescue; firefighter; wayfinding; long-term care (LTC) facility

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1. Introduction

With the aging population and the declining birthrate, more and more elderly or disabled people live in long-term care (LTC) facilities [1–3]. An LTC facility, sometimes referred to as a special type of hospital or as a nursing home, can provide a variety of medical or non-medical services in order to meet the needs of the residents who cannot care for themselves for long periods of time [1]. Literature shows that although the incidences of hospital fires are low, such fire events often cause serious casualties, especially for LTC facilities [4–6]. For instance, according to the U.S. National Fire Prevention Association, the average number of casualties caused by hospital fires from 2011 to 2015 was about 160 people per year, and of these, 48% came from LTC facilities [5,6]. In Asia, the number of deaths resulting from fires in LTC facilities is even higher due to the low cost of medical expenses and a high population density [7]. According to the literature, LTC facilities are likely to have more bedridden or low mobility residents, yet the number of paramedics has not increased [7–11]. Hence, when arriving at such a fire scene, firefighters may need to help paramedics move or take care of the residents in addition to extinguishing fires. In fact, from a practical point of view, a typical fire scene requires several fire suppression processes, each involving water supply, fire attack, ventilation, search and rescue operations, etc. [4,5]. Water supply and ventilation in LTC facilities are usually not a problem because LTC facility owners need to regularly perform the inspection in order to meet related regulations [5,7]. However, due to the low mobility of LTC residents, fire rescue operations have been acknowledged as the most challenging work [7].

Therefore, this research aims at finding out the safest and shortest rescue route from a firefighter to each evacuee inside an LTC facility. In other words, this research discusses only the planning of rescue routes in a typical search and rescue (SAR) operation. Since SAR problems are very complicated, this research does not consider how to evacuate trapped persons, nor does it address the issue of searching or locating trapped persons. The most special is to take into account that the doors and windows on a rescue route may be closed, which often happens in the LTC facility due to various management needs, and firefighters need to use forcible entry tools to destroy. Unlike other hospital emergency response literature [12], this study does not discuss the dispatch of fire vehicles to the LTC facility and the transfer of LTC residents to other safe hospitals. This study assumes that firefighters have arrived outside the LTC facility and acquired the facility's BIM model with good quality. Here, firefighters may need to use forcible entry tools to demolish doors, doorframes, windows, or even walls for passing through [7]. They may be able to select the shortest route but carry wrong forcible entry tools, which may take longer to perform dismantling work and may result in obstructing the given passage [13–15]. Meanwhile, there may be another route with less passage and/or dismantling time, which firefighters do not perceive [8]. Thus, firefighters may go back and forth several times to obtain the adequate tools they need or lose direction and get trapped in the fire scene [11]. For inexperienced firefighters, they may even not possess the dismantling knowledge and misuse forcible entry tools [15].

All aforementioned circumstances might cause time delays and further damage. For example, on 24 February 2016, there was a record of firefighters trapped in the scene because of a reinforced door [13]. The wrong tool was utilized to demolish such metal components, which caused further hazards [13]. In addition, firefighters may need to move each LTC bedridden patient with his or her bed together and remove parts of the door frames, so as to pass rooms smoothly. This not only makes fire rescue operations more complex but may result in heavy casualties. For example, a recent fire killed 12 people in a notable LTC facility in Taiwan [8], and in 2018 at least 37 LTC residents died at a hospital fire in South Korea [10]. Therefore, improving the efficiency and effectiveness of LTC fire rescue operations has become an urgent issue in many countries in Asia, and perhaps the world.

As building information modeling (BIM) has gradually become a mainstream technology in the construction industry, a building's spatial data such as floor maps can be obtained from BIM software without difficulty [16]. Meanwhile, several ontology models have been developed to enhance BIM to provide further semantic-rich information, such as logical relationships among rooms or spaces for spatial reasoning [17–22]. Nevertheless, firefighters require not only the location information pertaining all evacuees but the knowledge regarding the applicability of each forcible entry tool against various building components and materials encountered. If such information or knowledge can be synthesized with BIM models, firefighters could better plan rescue routes and carry the correct tools for dismantling particular building components and materials. Furthermore, the proposed model could be utilized to express varied, dynamic situations inside a LTC facility, which can be regarded as the facility's real-time digital twin during a fire, in order to assist firefighters in making correct decisions. Such combinations have not been seen in the literature and can be described as the main contribution from this study.

Thus, the objectives of this research involve: (1) development of a BIM-based ontology model to help rescue route planning, considering the factors such as path length, building components and materials, and forcible entry tools; (2) collection and analysis of the data set on the time use of each tool against different building components and materials; and (3) examination of real fire investigation reports to gauge the differences between the original routes and the ones generated from the proposed approach, with the help from domain experts. In this research, an ontology model plays an important role in integrating BIM data and dismantling knowledge, because it has been successfully used to express sophisticated knowledge for highly dynamic environments, similar to the fire rescue operations described in this research [23–27]. The manuscript is structured as follows: Section 2 reviews related literature, while Section 3 describes the proposed ontology model and the data collection process regarding forcible entry tools usage. Section 4 summarizes the use of the ontology model for rescue route planning and the results of the evaluation workshop from experts, followed by research conclusions and suggestions.

2. Related Work

A BIM model can be defined as a digital representation of the physical and functional characteristics of a facility [16,28]. The major difference between BIM and traditional three-dimensional computer-aided design (3D CAD) is that a BIM model can contain building materials information as well as construction stage data while 3D CAD tools cannot [29]. Today, building owners have demanded that after the completion of a facility's construction work, contractors or engineering consultants prepare and finalize the corresponding as-built BIM model [30]. As such, the facility's maintenance work can be readily realized through BIM-enabled facility management systems [31]. Likewise, correct and complete information regarding building materials and spatial relationships can also be extracted from the BIM model, in order to satisfy various maintenance requirements [31]. In the disaster prevention and relief domain, several studies have applied BIM models and demonstrated their effectiveness. For example, BIM data can be used to facilitate the deployment of fire hoses and ladder trucks, and such layout information can be integrated into a geographic information system (GIS) for further planning [32]. In a circumstance where all the doors inside a building are not locked, existing literature has demonstrated how BIM data can be utilized to support the shortest rescue route planning [33,34]. Nevertheless, currently, no researchers have investigated fire rescue route planning based on the challenges associated with the use of forcible entry tools for locked doors or windows, which frequently occur in LTC fire scenes.

From a theoretical point of view, a building can be represented by BIM elements or components, such as floor levels, rooms, doors, windows, and walls [29,35]. These BIM elements can have spatial relationships with each other, such as a floor level BIM element can contain several room BIM elements, and a room BIM element can contain several BIM elements such as doors, windows and walls [29]. All such BIM elements can contain attributes describing building materials utilized [29]. For example, a door BIM element can contain the wood material attribute. When querying a BIM model, one can know both the material information and the spatial relationships. For instance, if a certain wall is selected in a BIM model, one can know its material information (e.g., concrete), all of its windows and doors information, and all adjacent rooms sharing this wall. As a matter of fact, much building-related information should be created and entered a BIM model in the building design or construction stages and be never altered hereafter [31]. This is because in the real world, a building's geometry, materials and spatial layouts are rarely modified in the facility maintenance stage, thus making the BIM model highly reusable [31].

In addition, existing literature shows that the ontology technology often plays an important role in computerizing work or tasks governed by domain-specific business rules, such as ontology models for disaster mitigation processes [25,34]. An ontology model is a formal, explicit specification of a shared conceptualization [23]. For example, in the medical field, such ontology models have been successfully utilized to define a common vocabulary for describing disease symptoms, drugs and side effects, even though these concepts are complex with dynamic relationships in nature [25]. Physicians can use such ontology models to reason whether a given medication is appropriate for a specific patient [25]. Likewise, the technique of semantic web rule language (SWRL) has been seamlessly utilized to define rules to enhance ontology models [27]. For instance, in one study the ontology with SWRL rules was applied to both static and dynamic properties of a geographic scenario prescribing spatial, temporal, semantic, interactive, and causal relationships among environmental elements [17]. In another study, the ontology with SWRL rules was utilized with segmented image objects and extracted features for classifying landslide cases [36]. In the disaster prevention and relief domain, the decision support system for earthquake damage assessments was integrated with the ontology model and SWRL rules for generating various drill scripts for first responders to exercise [37]. Indeed, for achieving successful fire rescue operations, firefighters may need to possess the knowledge regarding the spatial relationships among rooms in a building. Further, they may need to memorize the dismantling relationships between forcible entry tools and building components or materials [38]. Such the requirement of combining more than two fields of knowledge is difficult to be realized if the technique of ontology with SWRL rules is not utilized [39–42].

Lastly, there have been numerous studies on the algorithms for route planning for varied problem domains. Literature shows that a graph, which consists of nodes and edges or links, is the commonly used data structure for routes representation [43–48]. Among all prestigious route planning methods, Dijkstra's algorithm is often employed to find the shortest route from one node to every other node within a graph [45]. If both start and end nodes are unknown, Floyd-Warshall algorithm can be used to calculate the shortest distance between every pair of nodes in the graph, rather than only calculating from a single node [45]. Additionally, the weight of a link in a graph can be expressed either by its length, or by the resources consumed or generated for passing the link. In other words, the weight of a link can be positive or negative, meaning that a positive value indicating typical resource consumption while a negative value representing resource production for passing the link [45]. In such circumstances, Bellman-Ford algorithm can be used because it is capable of handling graphs in which some of the link weights are negative [39].

In most commercial or residential buildings, usually firefighters can designate one of the doors for entrance for the following fire rescue operations [4,49]. Suppose that the location of each evacuee could be identified and reported to incident commanders during fire rescue operations. Once confirming the location of an evacuee, incident commanders can send a group of firefighters for rescuing him or her, etc. Therefore, Dijkstra's algorithm might be preferred here, provided that all doors and windows in the building are unlocked. This is because it requires only one node as the beginning (which will be the location of firefighters) and will generate the corresponding shortest routes to all other nodes (which will be the location of each evacuee currently identified). Under such assumptions, an ontology model could be customized to capture dynamic, complex phenomena such as locked doors issues. BIM software could play as a data source to provide the ontology model with needed building information, such as building geometry, components and materials. Thus, the ontology model should serve as the reasoning engine to determine the weight or feasibility of each link, in order to better consider real circumstances. Such an approach has not been seen in the literature, and hence the man goal of this research, in hopes of planning better routes for fire rescue operations in LTC facilities.

Based on related literature, the approaches to emergency responses similar to LTC fire rescue operations are summarized in Table 1. Common to each approach is the use of information technology to expedite the decision-making process for emergency responses. As mentioned previously, this study only discusses the route planning that firefighters may encounter when entering an LTC facility for fire rescue. This research neither discusses how to dispatch fire vehicles nor investigates how to send evacuees to a safe place. It is evident that any disaster may require firefighters to enter a building for rescue. In addition to the traditional, shortest path length issue, this research dwells on not only building components and materials encountered but forcible entry tools carried, which can be regarded as the main academic contribution of this manuscript, as listed in the final row of Table 1.

Table 1. Examples of different approaches to emergency responses similar to LTC fire events.

Theme and Source	Approach Used and Implications
Transport planning [12]	Hospitals can be described as the best place to take care of the casualty, but disasters in recent years may also have an impact on hospital operations, reducing their capability for caring patients. Moving patients to other functioning hospitals, or so-called transport planning, is the focus of this issue. At present, there is little such literature, leaving hospital managers and policy makers with nothing to follow.
BIM and GIS [32]	Positions of fire hoses and ladder trucks during a fire event can be planned using BIM. Then, GIS can be used to integrate such layout data, derived from BIM, for subsequent planning activities.
BIM and FDS [33]	Fire safety management can be supported by using BIM and a fire dynamics simulator (FDS), a computational fluid dynamics (CFD) model of fire-driven fluid flow. The distance of an escape route can be examined by using BIM to determine its acceptance level.
BIM, graph and TSP [34]	In a circumstance where all the doors inside a building are not locked, this work demonstrates that how BIM can be utilized to support the shortest rescue route planning, using the graph theory and the algorithm from the travelling salesman problem (TSP). The shortest route can be accurately obtained.
Ontology and CBR [36]	For emergency decision makers to effectively respond to emergencies, an ontology-supported case-based reasoning (OS-CBR) method was proposed. Since CBR is a mature technology, OS-CBR can help decision making by reasoning past disaster events.
DSS, ontology and SWRL [37]	An ontology model with SWRL rules was designed to help generate various drill scripts. An earthquake damage assessments tool was integrated with the proposed decision support system (DSS). Next, similar tools for other types of disasters can be integrated by using the same approach.
Vulnerability assessment [41]	During an emergency, building systems may fail. A vulnerability assessment, along with formalized vulnerability representation schema based ontology, for such failures was proposed.
BIM and ontology [42]	A knowledge management method, along with a unified and formalized plan repository, was designed to facilitate the efficient administrative and operational use of emergency plans. This method, based on BIM and ontology, can be used to help realistic visualization of the plan knowledge for better understanding.
WSN [43,44]	Because of an inexpensive price, wireless sensor network (WSN) technology can be used in fire rescue. It can provide a wide range of surveillance and monitoring applications, as well as collect comprehensive data sets. Several research challenges in terms of new protocols as well as hardware and software support were also examined here. Hence, WSN can be regarded as a very powerful and suitable tool to be applied in fire rescue.
Ontology and agent [45]	Combining alterable accessibility and human awareness, an evacuation model was proposed. Spatial and event knowledge have been also considered in such agents of the model. In fact, the alterable accessibility was represented by a semantic model, which should be timely updated and useful in real-time settings.
BIM and network analysis [46]	Indoor rescue and evacuation is very critical for disaster response operations. BIM and network analysis were utilized here to find the shortest route for each scenario. In the future, risks based on building materials and traffic of pedestrians can be adapted for network edge costs to enable the lowest utility route finding.

Table 1. *Cont.*

Theme and Source	Approach Used and Implications
BIM, sensors and optimization [47]	Traditional fire rescue maps are 2D-based. If the locations of firefighters and trapped occupants can be obtained in real-time update settings via sensors, optimal path planning in a dynamic environment can be achieved.
Serious game [48]	During search and rescue operation, the data are often generated from heterogeneous data sources. The concept of a time varying data analysis was presented and findings from a fire emergency serious game were discussed.
Optimization [50–52]	The following problems have been examined using optimization-based methods: (1) A method to maximize the number of evacuees moved from disaster-affected zones to safe locations, using public transportation systems, was proposed in [50]; (2) A scenario tree-based stochastic optimization model to reduce risk and cost was proposed in order to determine when and how different types of patients must evacuate to receiving hospitals [51]; (3) A two-stage stochastic mixed integer programming framework for patient evacuation was proposed, considering staging areas, the number of emergency medical service vehicles, and the EMS vehicle routing assignments [52].
BIM, ontology and SWRL [This research]	Currently no researchers have investigated fire rescue route planning based on the challenges associated with use of forcible entry tools for locked doors or windows, which frequently occur in LTC fire scenes.

Finally, the SAR problem has been investigated extensively in the literature. SAR can be regarded as one of the most important and complex tasks of firefighters, including search, rescue, wayfinding, communication and coordination and assisting in the evacuation of trapped persons [53–56]. The goal of search work, not limited to fires or indoor buildings, is to find the locations of evacuees, or even the occurrence positions of disasters [57]. Generally, sensors or related information technologies are often used to assist in the positioning work. As for the rescue work, firefighters must be able to plan the route and perform wayfinding to the final positions [58–60]. Meanwhile, each firefighter on duty must be able to communicate and coordinate with each other all the time [58]. The rescue work can only be said to be successful if all the above-mentioned tasks are completed [58–60]. As for evacuation, it may be that a group of trapped people find their way out on their own, or firefighters help the evacuees leave the scene of the accident after arriving at the scene [61]. Overall, this study does not discuss the search, guidance, communication and coordination, and evacuation work of SAR. This study only discusses rescue route planning and possible related issues. As more and more smart buildings and sensors are installed, it seems that it may be no longer difficult to know the position of each evacuee. Likewise, in the LTC fire scenario referred to in this study, LTC residents are more likely to need firefighters to assist them in escaping the scene rather than walking out on their own.

3. Methodology

3.1. Overview

This section will describe the development process and main features of the BIM-based ontology model. In the ontology theory, a class is used to describe the abstract concept behind a group of similar objects or individuals in the real world, and each ontological class can have data properties (aka attributes) and object properties (aka association relationships). The former can represent a value that conforms to the current state of an object defined by the class, which usually changes over time. The latter can represent a present relationship of one object to link to another object. Although there are several approaches to the development of an ontology model, this research applied the most commonly used one [24], which includes: (1) identifying all relevant concepts in the domain as classes; (2) finding out all relationships between two classes as object properties; (3) defining relevant attributes of each class as data properties; and (4) elaborating on representative objects of each class as individuals for the ontology model, as shown in Figure 1.

In Section 3.2, the background for the development of this ontology model, key assumptions and sources of existing data will be described. By reviewing the literature and the consulting experts, the research team has defined 15 classes to encompass common LTC building components and materials, as well as typical fire rescue configurations that correspond to Step 1 of Figure 1. The research team believes that the 15 classes should be sufficient to express the research problem and provide decision-making suggestions. For example, building components such as columns are not included in the 15 classes because firefighters rarely dismantle these building components. Only the building components that firefighters can destroy are included in the ontology model.

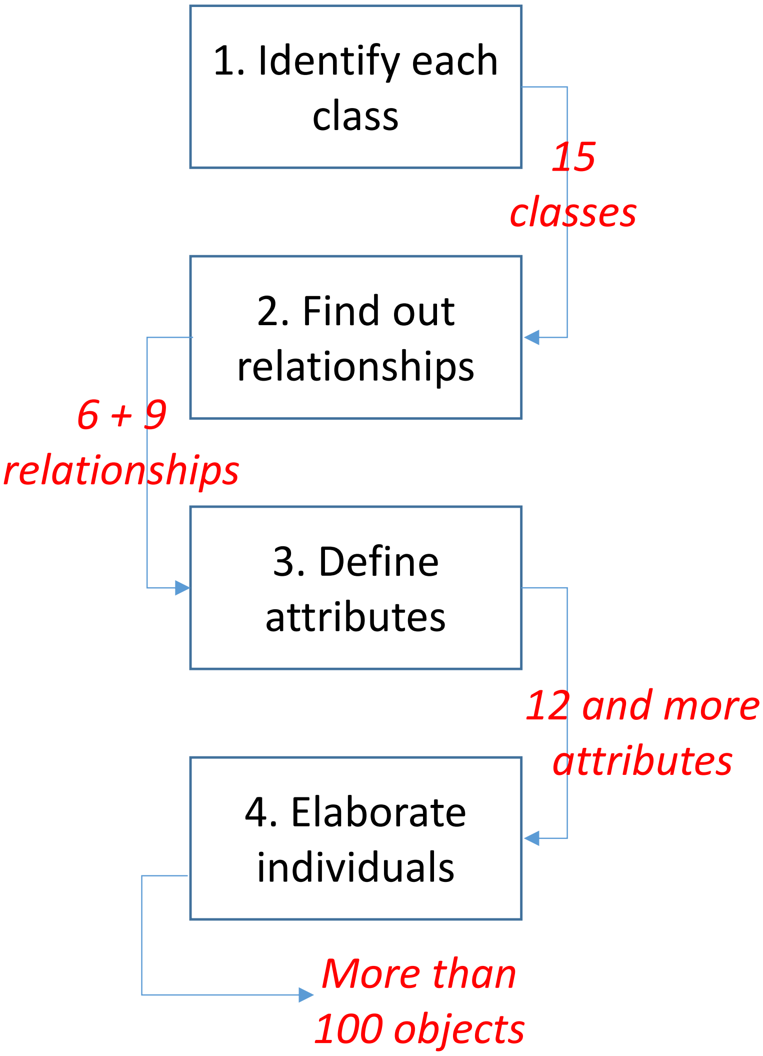


Figure 1. Overview of the ontology development process.

In Section 3.3, the detailed class definitions, attribute definitions and origins, relationship definitions and reasons will be described, which correspond to Steps 2 and 3 of Figure 1. Note that there are two types of relationships in an ontology model: inheritance relationships and association relationships. The former depicts a subclass connecting to a superclass, which stores the common part of the two classes. The latter depicts the meaningful linkage from one class to another class. As shown in Figures 1 and 2, there are six association relationships and nine inheritance relationships. As for the attributes, since one can add an attribute to a class dynamically in an ontology model, currently only 12 attributes have been defined. In the future, attributes pertaining to varied fire conditions can be added to the model, depending on new requirements.

In Section 3.4, the individuals representing the dismantling knowledge will be explained, including the pairing of building components and materials, and corresponding forcible entry tools. This formed knowledge base is convenient for subsequent inferences about rescue paths and weights, which correspond to Step 4 of Figure 1. Note that in the ontology theory, objects must be created dynamically. At the beginning of the ontology model, considering all building components, materials, and forcible entry tools, there are about 100 objects. As the building volume increases, the fire scene changes, and new tools are purchased, the number of such objects will also vary.

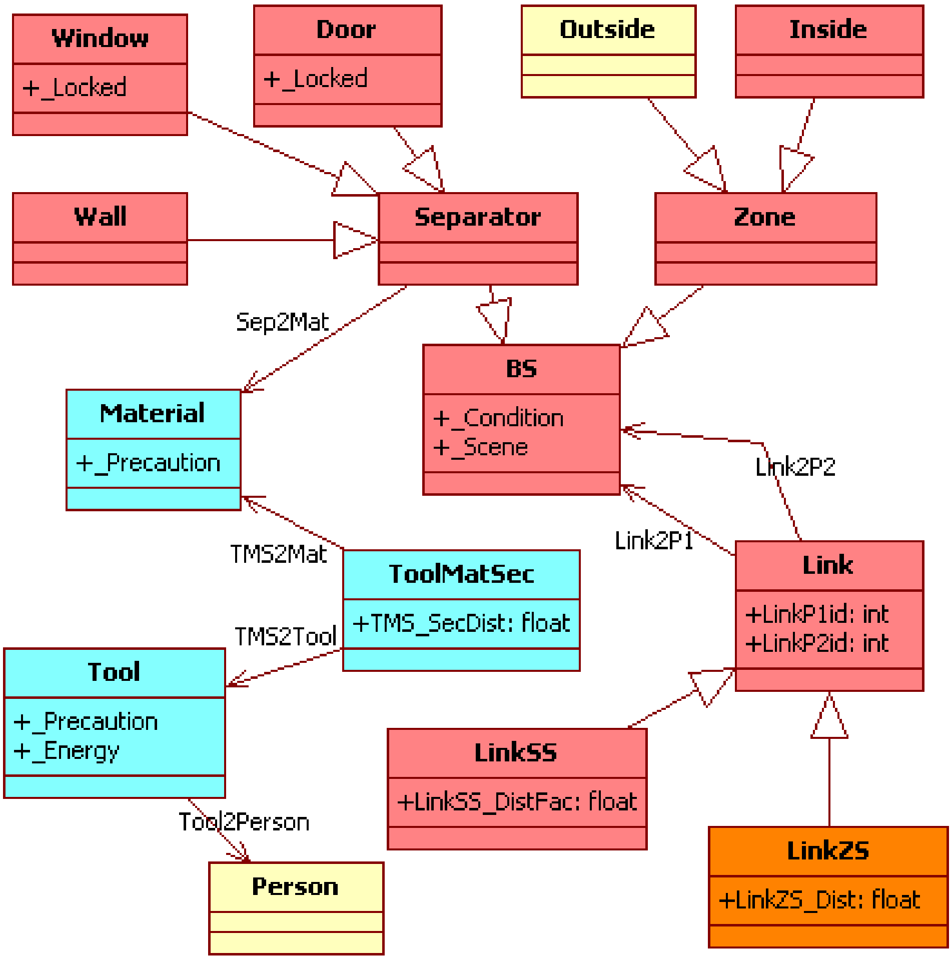


Figure 2. The proposed ontology model.

3.2. Development of BIM-Based Ontology Model

In short, a rescue route begins with the location of a specific entrance door in a LTC facility and ends with the location of an evacuee. If all such location information is available, and if all passages inside the facility are unobstructed, i.e., all doors in the facility are unlocked, planning the shortest rescue route for each evacuee is not difficult and has been examined extensively in the literature. However, in reality, when entering a LTC fire scene, firefighters usually need to use forcible entry tools to dismantle locked doors or windows for passing through. In fact, most firefighters prefer selecting such a rescue route that may be relatively long in length and may require use of forcible entry tools, but the overall time to reach the evacuee will be the shortest [62]. A route that conforms to such nature cannot be inferred directly from the BIM geometry data alone. The forcible entry tools carried by the firefighters, the building components and materials encountered, and the length of the route they travel must be jointly considered.

Hence, an ontology model based on a building's BIM data is proposed in this research, as shown in Figure 2, in order to realize the aforementioned goal. Today's BIM models can provide buildings' spatial geometry and materials data, but BIM software can neither be used to manage the data pertaining to forcible entry tools carried, nor can be extended to record the time required to destroy various building components and materials. Ontology, on the other hand, is flexible about managing varied types of data and, additionally, can infer newly derived information through pre-defined rules to assist in decision making.

Figure 2 shows the 15 classes for describing fire rescue-related concepts, and they can be grouped into three categories according to their information creation or access times. The first category, marked as blue in Figure 2, contains three classes and is designed to represent building materials or forcible entry tools. Objects in this category should be established before any fire rescue operations and are in fact independent of any building data. The second category, marked as red in Figure 2, contains nine classes and is designed to represent a specific building's BIM data. Objects in this category should be accessed by firefighters when they arrive on site. The third category, marked as yellow in Figure 2, contains two classes and is designed to represent the on-site staffing and rescue, such as the locations of firefighters and evacuees and the list of forcible entry tools currently carried during each fire rescue operation. It should be noted that there is a class marked as orange, which implies that it contains the definitions of both the red and yellow categories.

3.3. Definitions of Each Class, Attribute and Relationship

Material, **Tool**, and **ToolMatSec** are the ontological classes in the first category. Objects of **Material** refer to various materials commonly used in building components such as wood, concrete, and glass. Objects of **Tool** refer to forcible entry tools, which can have a data property pertaining to the source of energy used, such as manpower, oil, or electricity. In fact, a data property is denoted as text inside its class box, with a positive sign in front of the text to indicate its public status, as shown in Figure 2. Another data property regarding precautions of using tools to destruct materials can be added to **Material** and **Tool** respectively, in order to prompt firefighters. In addition, there is a many-to-many relationship between **Material** and **Tool**, which can be described by the two object properties, each denoted as an arrow in Figure 2. The TMS2Tool object property means that a certain tool can be used to destroy different types of materials. The TMS2Mat object property means that a certain type of materials can be demolished by different tools. Therefore, an individual of **ToolMatSec** is designed to represent the relationship between one tool and one type of materials. It contains the two aforementioned object properties and the TMS_SecDist data property, which initially is the time an ordinary firefighter spends in order to use the tool to destroy the materials. Then, this time value will be converted into a distance value, called the fabricated distance, which is the time multiplied by the fixed speed. This speed parameter is given externally, and the default value is 0.5 m per second, which is the walking speed of ordinary firefighters with a normal set of equipment. Hence, for example, if the firefighter spends 10 s using a particular tool to demolish a given building material, the final value of TMS_SecDist shall be 5 m. In fact, firefighters can experiment in advance to record the time spent for each tool destroying each material, in order to form the first category of the ontology model.

The second category is established based on a given building's BIM model and includes the following nine ontological classes: **BS**, **Door**, **Inside**, **Link**, **LinkSS**, **Separator**, **Wall**, **Window**, and **Zone**. A customized data transformation process, called the BIM-Ontology Converter, has been developed to extract needed geometry information from BIM data and create objects or values for these ontological classes. When firefighters arrive at a scene, they can apply this process to finalize all BIM-related preparation work. Basically, **Zone** is the generic concept of space, and one of its subclasses is **Inside**, which means every **Inside** individual represents a room in a given floor level of the building. It should be noted that in the ontology model the location of each evacuee must be one of the **Inside** individuals, meaning that evacuees are assumed to stay in certain room(s) inside the building.

The superclass of all BIM-related concepts is defined as **BS**, abbreviated from BIM Superclass, and it serves as the most generic building usage and common BIM interfaces here. Direct subclasses of **BS** are **Zone** and **Separator**. Basically, **Separator** represents the concept of real-world building components separating zones. If a building component, such as a wall, physically splits a large space into two rooms, it can be regarded as an individual **Separator**, which currently has three subclasses: **Door**, **Window**, and **Wall**. Individuals of **Door**, **Window**, and **Wall** represent real-world doors, windows, and walls respectively. A data property called Locked is added to **Door** or **Window** to enhance its versatility for reasoning the feasibility of a passage. The Sep2Mat object property, defined in **Separator**, can be used to link an individual of **Separator**'s subclass to the corresponding **Material** individual. Hence, when the BIM-Ontology Converter is performed, all relationships between building components and materials should be maintained consistently in the ontology model based on the information originally defined in the BIM model. It should also be noted that each time a firefighter enters a scene, they may face different conditions, therefore the individuals of **BS**'s subclasses may need to be changed accordingly. For instance, as the fire evolves, some building floor levels may have to be abandoned. Modifications of the individuals of **BS**'s subclasses to reflect the current conditions of the building may be needed. Indeed, more data properties such as fire scene conditions can be added to **BS** to cover the overall status data of a fire scene.

Further, a series of individuals of **Link**, which is the general concept of a link in a graph, can be used to represent a rescue route. The concept of a node in a graph is denoted by both the data property for representing the node's label, i.e., LinkP1id or LinkP2id, and the object property for representing the node itself as a specific building component, i.e., Link2P1 or Link2P2. Certainly, two nodes form a **Link** object. There are two **Link** subclasses: **LinkZS** and **LinkSS**. The former represents an ordinary link, without any obstruction, connecting two distinct **Separator** individuals inside a room, while the latter represents such a link passing a **Separator** individual to be dismantled. An individual of **LinkSS** usually contains the same **Separator** individual as the Link2P1 and Link2P2 object properties. This is because when a firefighter dismantles a real-world building component such as a door, typically s/he will encounter only one type of building material. Lastly, the LinkSS_DistFac data property represents the thickness adjustment factor and/or the additional time needed for passing through each real-world door, window, or wall and is defined inside an individual of **LinkSS**. It can be used to enlarge or diminish the time needed for firefighters to dismantle the building component with atypical thickness and to pass smoothly. For instance, it takes 55 s for an ordinary firefighter to employ a forcible entry tool of Saber Saw to dismantle a wall of Laminated Timber with the standard thickness of 5 cm. When the firefighter encounters the same type of wall with a thickness of 10 cm, the value of LinkSS_DistFac should be close to 2.0 for such additional time.

The third category of ontological classes includes **Person** and **Outside**. Certainly, each individual **Person** represents a firefighter. Because of the differences in task assignments and physical abilities, the forcible entry tools that a firefighter can carry are not the same. Such information can be represented in the Tool2Person object property and be entered into the ontology model after firefighters arrive at a scene. An individual **Outside** represents a possible entry point of a building.

Finally, an individual of **LinkZS** can be regarded as simply a link without any obstruction and be classified into the second and third categories. This is because such a link will be entered or accessed at multiple time points and, in fact, contains three variation cases: (1) Separator–Zone–Separator (aka the **SZS** case): this case implies that the link is inside a room and connects a **Separator** individual to another **Separator** individual through the **Inside** individual; (2) Outside——Separator (aka the **OS** case): this case implies that the link is in fact outside the building and connects an **Outside** individual to a **Separator** individual in the boundary room/zone; and (3) Separator–Evacuee (aka the **SE** case): this case implies that the link is inside a certain room containing evacuees and connects a **Separator** individual of the room/zone to the **Inside** individual representing the evacuee(s). Since the geometry and/or location information can be obtained from the BIM model, the value of the LinkZS_Dist data property can be calculated automatically and precisely. Additionally, all data in the **SZS** case should be created completely once the BIM model is available. Once the location information regarding firefighters and/or evacuees can be determined, the **OS** and **SE** cases should be finalized.

3.4. Collection of Time Use on Tools against Materials

Adequate use of forcible entry tools can be regarded as one of the most important tasks in fire rescue operations [62]. Today, many fire departments in Taiwan have contracted for the purchase of appropriate forcible entry tools, which need to meet related specifications and performance requirements, in order to be used in cases involving life trapping, hermetic room rescue, building structural fires, car or train accident rescue, earthquake disasters, etc. In Taoyuan City, where the research team is located, the fire department has selected the European standard of DIN EN 13204 (double-acting hydraulic rescue tools for fire and rescue service use—safety and performance requirements) and the ANSI/NFPA 1936 standard (performance requirements for powered rescue tools and components that are used by emergency services personnel to facilitate the extrication of victims from entrapment) for defining the specifications for such purchase contracts [38,62]. However, these specifications simply define whether materials of different shapes, diameters, thicknesses, or side lengths can be dismantled by each tool, thereby defining its performance level [63–68]. In other words, such specifications do not define any requirements regarding how long a given tool should be used to completely dismantle a certain type of building material [69–71]. Therefore, it is necessary to measure the time used in each pair of materials and tool in order to assist in rescue route planning.

In this study, ten firefighters, with an average of nine years of rescue experience, were invited to participate in the experiment for collecting the time used to destroy a given building component using a specific forcible entry tool. The experiment was designed to simulate LTC fire scenes as much as possible. Basically, 12 forcible entry tools, often utilized here in fire rescue operations, and 14 types of building materials were covered in the experiment, as listed in Table 2. The building components containing such materials were selected and dismantled for the experiment because they can be acquired almost free and are frequently utilized in construction projects in Taiwan. As indicated in Table 2, the materials can be classified into four categories: metal, wood, stone, and glass. The thickness of the mental materials and the wood materials is 1.5 cm and 2.5 cm, respectively. The diameter of the copper wire is 1.5 cm, and the diameter of the iron column is the same. The thickness of the concrete, stone, and tile is 2.5 cm, 2.5 cm, and 1.5 cm, respectively. There are three types of glass, all with a thickness of 0.8 cm. The value shown in each cell of Table 2 is the seconds averagely needed for one firefighter to use a given tool to dismantle a specific type of materials when he carries a full set of equipment.

Table 2. The experiment of dismantling time in seconds for different material vs. tool.

Material	**Metal**				**Wood**			**Stone**				**Glass**		
Tool	**Aluminum Frame**	**Copper Wire**	**Iron Column**	**Steel Panel**	**Artificial Timber**	**Laminated Timber**	**Green Timber**	**Concrete**	**Rock**	**Tile**	**Cement**	**Tempered Glass**	**Laminated Glass**	**Glass**
Saber Saw	76	71	95	123	43	55	81	218	292	187	229	13	10	3
Rock Cutter	168	117	192	N/A	171	198	213	29	49	23	31	29	23	3
Disk Cutter	38	36	43	76	39	45	78	94	214	75	89	20	12	3
Chain Saw	N/A	N/A	N/A	N/A	38	42	51	N/A	N/A	N/A	N/A	N/A	N/A	3
Hydraulic Spreader	18	15	24	N/A	43	62	80	52	N/A	71	57	14	11	3
Hydraulic Cutter	11	7	18	N/A	41	58	83	49	N/A	65	57	14	11	3
Hydraulic Pusher	19	N/A	42	N/A	153	219	226	51	198	39	47	55	49	3
Lifting Air Bag	N/A	N/A	N/A	N/A	N/A	N/A	N/A	92	212	159	128	N/A	N/A	3
Electricity proof	N/A	51	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	89	76	3
Manual Cutter	N/A	46	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	81	64	3
Crowbar	271	213	N/A	N/A	N/A	N/A	N/A	244	285	168	241	49	45	3
Fire Axe	259	157	N/A	N/A	224	245	319	210	242	145	202	56	51	3

Note: N/A means not applicable.

4. Model Demonstration and Discussions

4.1. Pseudo Codes for the Transformation and Reasoning Processes of the Ontology Model

The previous section explained the structure of the ontology model and the dismantling time of each forcible entry tool for various building materials. This section will describe the details about how to build and use the ontology model, such as how to extract and transform the required data from BIM software to the ontology model (see Algorithm 1) and what information firefighters need to enter when they are on the scene of a fire (see Algorithm 2). Finally, the ontological reasoning process for each fire rescue operation to get the shortest route will be described (see Algorithm 3), with the assistance from employing Dijkstra's algorithm. The following paragraphs describe each Algorithm in detail and highlight design considerations.

Algorithm 1 shows the steps to establish the initial version of the ontology model. As introduced previously, this model is in fact independent of any buildings and contains the information the fire department needs to possess and manage before any fire events. In other words, if firefighters would like to reuse the ontology model to plan rescue routes for other fire scenes of different buildings, they have to clean and restore the ontology model to the initial version.

Then, for a specific fire scene, firefighters need to obtain the BIM file describing the given building, preferably in the Revit file format. Algorithm 2 shows the steps to formally transform the BIM data into the ontology model. Once finished, the ontology model can be reused throughout the given fire scene.

In Algorithm 2, the first for loop (Line 1) deals with setting up objects or values for each room of a given floor level. Inside a room, the second for loop (Line 3) deals with setting up objects or values along each wall. Only three classes of individuals are allowed here: **Window**, **Door**, and **Wall**. For each BIM window or door element on a wall, the corresponding **Separator** individual will be created, meaning that it can be one of the candidate nodes for passing through the wall. However, if there is no BIM window or door element on a wall, the wall itself will become a **Separator** individual, meaning that firefighters may still break through this wall for passing, providing that adequate tools are carried and employed.

Algorithm 1 Set up general properties of **Tool**, **Material**, and **ToolMatSec** in the ontology model

```
Input:
    The information about all forcible entry tools available in the fire department and building
materials commonly used in the local area are needed.
Output:
    All individuals of Material, Tool and ToolMatSec in the ontology model will be completely
defined. The ontology model in such status can be called as in the initial version.
Steps:
    Create and set up all known Material individuals;
    Create and set up all known Tool individuals;
    For each pair of Material and Tool individuals according to Table 2:
    Create a ToolMatSec individual;
        Set up the TMS2Mat object property as the corresponding Material individual;
        Set up the TMS2Tool object property as the corresponding Tool individual;
        Set up the TMS_SecDist data property based on Table 2;
    End for
```

Algorithm 2 Set up BIM-related ontology classes

Input:

The BIM Revit file and the floor number of the fire scene are needed.

Output:

All individuals of **Inside**, **LinkSS**, **Door**, **Window** and **Wall** in the ontology model will be completely defined. The individuals of **LinkZS** in all the rooms, except the room(s) containing the evacuees, will be defined. In other words, the **SZS** case will be finalized after Algorithm 2 is performed.

Steps:

```
For each room in the given floor level:
    Create an Inside individual representing the room;
    For each wall of the room:
        bSep = False;
        For each BIM window or door element along the wall side:
            bSep = True;
            If there is no Separator individual associated with this BIM window or door element:
                Create a Window or Door individual whose parent class is Separator;
                Query the BIM element and set up the Sep2Mat object property as the Material individual;
            End if
        End for
        If bSep = False and there is no Separator individual associated with this BIM wall element:
            Create a Wall individual whose parent class is Separator;
            Query the BIM element and set up the Sep2Mat object property as the Material individual;
        End if
    End for
    For each Separator individual in the room:
        If there is no LinkSS individual containing this Separator individual:
            Set w as the current BIM wall element;
            Create a LinkSS individual;
            Assign the two Face.GeometryObject.IDs of w to LinkP1id and LinkP2id accordingly; // one wall side face, one Revit Face unique id
            Set up the LinkSS_DistFac data property based on its material thickness; // 1.0 means the ordinary thickness of its material
            Assign this Separator individual to both Link2P1 and Link2P2;
        End if
    End for
    For each pair of the Separator individuals within the room: // the individuals are defined as s1 and s2 respectively. Note that s1 is one of the Separator individuals in the BIM wall element (denoted as w1), and so for s2 and w2, where w1 is not equal to w2. Moreover, note that firstly, s1 or s2 should represent each unlocked BIM window or door element. Only if there is no such element along each wall side can s1 or s2 be used to represent each locked BIM window, door or even wall element along the wall side.
        Create a LinkZS individual; // for example, there will be six LinkZS individuals for a typical rectangular room, with each wall side containing just one Separator individual.
        Assign s1 and s2 to Link2P1 and Link2P2 accordingly;
        Get the two Face.IDs from s1 and s2 of the same room and assign them to LinkP1id and LinkP2id accordingly;
        Query BIM geometry and set up the LinkZS_Dist data property based on the actual length;
    End for
End for
```

Algorithm 3 Finalize the ontology to generate the shortest rescue route

```
Input:
  An entry position (denoted as b) and a list of each evacuee position for rescue (denoted as e) are needed. Moreover, information regarding forcible entry tools carried by the firefighter is needed.
Output:
  The shortest route to each evacuee will be generated, along with the tools suggestion.
Steps:
  1: Set up the Person individual as the firefighter and all forcible entry tools he or she will carry as each Tool2Person object property;
  2: For each evacuee e position: // for the SE case
  3:    Find the e's room, which is assumed to be i pertaining to the Inside class;
  4:    If i has not been visited before:
  5:      For each Separator individual in i:
  6:        Create a LinkZS individual and assign (this Separator individual, i) to Link2P1 and Link2P2 accordingly;
  7:        Assign the Face.ID of this wall side to LinkP1id;
  8:        If e does not have a unique integer:
  9:          Generate a unique integer for e;
  10:       Else
  11:         Assign e's integer to LinkP2id;
  12:       End if
  13:       Query BIM geometry and set up the LinkZS_Dist data property based on the actual length;
  14:     End for
  15:   Else
  16:     Record that this e's route is the same as the one defined in the i's previous visitation;
  17:   End if
  18: End for
  19:// Assume that the given entry point can have many nearby Separator individuals in different rooms, all within 15 m (the OS case).
  20: Create an Outside individual o for b and generate a unique integer for b;
  21: For each Separator individual pertaining to a BIM window or door element, all within the predefined radius distance of b:
  22:   Create a LinkZS individual and assign (o, this Separator individual) to Link2P1 and Link2P2 accordingly;
  23:   Assign b's integer to LinkP1id;
  24:   Assign the Face.ID of this Separator individual's outer wall side to LinkP2id;
  25:   Query BIM geometry and set up the LinkZS_Dist data property based on the actual length;
  26: End for
  27:// At this line, the final version of the ontology model can be obtained.
  28: SWRL-1: // this SWRL command can be used to help the firefighter know which forcible entry tool best for dismantling a given building component.
  29:       RDP:LinkSS(?z) ^ RDP:Link2P1(?z, ?p1) ^ RDP:Link2P2(?z, ?p2) ^
  30:       RDP:Sep2Mat(?p1, ?m1) ^ RDP:Sep2Mat(?p2, ?m2) ^
  31:       RDP:TMS2Mat(?tt1, ?m1) ^ RDP:TMS2Mat(?tt2, ?m2)
  32:       ^ RDP:TMS2Tool(?tt1, ?t1) ^ RDP:TMS2Tool(?tt2, ?t2)
  33:       . sqwrl:makeSet(?sMat, ?m1) ^ sqwrl:makeSet(?sMat, ?m2)
  34:       ^ sqwrl:groupBy(?sMat, ?z) . sqwrl:element(?eMat, ?sMat) ^
  35:       RDP:TMS2Mat(?eTMS, ?eMat) ^ RDP:TMS_SecDist(?eTMS, ?eDist) ^
  36:       RDP:TMS2Tool(?eTMS, ?eTool) -> sqwrl:select(?z, ?eMat, ?eDist, ?eTool)
  37:       ^ sqwrl:orderBy(?z, ?eDist)
  38: SWRL-2: // this SWRL command can be used help the firefighter know the inferred, fabricated distance for using the best tool dismantling a given building component
  39:       RDP:LinkSS(?z) ^ RDP:Link2P1(?z, ?p1) ^ RDP:LinkSS_DistFac(?z, ?fa) ^
  40:       RDP:Sep2Mat(?p1, ?m1) ^ RDP:TMS2Mat(?tt1, ?m1) ^
  41:       RDP:TMS2Tool(?tt1, ?t1) ^ RDP:TMS_SecDist(?tt1, ?d1) ^
  42:       RDP:Tool2Person(?t1, ?per1) ^ sameAs(?per1, RDP:iPerson)
  43:       . sqwrl:makeSet(?ss, ?d1) ^ sqwrl:groupBy(?ss, ?z) .
  44:       sqwrl:min(?min1, ?ss) ^ swrlb:multiply(?min2, ?min1, ?fa) ^
  45:       sqwrl:max(?maxx, ?ss) -> sqwrl:select(?z, ?min2, ?fa, ?min1, ?maxx)
  46:// End of SWRL work
  47: Formulate the distance matrix and run Dijkstra's algorithm from b to all end points and then run filtering to get the route to each rescue point e;
```

As indicated previously, a **LinkSS** individual contains two identical **Separator** individuals, which is designed to represent the BIM window, door, or wall element. When determining the best rescue route, each such **LinkSS** individual is used to represent a fabricated link with a prolonged distance, to denote the time needed to dismantle the building component and to pass smoothly. Certainly, there will be a set of distinct **LinkSS** individuals with different fabricated distances to indicate each passing path of the same wall using different forcible entry tools for the specified building components.

The final for loop (Line 26) deals with the **SZS** case for the **LinkZS** class. Basically, firefighters would like to select such a link that will pass through the room and contain both the **Separator** individuals all with the unlocked status. If there is no such link, firefighters will have to dismantle at least one locked door or window component. The worst case is the link containing both the **Separator** individuals representing two distinct walls, which implies that firefighters will spend much time demolishing the two wall components in order to reach the next room or zone.

After running Algorithm 2, firefighters will begin to enter the building for fire rescue operations. Algorithm 3 can help them obtain the shortest route(s) from their current position, i.e., outside the building, to the location of each evacuee inside the building. Firefighters need to reuse the ontology model after having run Algorithm 2, as well as to input the positions of the candidate entry point and the evacuees. In addition, they can enter the list of forcible entry tools they currently carry to the ontology model, to better reflect the current conditions of the fire scene. It should be also noted that since the process of shortest rescue route generation involves ontological inferences, Algorithm 3 contains two SWRL commands to facilitate the reasoning process.

In Algorithm 3, Line 1 deals with setting up the relationship between the firefighter and the forcible entry tools carried. In fact, each fire rescue operation may involve a different set of forcible entry tools and can contain several rescue routes to all the evacuees currently identified. Hence, in Line 2, this for loop deals with setting up the **SE** case for the **LinkZS** class, i.e., a link from the **Separator** individual on the wall to the position of the evacuee (denoted as e). Note that each BIM wall element should have at least one **Separator** individual. If such a **Separator** individual pertains to a BIM window or door element, undoubtedly it will be selected to form a **LinkZS** individual.

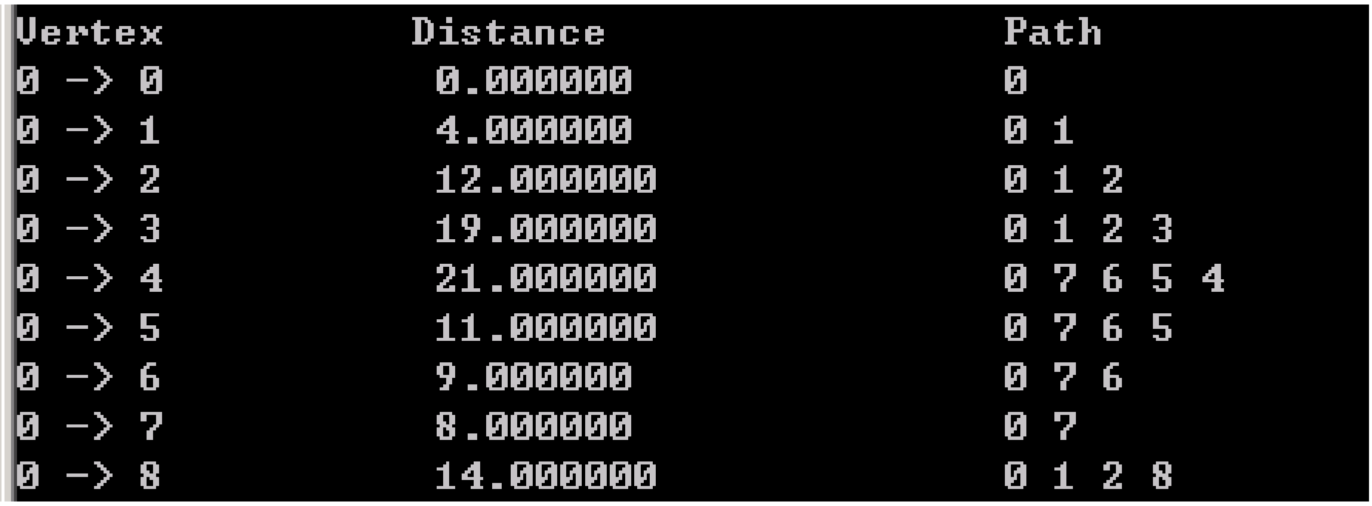
Lines 19–26 deal with setting up the **OS** case for the **LinkZS** class. Suppose that firefighters can tell the ontology model about their current position (denoted as b). Line 21 shows that the BIM software will be employed to find out all **Separator** individuals, which are located within a prescribed distance and pertain to BIM window or door elements. These individuals will be used to create the corresponding **LinkZS** individuals to form the candidate entry paths. In Line 27, the ontology model can be regarded as in the final version and is ready for the following reasoning work.

Lines 28–37 pertain to the first SWRL command and are designed to help the firefighter pick the best forcible entry tool for dismantling a specified building component. This SWRL output tuple consists of: (1) **LinkSS** individual; (2) **Material** individual; (3) the fabricated distance without considering thickness adjustment; (4) **Tool** individual. Here, because SWRL is good at reasoning about the relationship between objects, this command will generate multiple records representing the forcible entry tools all applicable to a given building component and sort out the results according to the prefabricated distances from short to long. The firefighter should always pick the first suggested tool unless the firefighter is unfamiliar with the tool or has other considerations.

Lines 38–45 pertain to the second SWRL command and are designed to list the inferred, fabricated distance for the best tool suggested for each building component requiring demolishment. This SWRL output tuple consists of: (1) **LinkSS** individual; (2) the final inferred, fabricated distance; (3) the thickness adjustment factor; (4) the fabricated distance without considering thickness adjustment. These inferred distances can then be used to form the graph that allows each fabricated link to have the correct distance, and finally, the shortest path from the firefighter to all evacuees can be determined.

After running the two SWRL commands, all **Link** individuals, whether pertaining to the **LinkZS** class with real length or pertaining to the **LinkSS** class with fabricated length, now have known distance values. Next, a distance matrix, often used in graph theory, can be formed using these distance values derived from SWRL, and N means the total number of nodes. In this matrix, the entries on the main diagonal line are all zero, i.e., $x_{ii} = 0$ for all $1 \leq i \leq N$, and the matrix is symmetric ($x_{ij} = x_{ji}$). Moreover, all the off-diagonal entries are positive ($x_{ij} > 0$ if $i \neq j$), i.e., a non-negative matrix. Further, if the two building components represented as the nodes in the graph are not connected, the corresponding cell value in the matrix is zero. This is because the first building component to which the corresponding column index belongs and the second building component to which the corresponding row index belongs should not be able to form a **Link** individual.

Once the distance matrix has been determined, Dijkstra's algorithm can be employed to find the shortest path between a given source node and every other node. The position of the firefighter can be regarded as the source node and should be placed in the first column/row index, while the position of each evacuee can be regarded as a target node placed in any other column/row index. Because Dijkstra's algorithm is very popular and commonly used in different domains, this research simply applied it to the problem domain and does not show the algorithm steps. Figure 3 shows a sample output with the path information based on Dijkstra's algorithm for the proposed ontology model.



```
Vertex          Distance                Path
0 -> 0           0.000000               0
0 -> 1           4.000000               0 1
0 -> 2           12.000000              0 1 2
0 -> 3           19.000000              0 1 2 3
0 -> 4           21.000000              0 7 6 5 4
0 -> 5           11.000000              0 7 6 5
0 -> 6           9.000000               0 7 6
0 -> 7           8.000000               0 7
0 -> 8           14.000000              0 1 2 8
```

Figure 3. A sample output showing the detailed path of each rescue route based on Dijkstra's algorithm.

4.2. Ontology Model Evaluation Results

To validate the usability of the proposed approach, a recent LTC fire investigation report was chosen as the input to the ontology model. In this three-story LTC facility, a fire broke out in the early hours of a morning in February 2019 and should have started in the laundry room on the second floor, as shown in the red dot in Figure 4. Arranged by the nursing staff, the evacuees were concentrated in the storage room (see Point S6 of Figure 4), which was far from the origin of the fire. The nearby stairwell was not used for many years and was full of debris, which was not conducive to the passage of firefighters. Hence, the field commander decided to take the stairs next to the entrance gate to the second floor (see Point S1 of Figure 4). According to the investigation report, the firefighters went to the evacuees' place (Point S6) after passing through the main corridor (see the red dotted line of Points S1, S2 and S3 in Figure 4). Since most of the left half of the second floor was the bedroom area and the right half was the public space, the LTC facility owner already set up a door to separate the two zones. This door was made of laminated timber and had a thickness of 5 cm (see Point S3 of Figure 4).

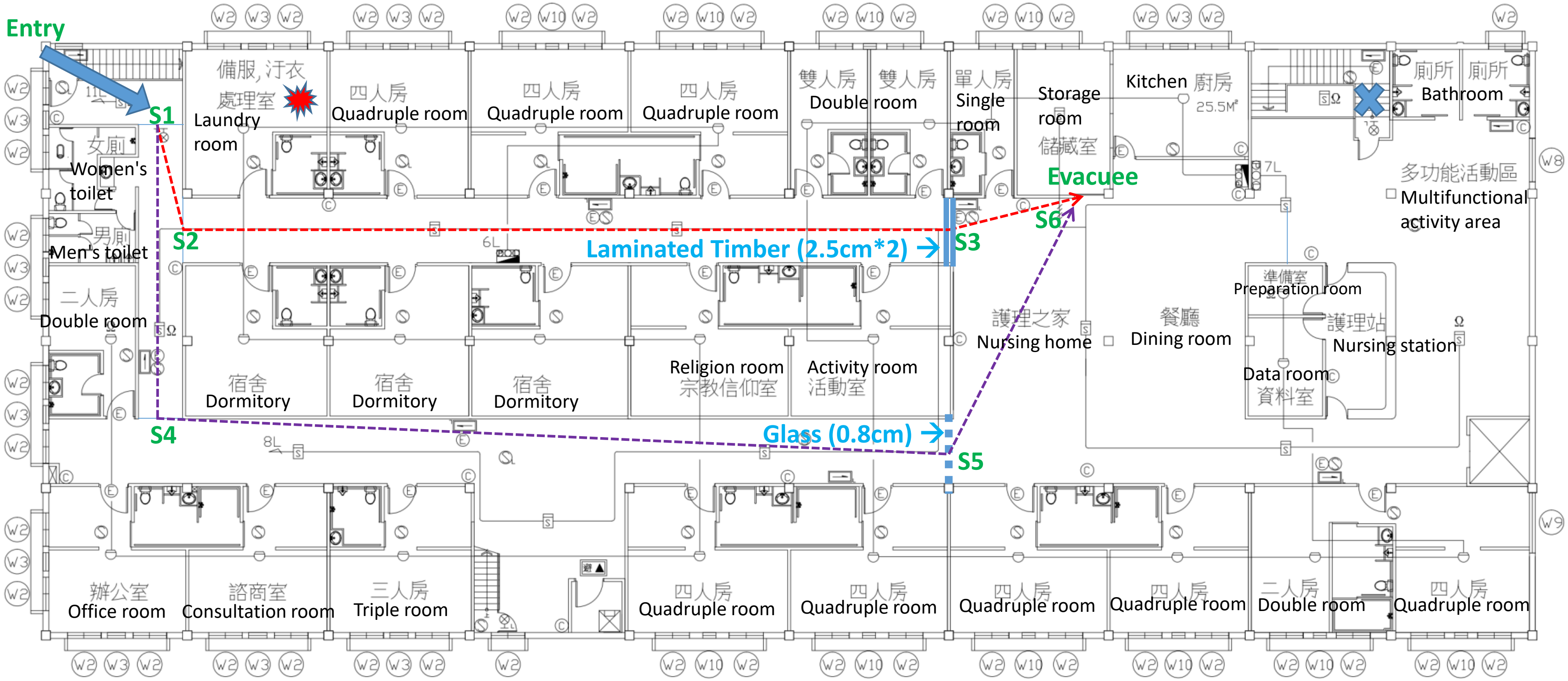


Figure 4. A recent LTC fire scene for model validation.

During the fire rescue operation, one firefighter used a disk cutter to dismantle this door for passing through, which took 90 s for complete demolishment. It should be noted that if the thickness of the door is only 2.5 cm, it would only take 45 s to destroy it with this tool, based on the measurement data listed in Table 2. According to the recorder on the firefighter's body, between 3:45:15 AM and 3:47:43 AM, the firefighter traveled from Points S1 to S2 to S3 to S6, with a total length of 29.4 m, and it took a total of 148 s (including the dismantling time). The average walking speed of the firefighter was 0.509 m per second.

The research team prepared the ontology model applicable to this fire scene and inputted relevant data. Using the proposed approach, the final ontology model suggested another rescue route, which is longer in length and requires breaking a glass door (see Point S5 of Figure 4). Basically, the new route indicates that a firefighter should go to the evacuees' place after passing through another corridor (see the purple dotted line of Points S1, S4 and S5 in Figure 4). The model output also includes the use of another forcible entry tool and expresses that the firefighter should use a crowbar to dismantle this glass door for passing through. The estimated time for such complete demolishment is just 3 s. Hence, the suggested fire rescue route is from Points S1 to S4 to S5 to S6, with a total length of 47.6 m, and it should take a total of 97 s (including the dismantling time). It should be also noted that the average walking speed of the firefighter was the same in both cases. Obviously, compared to the original route, the new route is shorter, requires less time to walk, and should be safer.

After the comparison, seven senior firefighters, with an average of 15 years of rescue experience, were invited to attend the evaluation workshop. Fundamental BIM and ontology concepts as well as the related literature and research results were introduced. The experts' further opinions on the use of the proposed approach as well as managerial insight were collected and are summarized as follows:

- There are four phases in a typical building structural fire: inception, growth, full development and decay. When firefighters arrive at a scene, if they identify the current situation is in the first or second phase, the length of a rescue route is often not a top priority. Almost all routes involve the use of forcible entry tools (hereinafter referred to as tools). Only by choosing the right tools can the overall time be shortest.
- Firefighters may not be familiar with building materials and it sometimes happens that they spend much time using the wrong tools for dismantling certain building components.
- At a fire scene, firefighters may need to search elsewhere to find a better rescue route. Although such a route is relatively long, the overall time could be shorter due to the use of correct tools.
- When the fire scene is a basement because the underground structure of a building is usually solid, airtight and not easy to ventilate, it is difficult for firefighters to judge the fire situation from the ground. Firefighters first need to enter the basement to assess the situation; hence, it is important to carry and use the right tools, so they can go down just once. In the past, there have been cases of smoldering caused by firefighters dismantling components for too long due to selecting the wrong tools. Such cases may also be due to the fact that firefighters want to carry light tools, which might lead to going back and forth several times until the right tools are utilized.
- Some tools are very effective in dismantling certain materials, which might make firefighters mistakenly believe that the tools are also effective in demolishing other similar types of materials. For example, a chain saw has a good destructive effect on wood materials and firefighters might misuse the tool to dismantle softer metals, such as aluminum. Because the blade of a chain saw is running at high speed, when it first touches the metal, it can smoothly cut a small gap on the surface. However, when it is broken down, the sharp chain often causes the chain to jam instantly due to insufficient damage to the metal, which is harmful to the operator.
- Some tools need to be assembled before use and the selection of tool parts is in fact dependent on the type of the material demolished. For instance, a disk cutter can

be regarded as one of the most frequently used tools by firefighters, and it has two cutting wheel options during assembling: resin or diamond. At present, the Taoyuan Fire Department only uses resin cutting wheels for assembling a disk cutter, even for dismantling concrete. However, in other fire departments in Taiwan, due to the use of different tool brands, some use diamond cutting wheels for dismantling clay bricks, which can have better damage effects.

- Before firefighters demolish a building component, they may need to be aware of the legal issue regarding the financial value of the component to be demolished. For the civil codes in most countries, the statement similar to the following may exist: a person acting to avoid an imminent danger menacing the life, body, liberty, or property of himself or of another is not liable to compensate for any injury arising from his/her action, provided the action is necessary for avoiding the danger and does not exceed the limit of the injury which would have been caused by the said danger. In other words, firefighters may need to compare the cost of the component to be demolished with the price of not performing the rescue operation. The experts believed that the price value could be directly obtained from BIM software, which definitively helps firefighters assess whether to run the rescue operation.
- Although this study is meant to help to start planning the best route when firefighters arrive at a fire scene, from the management perspective, the proposed approach should assist in the decision regarding dispatching which types of fire vehicles. The reason is that, in fact, each type of fire vehicle often has specific disaster relief tasks and functions and the tools that can be carried by one fire vehicle are limited. When the public reports a fire, if firefighters can access the facility's BIM data, they should be able to know which tools they should carry once the rescue route and building materials information are available. In the local governments of the United States and Japan, due to the similar fire organization to Taiwan, local firefighters also need 2D building maps for disaster relief work. Some fire departments have new information technologies to assist in disaster decision making. For example, firefighters in San Francisco can use mobile apps to check the water sources near the facility [72]. However, it is slightly insufficient for disaster relief assistance in buildings.

5. Conclusions

This research proposes a BIM-based ontology model for fire rescue operations in LTC facilities. When firefighters arrive at a fire scene, through the proposed SWRL-based algorithms and codes, the final ontology model can help firefighters find the shortest rescue route to each evacuee identified. The model output includes what forcible entry tools should be used by firefighters whenever they encounter a door, window or wall that needs to be destroyed. This is because the mobility of LTC residents is poor, and many doors and windows of an LTC facility are often closed due to management requirements.

Although BIM models have building geometry and materials information, it is not easy to add non-building attributes to such models for other management purposes. The BIM software itself does not have reasoning functionality either. Therefore, this study integrates BIM and ontology technology. The proposed ontology model can fully express many dynamic relationships such as the characteristics of a firefighter, forcible entry tools currently carried, building components and materials encountered and rescue routes. The model output has been verified through the experts' evaluation workshop, in order to show the correctness and practicability of the proposed approach.

Due to the poor visibility of many fire scenes, future research needs to enable firefighters to perceive a given building's spatial layout in advance. For example, once the current location of a firefighter is known, the future version of the proposed approach shall display what building elements he or she is facing and what forcible entry tools are recommended to use if needed. In addition, when some forcible entry tool is in use if the tool encounters certain building materials, the results of forcible use will be harmful and have been reported in the literature. If the future version of the proposed approach can more actively remind this kind of knowledge, it is bound to avoid such secondary disaster events and shall improve the overall efficiency and effectiveness of fire rescue operations.

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