Comparison Between Current Methods of Indoor Network Analysis for Emergency Response Through BIM/CAD-GIS Integration

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Abstract

The main mission of the fire service is protecting life, assets, and natural resources from fire and other hazardous incidents. Geographic Information System (GIS) is supposed to ideally decrease the required time for dispatching first responders to the incident site, while it has some deficiencies in showing and analyzing indoor space and routing. Building Information Modeling (BIM) is a data-rich, potential source for finding the most efficient routes within a building. Researchers have developed the methods, algorithms, and platforms to make indoor navigation analysis easy and understandable for occupants. They have worked on different alternatives of indoor network analysis through a process of applying the different methods to a study model, but it has not been defined which method is more appropriate to first responders' responsibilities. This paper reports on indoor networks analysis for first responders considering the importance of route finding in emergencies. We analyzed the similarities and differences of each method and algorithm, created an indoor network through ESRI's Campus Viewer Tool and conducted interviews with a fire marshal and his team. Participants reviewed eight models, including the indoor network analysis model created by the researchers. Findings revealed the indoor network analyses most compatible with the 3D model, easy to read, and understood by first responders.

Keywords

Computer-Aided drawing (CAD) • Building information modeling (BIM) • Geographic information system (GIS)
Indoor network analysis • First responders • Emergency

75.1 Introduction

The mission of the fire service is to protect life, assets, and natural resources from fire and other hazardous incidents. According to the National Fire Protection Association (NFPA) Research, Data, and Analytics Division, in 2016 U.S. fire departments responded to 1,342,000 fire incidents [1]. Statistics from 2016 include 475,500 structure fire incidents, which led to 2950 deaths, 12,775 injuries, and approximately $7.9 billion lost in the property. These statistics prove that structure fires must be taken more into consideration due to the critical and desperate nature of consequences from this type of fire incident. Every second is valuable and any delay in response to a fire can make a difference between saving a life, injury, and even death. It is important that both building occupants and firefighters be secured from injury when a fire incident happens.

For over 40 years the U.S. Fire Administration (USFA) has monitored firefighter fatalities resulting from reported fire incidents. In 2016 a total of 159 firefighters lost their lives in their attempt to extinguish structure fires, the majority of which was a result of the firefighter losing orientation and navigating errors inside the structure during the fire [2]. Search and rescue in unfamiliar buildings is a vital part of firefighters' responsibilities that can lead to a subsequent hazard. Providing

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firefighters with precise building information is a potential solution for mitigating the hazard of getting lost inside the building [3].

Tashakkori et al. [4] emphasize that it is vital for first responders to be aware of the incident environmental situation in a building. They believe that if first responders are prepared with information about interior spaces, number of building occupants in each space, and other critical information about the facility in advance, their capabilities would increase dramatically [4]. Results from a study by Boguslawski et al. [5] revealed the importance of precise evaluation of an incident and how inappropriate decisions can extend the response time. The study concluded it is essential that when arriving at an incident the first responders have actual and reliable information about: (1) the building's interior, (2) surrounding neighborhoods and facilities, and (3) quickest routes to the incident location inside the building [5].

Holmberg et al. [6] reported the importance of an integrated plan to provide emergency responders with building information so they have a comprehensive understanding of the indoor and outdoor environment. Additionally, first responders should have information about the building's interactions with adjacent facilities to decrease the potential for wandering during the response to the incident location. The study recommended remote access to building information would improve the first responder's knowledge about the building and thereby enhance safety and minimize injuries and damages [6]. Unfortunately, most of the required facility emergency information is not provided to firefighters until reaching the scene, which threatens the lives of firefighters and makes their decision making a complex process [4].

Geographic Information System (GIS) is an outdoor environment analysis tool with the potential to supplement the decision-making process at an incident site and even assist with decisions during dispatch to the site. A study by Chen et al. [7] discovered the recommended approach for emergency response is one that analyzes and provides first responders with optimal routes for navigation both outside and inside the building.

Although the capabilities of GIS has advanced in recent years further development to improve on the display and analysis of the indoor environment for the purpose of emergency response navigation during a fire. The negative effect of insufficient knowledge about a building's indoor environment impedes firefighters' capabilities and jeopardizes their safety [8].

While GIS technology has proven capabilities for the outdoor environment, a data rich building information modeling (BIM) is a potential source for finding the most efficient interior routes in the future [9]. The two modeling domains of BIM and GIS are broadly utilized for design and construction modeling, but not so much for use in emergencies.

Vanclooster and De Maeyer [10] suggested that a suitable indoor routing needs a well-defined indoor network, semantic information, and linkage between indoor and outdoor network which may be achieved by the integration of BIM and GIS. The implications of developing an integrated model in which BIM and GIS technology combined with a solution for reliable indoor navigation is important [11, 12].

Indoor network analysis as a part of BIM-GIS integration has gained momentum in recent years with researchers [4, 12–17]. Although new methods, algorithms, and platforms have been developed to make indoor navigation analysis easy and understandable for first responders and building occupants, it is unclear which method best meets the needs of first responders. The study reported in this paper seeks to add some clarity to the topic through its literature review and qualitative analysis of interview responses. The literature review is organized into three sections: (1) Application of BIM in network analysis and navigation, (2) Application of GIS in network analysis and navigation, and (3) Application of BIM-GIS integration in network analysis and navigation. Findings from interviews follow the literature review.

75.2 Literature Review

75.2.1 Application of BIM in Network Analysis and Navigation

BIM remains a dynamic topic in the design and construction fields of research with an increased focus on the integration of information. As result expectations are that BIM will continue to enhance the integration process and interoperability of technologies across disciplines. Industry Foundation Classes (IFC) is a file format developed by the International Alliance of Interoperability (IAI, also known as buildingSMART) for the purpose of interoperability between the many different software platforms potentially accessed for building information during the facility lifecycle [18]. The IFC format provides for the exchange of data rich three-dimensional facility representation that can be accessed by first responders before arrival and entry to an emergency incident. Expectations are this integrated information would enhance their capability and improve their safety in the building at the time of incident [4, 19].

Although BIM can provide a basic model in emergencies there is a need for first responders to have a real-time indoor model to automatically generate navigable indoor networks [5, 20]. In a recent study Li et al. [3] completed interactive interviews with the Los Angeles Fire Department (LAFD) first responders and found the first responders have a low access to BIM, however they anticipate access would increase in the very near future. The opportunities BIM provides first responders offers a possible solution to a gap reported by Ruppel, Abolghasemzadeh, and Stubbe [21] where the development of a BIM based environment with an evacuation route for endangered people and real representation of the building posed challenges for emergency management.

In another study by Xu et al. [22] multiple problems were discovered with current methods for indoor navigation. The first problem is the two-dimensional format of indoor navigation instead of a three-dimensional form of building geometry with vertical networks. (To be concise in this paper, the two-dimensional representation of building as a floor plan is summarized to 2D plans and a three-dimensional form of the building is summarized to 3D models). The other problem is lacking the building semantic information which needs further development. One possible solution to the problems facing indoor navigation is a Variable Density Network (VDN) in which automated egress paths are constructed [5]. VDN is utilized to determine an indoor routing including an entire 3D model with topology attributes which represent the connection between spatial elements. In comparison between VDN and other navigation approaches, researchers claim VDN is more accurate in the way finding.

In 2010 Ruppel et al. [21] developed a method for first responders to find the quickest route in a complex building. The Their study concluded that generating a BIM for the indoor network is a time-consuming task with an intricate data structure not necessary for the purpose of emergency response [21]. A similar conclusion was reported by Wu and Zhang [12] who found that while all semantic and geometric information supports interoperability, however data redundancy should be reduced in the BIM model with data transformation specific to the goals for first responders. Another study on this topic by Tashakkori et al. [4] emphasized the simplicity of methods used to present building information due to the limited time first responders have after dispatching until arrival the scene to get information from the model. Therefore, the information included in the building model must be chosen with enough knowledge and care [4].

Xu et al. [22] used BIM as the 3D model for mapping inside the building and focused on indoor routing around known obstacles such as furniture in a multistory structure. With a new methodology Vandecasteele et al. [8] proposed an outline based on semantic information and computer technology to develop navigation and route finding under fire emergency hazards. Their method was novel because of semantic relationship between BIM and the objects captured by visual and thermal imaging cameras [8].

75.2.2 Application of GIS in Network Analysis and Navigation

GIS provides many tools and data related to the exterior properties of a facility. Taking advantages of some tools and extensions, like network analysis, firefighters could arrive at the incident location well prepared. The need to model the indoor environment for routing has led researchers to use a variety of technologies, such as laser scanning and CAD data to build the 3D model of the facility, however many are not helpful for firefighters due to the lack of semantic information like material types, doors, and windows properties. In 2016 Jamali, Abdul Rahman, and Boguslawski presented indoor modeling with Dual Half Edge (DHE) data structure and integrated it with the outdoor network from Open Street Map (OSM). They gained 3D data and modeled the building through Trimble M3, which is a surveying tool that does not include a BIM model of the building [23]. To generate a 3D model of the building, Tsiliakou and Dimopoulou [24] used CityEngine for the exterior of the building and ArcScene for indoor elements, both tools are commercially available through Esri. Although BIM was not used to create the building model, the study referenced BIM as a technology with features to represent the indoor environment both semantically and geometrically [24].

75.2.3 Application of BIM/CAD-GIS Integration in Network Analysis and Navigation

Zverovich et al. [14] proposed a new approach to find the safest indoor route that considers a hazardous event like fire with some epicenters are happening. Their concern was finding the shortest route considering proximity to hazard and they could find the safest route which is a trade-off between length and closeness to hazard. Their new algorithms were based on algorithms introduced by Boguslawski et al. [5] and they used an integrated BIM-GIS model as an underlying 3D model of the building [5, 14]. The other research conducted by Tashakkori et al. [4] presented a new method for indoor way finding. They developed their method in three parts: (1) indoor building information, (2) semantic information of building, and (3) outdoor emergency information and connecting outdoor to indoor information [4].

Teo and Cho [17] proposed a multi-purpose geometric network model (MGNM) based on BIM and made a link between indoor and outdoor routes. They converted IFC to MGNM and then created the topological relationship of MGNM to GIS Geodatabase [17]. Early researchers such as Isikdag et al. [18] investigated the approach of transferring BIMs into the geospatial environment and focused on fire emergency response. Li and He [15] tried to link BIM model and 3D GIS system and developed the 3D building with a route-oriented semantic model. They built a topological relationship through the medial axial transformation algorithm and created an indoor network with the Dijkstra's algorithm [15].

Furthermore, IndoorGML as a new approach to indoor navigation is an "Open Geospatial Consortium (OGC) standard for representation and exchange of indoor navigation models (geometry and network). It provides a framework to represent indoor spaces and their topology (connectivity), which are needed for the components of navigation networks. It is seen as a complementary standard to CityGML and IFC" [25]. Alattas et al. [26] concluded that the IndoorGML goal is to represent the principles of indoor navigation through a comprehensive framework to depict 3D models for the indoor network.

Xu et al. [16] developed two navigation methods. In the first method, they created routes inside a building by its 2D floor plans and limited semantic information and linked with GIS technology. For creating an indoor network, they utilized Triangulated Irregular Network (TIN). As the second method, they imported BIM model into ArcGIS™ through the Data Interoperability Extension in ArcGIS™. This means that using Data Interoperability Extension, they could translate IFC to a file geodatabase which is required for routing in ArcGIS™ [16]. Another recent study by Wu and Zhang [12] presented BIM-GIS integration for indoor geo-visual analytics. They used BIM just for visualization and did not consider semantic information in the integration process [12]. As a recent navigation tool, ESRI's Campus Viewer Tool is a set of tools for converting indoor CAD to GIS and creating a 3D network [27].

Tashakkori et al. [4] concluded that the current approaches in BIM-GIS integration for indoor navigation suffer from "(1) they emphasize the architectural elements, (2) they are designed for visualization purposes only, (3) the lack of necessary emergency information required about the incident and its area" [4]. However, this research does not consider what information can help first responders to meet their goals to save lives and properties using BIM-GIS technology and it will be for the future research.

The following sections further investigate the usefulness of these methods and approaches previously tested by researchers in an attempt to find which one could best assist first responders. The result of the comparison is summarized in Table 75.1.

75.3 Methodology

In this study, we conducted a literature review on BIM/CAD-GIS integration for indoor network analysis and compared and categorized the scholars' approaches towards indoor navigation. A building was then modeled through the recently-published Esri tool (Campus Viewer Tool) for indoor navigation and a focus group meeting with a fire marshal was conducted. The 2D plans and 3D models of buildings, the results of eight research papers mentioned in Table 75.1, were given to first responders. We wanted them to compare the 2D plans and 3D models to find the level of readability and understandability of each method. The workflow for creating an indoor network through Esri Campus Viewer Tool is presented in the next section.

75.4 Workflow

This section details the work tasks performed in this study. As shown in Fig. 75.1, we first generated a 3D indoor and building model using ArcGIS Pro from CAD files and building footprints, respectively. In this research we used Esri's Campus Viewer Tool, which is incorporated into the latest update for ArcGIS Pro 10.4 and supports the workflow of producing indoor geodatabase datasets from CAD drawings. Moreover, our input CAD conformed to the American Institute of Architects (AIA) specifications for the indoor environment.

With this tool, a user can find people or places in a 3D model and operate the program in a web browser. A search widget can help to find personal or office numbers and generate 3D routes between any two locations in the scene. The tool supports the use of route restrictions for elevators or stairs and reports a summary of total travel time and distance. We imported the building model, which includes various spaces such as offices, conference rooms, corridors, and interior walls, from CAD to GIS.

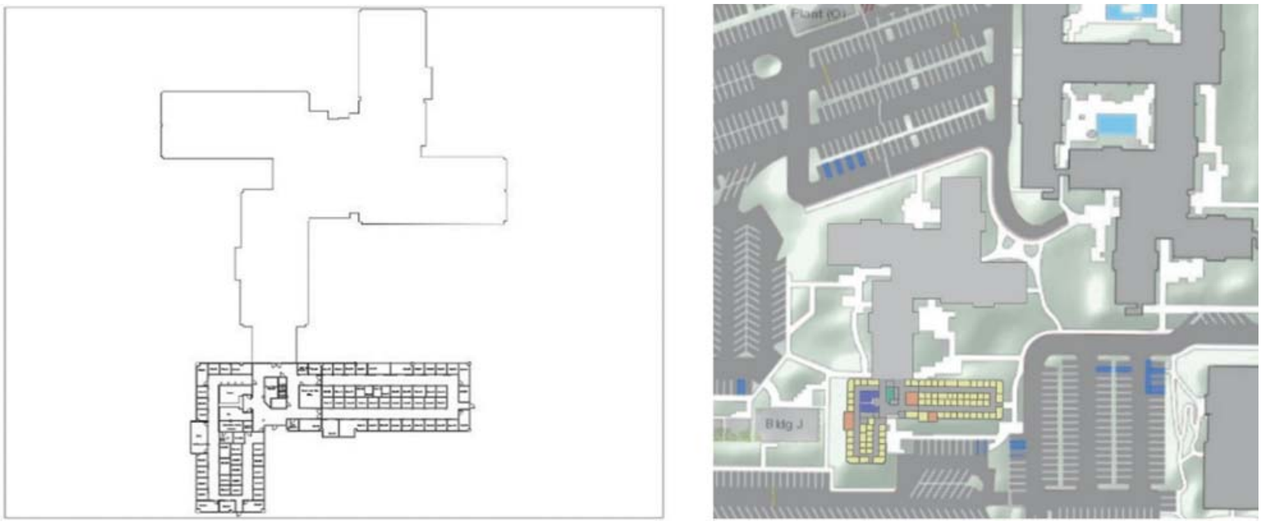

Fig. 75.1 Architectural plans of a part of OOA building. The details of each step using Campus Viewer Tool are discussed in the following section

A portion of building OOA on the Esri campus in Redland, California was used to create the indoor network. The CAD files inserted into ArcGIS Pro included floorplans, building rooms, walls, doors, stairs, and the elevator polygons which were all required for routing (Fig. 75.1).

75.4.1 Geodatabase Creation from CAD Data

We imported CAD data for indoor spaces and building into an ArcGIS™ Geodatabase using the Indoor CAD to GIS geoprocessing tool. The Indoor CAD to GIS tool is designed to work with CAD drawings that have consistent layer naming and are in a real-world coordinate system. This tool is a Python tool and has configuration macro that converts CAD to GIS layers in the Local Government Information Model (LGIM), or to a "generic" indoor dataset. We exported our model to the Esri LGIM directly from the tool as a preferred output.

After running the tool, the output included these layers: Building, BuildingFloor, BuildingFloorplanLine, and BuildingInteriorSpace. Furthermore, the output layers had a Z coordinate system and were enabled to have 3D applications (Fig. 75.2).

75.4.2 Indoor Network

The first step in generating the indoor network was to create a contiguous lattice that covered every floor's extent inside the building, but is cut by any barriers to walking transportation, such as walls or columns. Through the Create Network Lattices

Fig. 75.2 **a** 2D building floorplan, **b** 3D building floorplans, **c** 3D building form with space classification as polygons (The Authors, 2018)

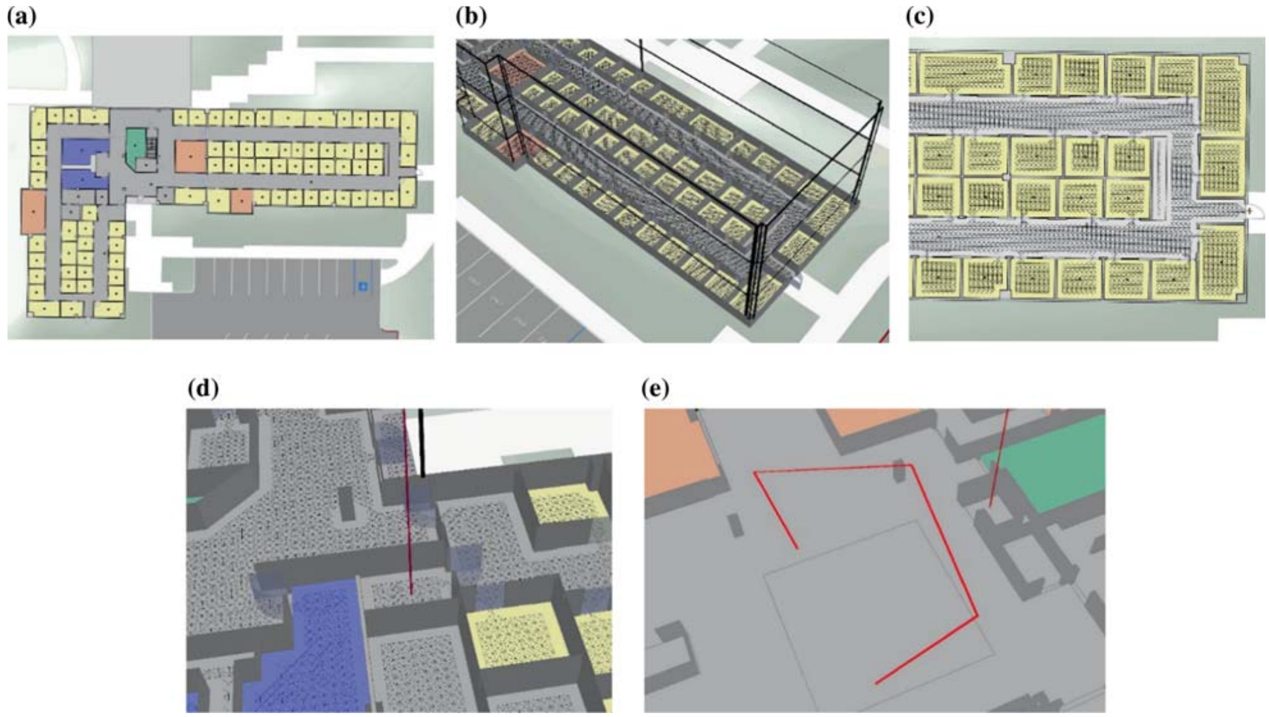

Fig. 75.3 The Indoor Network process, **a** spaces centerlines, **b** lattice, **c** ground floor entry, **d** vertical transition lines—elevator, **e** vertical transition lines—stairs (The Authors, 2018)

tool, part of the Campus Viewer Tool, we created a preliminary network lattice for each floor of a building. It was important to specify the building's entrances from the ground level. To do so we specified entrance doors to the building using Ground Floor Entry Points. Then, for the purpose of transition, we created and added transition lines which were based on vertical routing elements, such as stairs and elevators. The Campus Viewer Tool does not support creating the vertical routes automatically, and the process has to be done manually.

Through running the Network Analysis tool, which is an ArcGIS Pro Extension, the final part of the process can be done. We did not publish the result of Campus Viewer Tool on the web (Fig. 75.3).

75.5 Model Testing and Results

A pilot study was designed to explore a first responder's preferences for 2D or 3D representations to route and navigate through a building in the event of an emergency. This study limited participation to one domain expert with over 20 years of experience as a first responder and fire marshal. The intent was to develop procedures for future research based on testing questions and representations used for this study. A single interview was performed to measure the response for each representation of indoor navigation as shown eight of the thirteen studies in Table 75.1. The other remaining five studies did not include 2D plans or 3D models of the building, therefore they were not included in this study. In addition to the eight representations used in Table 75.1, the representation created as a result of our indoor network analysis in the ESRI Campus Viewer Tool was used as a comparison to each of the other representations. Objectives of this research were to discover: (1) if the 2D and 3D representations for each building "understandable", and (2) if the route finding in each of the 2D and 3D representations was "readable". The term "understandable" was used to measure the participant's response to the navigation information shown in the 2D plans and 3D models.

According to Rensink [28], visualization allows the viewer to understand information at a higher pace as connections and relationships are best conveyed through visual methods. He believed information representation through visualization is the best means to understandability—by using the right visualization techniques for the right dimensions and conveying the information to the viewer at the right time [28]. So, the term "understandable" was used to measure the participant's response to the navigation information shown in the 2D plans and 3D models. A representation is counted as successful where it is

Table 75.1 Comparison between current application of BIM and GIS in navigation methods

Authors	BIM/CAD	GIS	Visualization	Semantic info	2D	3D	Graph algorithm	Application	Fire simulation	Other notes
Zverovich (2016)	Y	Y	Y	Y		Y	Dijkstra, DHE data structure	Evacuation	N	
Li (2008)	Y	Y	Y	Y		Y		Indoor navigation	N	
Choi (2014)	Y	N	Y	Y		Y		Evacuation	N	
Xu (2016)	Y	Y	Y	Limited	Y	Y	Triangulated irregular network (TIN)	Evacuation	N	2 Parts: 2D and 3D
Xu (2017)	Y	N	Y	Y		Y		Indoor navigation	N	
Brown (2013)	IFC	Y	Y	N				Indoor navigation	N	
Wu (2016)	Y	Y	Y	N		Y	ArcScene network analysis	Evacuation	N	
Vandecasteele (2017)	Y	N	Y	Y		Y		Evacuation, indoor navigation	Y	Sensor and thermal Camera
Tsiliakou (2016)	N	Y	Y	Y		Y	ArcScene network analysis	Indoor navigation	N	ArcGIS, CityGML for Visualization
Teo, 2016	Y	Y	Y	Y		Y	Dijkstra	Indoor navigation	N	MGNM
Boguslawski (2016)	Y	N	Y	Y		Y	Variable density network (VDN)	Evacuation	N	Revit > gbXML, DHE data structure
Jamali (2016)	N	Y	Y	N		Y	In(DHE) + Out (OSM)	Indoor navigation	N	
Campus Viewer Tool	Y	Y	Y	N		Y	ArcGIS Pro network analysis	Indoor navigation	N	

able to encode information in a way that the viewers' brains can understand, and eyes can encode. Achieving this goal can be possible by studying human perception and it is a science than an art. Translating abstract information into visualization which can be decoding in an efficiently, easily and meaningfully manner is the goal of understandability [29]. We used understandability concept to measure the first responder's perception of the building model to get how much they can encode the building information presented by 2D plans and 3D models.

Typically, the term "readability" refers to the clarity and speed with which content can be digested over the written text. The definition of readability was expanded by Lambert, Bourqui and Auder [30] to measure the legibility of graphical elements used to represent graphical information like routing and navigation, and is the definition used for this study.

Results from this study indicated a preference to use 2D plans for navigation, and that the elaborated level represented in the 3D models initially had a negative impact on understandability. According to the results from this study, the greatest importance for first responders is to fully understand the building's layout; access points; room and corridor locations; hazardous material locations; and location of occupants. Although the preference was for the 2D plan to navigate routes through the building, there was evidence that a 3D model of the building contributes to further understanding the building's overall volume, vertical adjacencies, and boundaries. Further research is needed to explain the discrepancies between the results reported from this study. It appears that the difference in the quantity of information represented by 2D plans and 3D models had an impact on the cognitive load required for processing, which may have impacted the understandability and readability reported in this study.

75.6 Conclusion

The indoor network was created for a building and tested by first responders in a campus environment. An analysis of opinions communicated about the 2D plans and 3D indoor network of the building representations. Participants claimed that the indoor location information is one of the most important items in all stages of building emergency response operations, and having a ready to use, simple and quick access platform can help first responders to safely meet their goals more efficiently. It is also vital to provide first responders with accurate, robust, and real-time indoor location information so that first responders can prioritize spaces that are more likely to have occupants when planning the search and rescue routes and protect their own safety during the operations. This would help first responders avoid the possibility of getting lost in buildings, as well as avoiding the associated fatalities and injuries.

The results of this research show both 2D plans and 3D models of the building are useful for first responders. It was also reported by participants that fire stations are in the process of switching from the traditional paper-based 2D representations to digital interactive representations of routes and buildings for reference during an incident. Ultimately it was revealed that the 3D model of a building is an appropriate method for providing an understandable overview of the building and its spaces for first responders, while the 2D floor plans are more readable for the purpose of navigation. Expectations are both 2D plans and 3D forms of buildings with automatic route finding will enhance the capabilities and decision making of first responders in hazardous situations.

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