A MODEL-BASED GUIDANCE AND VULNERABILITY ASSESSMENT APPROACH FOR FACILITIES UNDER THE THREAT OF MULTI-HAZARD EMERGENCIES

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ABSTRACT

A MODEL-BASED GUIDANCE AND VULNERABILITY ASSESSMENT APPROACH FOR FACILITIES UNDER THE THREAT OF MULTI-HAZARD EMERGENCIES

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Disasters (e.g. earthquakes) and emergencies (e.g. fire) threaten the safety of occupants in the buildings and cause injuries and mortalities. These harmful effects are even more dangerous when secondary hazards (e.g. post-earthquake fires) emerge and it is commonly observed that the disasters/emergencies trigger secondary hazards. An effective indoor emergency guidance and navigation approach for occupants and first responders can decrease the number of injuries and mortalities during building emergencies by improving the evacuation process and response operations. For this reason, this research will propose a model-based guidance and vulnerability assessment approach for facilities that are under the threat of multi-hazard emergencies. The approach can be used to guide occupants from the facility affected by disasters/emergencies to safer zones and to direct the first responders by supplying them necessary building related information such as identified vulnerable locations in the indoor environments. An integrated utilization of Building Information Modeling tools, sensors, shortest path algorithms, and vulnerability assessment algorithms is proposed for the system in this research.

The research steps of this thesis include (1) determination of requirements of an indoor navigation during emergency response and disaster management, (2) review, comparison, and evaluation of shortest path algorithms from an emergency response and disaster management point of view, (3) proposing a vulnerability assessment approach, and (4) proposing a real-time indoor emergency guidance and navigation system framework for buildings under the threat of multi-hazard emergencies. The findings of the research can be used in future studies on emergency response and disaster management domains.

Keywords: Emergency Response and Disaster Management, Indoor Emergency Guidance and Navigation Systems, Vulnerability Assessment, Shortest Path Algorithms

ÖZ

ARDIŞIK TEHLİKELER ALTINDAKİ YAPILAR İÇİN MODEL TABANLI YÖNLENDİRME VE HASSASİYET ANALİZİ YAKLAŞIMI

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Yüksek Lisans, İnşaat Mühendisliği Bölümü

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Afetler (örn. depremler) ve acil durumlar (örn. yangınlar) binalardaki kişilerin güvenliğini tehdit etmekte, yaralanmalara ve ölümlere sebebiyet vermektedirler. Afet ve acil durumların zararlı etkileri ardışık tehlikelerin (örn. deprem sonrası yangınlar) ortaya çıktığı durumlarda daha da tehlikeli bir hal almakta ve afetlerin/acil durumların ardışık tehlikeleri tetiklemesi sık görülmektedir. Bina içindekiler ve acil durum müdahale ekipleri tarafından kullanılabilecek etkin bina içi afet/acil durum yönlendirme yaklaşımları, binalardaki acil durumlar sırasında tahliye ve acil durum müdahale süreçlerini iyileştirerek söz konusu yaralanmaların ve ölümlerin sayısını azaltabilecek mahiyettedir. Bu nedenle, bu araştırma kapsamında, ardışık tehlikeler altındaki yapılar için bir yerel yönlendirme ve hassasiyet analizi sistemi önerilmektedir. Bu yaklaşım, afetler/acil durumlardan etkilenen binalarda, bina sakinlerinin güvenli bölgelere tahliyesi ve acil durum müdahale ekiplerine bina içindeki hassas bölgeler gibi gerekli bina

bilgilerinin sağlanması suretiyle ekiplerin yönetilmesi amaçlarıyla kullanılabilecektir. Çalışma kapsamında önerilen sistemde, Yapı Bilgi Modeli araçları, sensörler, en kısa yol algoritmaları ve hassasiyet analizi algoritmalarının bütünleşik olarak kullanılması önerilmektedir.

Tez kapsamında yapılan araştırmalar; (1) acil durum müdahalesi ve afet yönetimi sırasında bina içi yönlendirme sistemlerinin gereksinimlerinin belirlenmesi, (2) en kısa yol algoritmalarının acil durum müdahalesi ve afet yönetimi bakış açılarıyla değerlendirilmesi, yorumlanması ve kıyaslanması (3) hassasiyet analizi yaklaşımı önerilmesi, ve (4) gerçek zamanlı bina içi acil durum yönlendirme sistemi önerilmesi aşamalarından oluşmaktadır. Çalışma bulgularının, acil durum müdahale ve afet yönetimi alanlarında gelecekte yapılacak çalışmalarda kullanılabileceği düşünülmektedir.

Anahtar Kelimeler: Afet ve Acil Durum Yönetimi, Bina İçi Acil Durum Yerel Yönlendirme Sistemleri, Hassasiyet Analizi, En Kısa Yol Algoritmaları

To my Family and Friends

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BIM	Building Information Modeling
CA	Cellular Automata
CAD	Computer-Aided Design
ERG	Emergency Response Guidebook
GIS	Geographic Information Systems
GPS	Global Positioning Systems
IDEF0	Integration Definition for Function Modeling
IFC	Industry Foundation Classes
MSDS	Material Safety Data Sheets
MIT	Massachusetts Institute of Technology
NIST	National Institute of Standards and Technology
PERT	Program Evaluation and Review Technique
RFID	Radio Frequency Identification
US	United States
UWB	Ultra Wide Bands
WLAN	Wireless Local Area Networks
XML	Extensible Markup Language

CHAPTER 1

INTRODUCTION

Disasters and emergencies such as earthquakes, fires, and explosions have caused significant amount of injuries, mortalities, and property losses throughout the history. Moreover, the number of injuries and mortalities due to disasters and emergencies is increasing in the modern buildings of today. Survey studies provide a solid support for this statement, as there were 17000 mortalities on average annually during the 20^{th} century around the world (Scawthorn and Chen, 2003). The underlying reasons for the increase in the number of injuries and mortalities in today's buildings compared to past times can be briefly listed as (1) larger sizes of modern buildings in terms of number of floors and building areas, (2) increase in the complexity of indoor environments, (3) larger occupancy capacities of buildings, and (4) the difficulties faced during evacuation of occupants (Park and Lee, 2008; Pu and Zlatanova, 2005). Shortly, the reason for the increase in the number of injuries and mortalities is the changes in the conditions of today's modern buildings.

Disasters (e.g. earthquakes) and emergencies (e.g. fire) threaten the safety of occupants in the buildings. Changes in the conditions of modern buildings augmented the perceivable and harmful effects of disasters and emergencies. These harmful effects are even more dangerous when secondary hazards emerge and it is commonly observed that the disasters/emergencies trigger secondary hazards. Secondary hazards are defined as emergencies that occur after a major disaster or an emergency (Binder and Sanderson 1987; Young et al. 2004). For example, fires are the most commonly observed secondary hazards in the aftermath of earthquakes (Pu and Zlatanova, 2005). In other words, secondary hazards are triggered because of the disturbance generated by an initial disaster/emergency. Previous incidents in the history have shown that the damage caused by the secondary hazards can be more significant than the disaster/emergency itself (Charles 2003, Haddow et al. 2007). Especially in large and tall buildings such as large public buildings and hospitals, the mentioned effects are even more drastic since these buildings have architecturally complex indoor environments and huge variety of hazardous contents (i.e. explosive materials) (Stringfield, 1996). Hazardous contents are the contents that have the possibility to cause further injuries and mortalities following a disaster/emergency. Hazardous contents can become harmful and threat human health during a disaster/emergency or can create secondary disasters, such as explosion or fire. Hazardous contents do not cause damage on their own. However, due to a disturbance generated by an initial disaster/emergency (e.g. an earthquake), hazardous contents can become dangerous and the location that is bearing such contents will become a vulnerable location (Leite et. al, 2008). Although hazardous contents can be stored in a building for daily usage (e.g., fuel oil used for heating in boiler rooms); it turns to a threat upon interaction with a disaster/emergency (e.g., fire) and/or it directly causes a secondary disaster (e.g., explosion). For example, ethyl acetate, which is used in perfumes and paint, bears a potential to cause suffocation (i.e., secondary disaster) when it spills out of its container in case of a fire (i.e., main emergency). Another example can be the fire caused by overturning of a heating stove because of an earthquake. In this example, it can be said that the earthquake is the initial disaster and the heating stove is a hazardous content. Due to the disturbance generated by the earthquake, overturning of the heating stove is the incident that caused hazardous content to become dangerous. Finally, the fire is the secondary hazard and the location where this fire affects is a vulnerable location. As stated before, in some cases, the damage caused by the secondary hazards can be more harmful than the disaster/emergency itself. For example, damage caused by the post-earthquake fires may be substantially larger than the earthquake (Chen et. al, 2004). The secondary hazards in the aftermath of a disaster are not only limited to fires and explosions. Following an earthquake, there are various causes of injuries and mortalities ranging from building collapses to tsunamis, chemical material spills to radioactive leakages (Scawthorn and Chen, 2003). Therefore, following a disaster/emergency, effective evacuation of a building is crucial considering the current damage and the potential secondary hazards that can be triggered (Ayhan et. al, 2012).

An effective evacuation process can decrease the number of injuries and mortalities during building emergencies. Evacuation involves two parties: (1) occupants in the building, and (2) first responders. Following a disaster/emergency, occupants will evacuate the building to reach to safer zones. In the meantime, first responders will help the occupants to evacuate the building who cannot do it with their own efforts.

Both parties will require critical information about the building during evacuation phase. First responders try to gather this information (e.g. non-accessible locations in the building, etc.) that can guide and support them during response operations to perform an effective evacuation and response process. In the meantime, the occupants in the building require such information to leave the building safely by using the safest possible evacuation route. When a disaster/emergency occurs, the occupants usually panic. Consequently, evacuation process could not be performed uneventfully in a panic environment and due to the lack of information related to the building status, occupants are usually faced with further injuries (Güven et. al, 2012).

With an emergency guidance and vulnerability assessment approach, this research will mainly focus on effective evacuation issues for buildings that are under the threat of multi-hazard emergencies (e.g. under the effects of main disaster and the consequent secondary hazard). An effective evacuation approach will be proposed for both the occupants and the first responders. Below sections will briefly summarize the motivating cases for this research, state the problems that resulted this research, establish the aims and objectives of the thesis, introduce the methodology of the research along with the scope and limitations, and finally present the organization of thesis.

1.1 Motivating Cases

Several incidents in the recent history have been examined and selected as motivating cases of this dissertation to (1) understand the stated problems better, (2) realize the outcomes of a disaster/emergency, and (3) draw attention to the devastating effects of secondary hazards.

The selected cases are 1906 San Francisco Earthquake and 1994 Northridge Earthquake in the USA, 1923 Great Kanto Earthquake and 1995 Kobe Earthquake in Japan.

1.1.1 Motivating Case 1: 1906 San Francisco Earthquake - USA

San Francisco Earthquake in the USA affected an area of 12 km^2 and caused demolition of more than 28000 buildings. The predicted number of mortalities is over 3000 and the predicted economic loss is approximately 250 million USA Dollars in 1906 (Chen et. al, 2004). In the first 17 minutes following the earthquake, 66 fires that primarily occurred due to overturning of oil lamps, oil and gas stoves, boilers and furnaces, collapse of chimneys, and contact of flames with flammable materials were reported (Strand, 2006). The devastating effects of post-earthquake fires following the San Francisco Earthquake pulls the attention to the risks possessed by the secondary hazards (i.e. post-earthquake fires). It is predicted that the damage due to the post-earthquake fires following the 1906 San Francisco Earthquake caused 10 times more damage than the earthquake itself (Scawthorn and Chen, 2003).

1.1.2 Motivating Case 2: 1923 Great Kanto Earthquake - Japan

It is determined that 1923 Great Kanto Earthquake in Japan caused more than 140000 mortalities and destroyed more than 575000 buildings. The majority of the structures in the earthquake region were wooden buildings and because of this, 77% of the losses were due to fires and explosions following the earthquake (Usami, 1996). Total of 98 immediate post-earthquake fires were reported after the earthquake (Kobayashi, 1985). According to Japan Bureau of Social Affairs, it is estimated that 100,000 mortalities out of 142,000 were due to the fire or smoke inhalation. The causes of secondary hazards, especially post-earthquake fires in this disaster, are hazardous contents such as medicine, gunpowder, cooking stoves, kerosene stoves, etc. and gas leakages (Ohnishi, 1996). Thus, it can be stated that hazardous contents should also be considered in the aftermath of disasters/emergencies since they have the potential to cause secondary hazards.

1.1.3 Motivating Case 3: 1994 Northridge Earthquake - USA

1994 Northridge Earthquake in the USA is another case where the secondary hazards caused more serious damages than the main disaster. 57 deaths, more than 9000 injuries and more than 20 billion USA dollars of damage have been reported in relation to Northridge Earthquake (Borden, 1996). The main causes of secondary hazards following this earthquake are gas and electricity leakages. Similar to previous motivating cases, post-earthquake fires caused serious damages. In the first 27.5 hours following the disaster, 158 buildings reported fire incidents (Strand, 2006). Causes of the secondary hazards have been analyzed after the earthquake. The results show that 22.2% of the fire incidents were caused by hazardous conditions and 10.1% were caused by hazardous materials and chemicals (Borden, 1996). Similar to 1923 Great Kanto Earthquake in Japan, looking at these data about the Northridge Earthquake, it can be said that to mitigate the effects of secondary hazards, precautions should be taken against the causes of secondary hazards (i.e. hazardous materials). Locations containing hazardous materials and threat bearing contents that have the possibility to cause further injuries and mortalities will be referred as vulnerable locations in this dissertation. In other words, vulnerable locations are either affected by secondary hazards or have a high-risk potential of being affected by secondary hazards. In the light of the data about the Northridge Earthquake, it can be said that vulnerable locations should be avoided during evacuation as much as possible.

1.1.4 Motivating Case 4: 1995 Kobe Earthquake - Japan

According to the National Fire Protection Association of Japan (1995), 1995 Kobe Earthquake resulted in more than 6,000 deaths, at least 30,000 injuries, and destroyed more than 100,000 buildings. It is also reported that 148 distinct fires are observed and more than 50% of them directly caused by the ground motion. These fires destroyed 6,513 buildings. The causes of the secondary hazards, especially fires, were gas and electricity leakages (Ohnishi, 1996). According to Kobe's International Department, 89% of the mortalities are caused by the collapse of buildings, while 10% were due to post-earthquake fires (National Fire Protection Association of Japan, 1995). These numbers also highlight the risks possessed by the secondary hazards.

1.1.5 Summary of Outcomes from Motivating Cases

All of the selected motivating cases are earthquake cases because; earthquakes affect significantly larger areas than other disasters/emergencies. In addition, the varieties of the secondary hazards that can occur in the aftermath of earthquakes are wider. Although post-earthquake fires are the most commonly observed secondary hazards following the earthquakes, the causes of these fires are various, ranging from overturning of stoves to flammable material spills. Moreover, other hazards (i.e. explosions, suffocation due to hazardous material releases, and contact with chemical/biological/radioactive/nuclear contents) are more likely to occur after earthquakes compared to other disasters/emergencies.

The common point of all these disasters given as motivating cases is secondary hazards being a significant cause of injuries and mortalities. Following the mentioned disasters, occupants became prone to the threats by secondary hazards, such as fires and explosions, and consequently the number of injuries and mortalities increased. In all these cases, appropriate precautions, effective evacuation and response procedure could have minimized the harmful effects (Scawthorn and Chen, 2003; Usami, 1996; Borden, 1996; Ohnishi, 1996). Thus, the given motivating cases point out the significance of the disasters/emergencies and the importance of effective evacuation in the aftermath of disasters/emergencies for reducing the number of injuries and mortalities, especially in buildings under the threat of multi-hazard emergencies.

1.2 Problem Statement

Following a disaster or an emergency in a facility, a timely and effective response is crucial for saving more lives. However, complex architecture of the indoor environments, high occupancy capacities of the buildings, non-accessible locations in the indoor environments after disasters/emergencies, threats caused by the secondary hazards, and wide variety of hazardous contents in the buildings are obstacles in front of achieving effective evacuation.

The problems faced with during and after disasters/emergencies will be examined in two groups as problems faced by occupants and problems faced by first responders.

1.2.1 Problems Faced By Occupants

It is especially difficult for occupants to find their way out of a building with complex architecture. Burnett et. al (2001) claims that it is a difficult activity for an individual to find the way that will bring him/her to the desired location in real or virtual environments. This activity is known as guidance or navigation (Yuan and Zizhang, 2008). Although navigation is usually related with guidance of vehicles (e.g. automobile navigators), occupants in the buildings also need guidance to reach to a target destination starting from an origin point (Ivin et. al, 2008; Richter and Klippel, 2005). However, in the current practice, occupants generally try to evacuate the buildings with their own efforts and this practice has drawbacks. To begin with, when a disaster/emergency occurs, the occupants generally panic and the panic affects the evacuation process negatively (Güven et. al, 2012). In addition, the occupants usually have little or no information about what they are going to face with on their evacuation paths (i.e. blocked corridors, fires) since they lack critical building related information. As a result, occupants are usually faced with further injuries. Thus, guidance of occupants during evacuation is an important component of effective evacuation process.

In the current practice, evacuation process of occupants mainly depends on evacuation plans and direction signs (i.e. exit signs). However, for an individual, who is not familiar with the building or who barely knows the building, evacuation plans and direction signs may not be sufficient (Pu and Zlatanova, 2005). For example, evacuation plans show the current location of the occupant and directs him/her to the closest exit, say exit B. However, that occupant may not find exit B during a disaster/emergency since he/she is not familiar to the building. Thus, a guidance system with evacuation plans and direction signs may not be sufficient for the guidance of that individual. In addition, although an individual is familiar to the building, in the panic during the disaster/emergency, he/she may not be capable of finding the path to the exit. In such cases, the problem is the lack of a guidance system that is capable of guiding the occupants who are not familiar to the building or who are in panic.

Another problem in the current evacuation practices is that each disaster/emergency will cause different outcomes in the building depending on its magnitude and conditions. For example, the destructive effects of two earthquakes of different magnitudes in Richter scale (i.e. an earthquake with 3.1 magnitude in Richter scale and another with 6.8 magnitude) will be different on the building. Even if the magnitudes of the earthquakes would be same, depending on factors such as the hazardous contents in the building, population density in the building, construction type and its usage, and even the date and the time of earthquake occurrence, the variety of secondary hazards can change (Pu and Zlatonava, 2005). For example, an earthquake that occurs in winter times is more likely to cause post-earthquake fires than an earthquake in the summer times due to the utilization of heaters. Thus, considering variable effects of disasters/emergencies on buildings, current evacuation systems via evacuation plans and direction signs will be insufficient for guidance of occupants.

Occupants should be protected against the harmful effects of secondary hazards in the aftermath of disasters/emergencies. Therefore, depending on the occurrence of the secondary hazards, occupants should be evacuated without being affected by the secondary hazards. For example, an occupant should not be guided to a path that is under the effects of a fire. Unfortunately, evacuation practices depending on evacuation plans and direction signs are incapable of warning the occupants against the secondary hazards. In the light of these, it can be stated that there is a need for a real-time emergency guidance system and it is lacking in the current practice.

Besides the architectural complexity of the modern buildings of today and the drawbacks of the current evacuation practices, especially against secondary hazards, non-accessible locations and blockages may also avoid evacuation of occupants. There may be people blocked in the buildings after earthquakes who cannot leave the building with their own efforts. Partial building collapses or collapse of a middle floor can be given as examples to such incidents. In Figure 1.1, a hotel building that experienced middle floor collapse after the 1985 Mexico Earthquake can be seen. If there were any occupants on the floors higher than the collapsed floor, they would have been blocked in the building.

Figure 1.1: A picture of a hotel building that has a collapsed middle floor due to the impacts of September, 19 1985 Mexico Earthquake (Photograph taken from: http://www.smate.wwu.edu/teched/geology/GeoHaz/eq-Mexico/eq-Mexico-08.jpg)

Blocked people are more vulnerable to the threats caused by the secondary hazards. In blockage cases, first response teams need to start the response operations immediately, rescue the blocked occupants and evacuate them to safer zones as soon as possible. Time is even more critical in such cases. As occupants are more likely to panic after disasters/emergencies, blocked occupants tend to spread inside the building in search of an exit pointlessly. Therefore, when response teams start the operations, they need to locate all occupants spread around one by one. Such a practice will decrease the efficiency of the response operation. However, with an effective evacuation approach, blocked occupants can be guided to relatively safer zones in the building and grouped together so that the response teams can get to all occupants easily, which will increase the efficiency of the response operation and potentially decrease the number of injuries and mortalities.

Considering all of the mentioned problems in this section, it can be claimed that the lack of guidance of occupants is a significant problem during evacuation process. In addition, the current practices are incapable of performing real-time emergency guidance that will decrease the harmful effects of secondary hazards and deal with blockage cases.

1.2.1 Problems Faced By First Responders

It is difficult to predict the current or possible events in the indoor environments after disasters/emergencies (Leite et. al, 2008). Thus, it is crucial for first responders to access critical information related to a damaged building in a timely manner (Kwan and Lee 2005; Jones et al. 2005; Tsai et al. 2008; Leite et al. 2008; 2009; Güven and Ergen 2011). Response teams usually require critical information about the responded building such as the floor plans of the building, the hazardous contents in the building and their current states, locations of fires, non-accessible locations in the building, etc. during their decision-making and planning processes. In the current practice, response teams do not have the sufficient information about the damage status of the building after the disaster/emergency, hazardous contents in the building, secondary hazards, and occupancy conditions (Jones and Bukowski, 2001; Evans et. al, 2003; Son and Pena Mora, 2006). Instead, responders perform visual investigations and query the occupants that came out of the affected building to obtain the required information. However, this approach might result in obtaining incorrect and misleading information that might increase the number of injuries and mortalities as the critical time needed for starting the emergency response activities is wasted during querying the occupants and collecting data. Moreover, additional time will be wasted if the collected information is incomplete or unreliable since occupants might not know all details about the hazardous contents and vulnerable locations (Ergen and Seyis, 2008; Ergen et. al, 2009). Thus, the lack of the critical real-time information about the responded building is a problem in the current practice that affects the response operations negatively and causes further injuries and mortalities during emergencies (Kwan and Lee, 2005; Ergen and Seyis, 2008).

Securing the response process and responding crews is another problem faced by response teams (Arıoğlu et. al, 2000). It is also related with the completeness of the information required by the response teams. For example, during 9/11 World Trade Center disaster, towers have collapsed while fire fighters were inside the building to rescue people. This incident shows the importance of gathering the critical information and points out the costs when this information is lacked.

In the light of these, it can be claimed that the lack of real-time guidance of first responders is a significant problem during response operations.

1.3 Aims and Objectives of the Research

Effective evacuation is a difficult task for buildings with complex indoor environments and extreme occupancy rates. In addition, lack of real-time guidance of occupants and first responders cause significant problems. Thus, a method to achieve effective evacuation is required. One of these methods is developing indoor emergency guidance and navigation systems for the occupants and the first responders following a disaster/emergency. This research is aiming to propose such a system.

Indoor emergency guidance and navigation systems have some requirements in order to perform the necessary guidance. Although there a few studies such as Nagel et. al (2010), there are not many studies focusing on these requirements. Therefore, the first objective of this thesis is to determine the requirements of indoor emergency guidance and navigation systems during emergency response and disaster management.

Indoor emergency guidance and navigation systems depend on algorithms that are capable of generating evacuation paths for guidance of occupants and/or guiding first responders by giving them the necessary information about the indoor environment. To achieve this, such systems require building related information (e.g. building plans, content information). Using the building related information, necessary adjustments take place (e.g. generation of graph networks) so that algorithms can work on and generate the evacuation paths. To generate evacuation paths, shortest path algorithms can be utilized in these systems (Meijers et. al, 2005). However, several different shortest path algorithms are present in the literature with different properties, performances, and limitations depending on the requirements of the problem and the desired outcomes. Thus, the question of which algorithm should be utilized in such systems arise. Although there are studies that evaluate and compare these various shortest path algorithms (can be found in Chapter 4), there is a lack of detailed evaluation of shortest path algorithms for utilization in emergency guidance and navigation systems in the literature. Thus, this research aims to fill this gap by (1) identifying the most commonly preferred shortest path algorithms in the literature, (2) determining the properties, performances, and limitations of them, (3) determining evaluation criteria considering the requirements of the emergency guidance and navigation system that will proposed in this thesis, (4) comparing the algorithms with each other according to the determined criteria, and finally, (5) making a suggestion for which shortest path algorithm to use in such systems. The literature review on the shortest path algorithms will be given in Chapter 2 and the details of the related research will be given in Chapter 4 of this dissertation.

Besides occupancy guidance and evacuation, the system should also guide the first responders to increase the efficiency of response operations. For this reason, building related information should be supplied to first responders along with the information about the current conditions in the indoor environment such as locations of secondary hazards and hazardous contents. In the light of the supplied information, vulnerability assessment of the responded building should be performed. Thus, another objective of this study is to suggest a vulnerability assessment approach that can be utilized in such system. The literature review on vulnerability and vulnerability assessment will be given in Chapter 2 and the details of vulnerability assessment approach will be given in Chapter 5.

The ultimate goal of this research is to propose a real-time indoor emergency guidance and navigation system. Although there are several systems proposed in the literature (details can be found in Chapter 2), this research aims to propose a more comprehensive, combined, and automated system as a contribution.

1.4 Research Method

The studies about determination of requirements of an emergency guidance and navigation system will depend on use case scenarios. After use cases are generated, these cases will be examined and requirement analysis will be performed.

Shortest path review and selection related research will be based on literature reviews and outcomes of the requirement analysis. Evaluation criteria will be set according to the findings of the literature review and requirement analysis. Then, in the light of the determined criteria, a comparison will be made. The final goal of shortest path studies is to suggest an algorithm to use in indoor emergency guidance and navigation systems.

Similarly, vulnerability assessment approach related studies will also be based on the literature review findings and outcomes of the requirement analysis. A vulnerability assessment approach will be proposed depending on the types, the standoff distances, the risk levels, and the risk rankings of hazardous contents and secondary hazards.

Finally, as a summary of the findings of all these studies, a real-time indoor emergency guidance and navigation system for buildings under the threat of multi-hazard emergencies will be proposed.

1.5 Scope and Limitations

The proposed system in this thesis is generated considering large and tall buildings such as large public buildings and hospitals that is more likely to have more complex architecture, high occupancy density, and wide variety of hazardous contents. Thus, the proposed system may not give the exact same results when the parameters such as building type, reason of utilization, etc. are changed. In addition, the results from the utilized algorithms may also vary according to these changes. However, this research still has the aim to give an overall opinion about indoor emergency guidance and navigation systems.

A comprehensive study should be conducted for establishment of vulnerability assessment algorithms. Since this dissertation has other focuses, conducting such a study is not possible. Thus, this study only proposes and suggests a vulnerability assessment approach rather than conducting the studies to create the suggested approach.

Shortly, this thesis only aims to propose a real-time indoor emergency guidance and navigation system for buildings under the threat of multi-hazard emergencies. The further details (e.g. software modeling, etc.) and application of the system can be considered as future works and will not be included in the scope.

1.6 Organization of Thesis

In the second chapter of this study, the literature review on emergency response and disaster management, graph theory, shortest path algorithms, vulnerability and vulnerability analysis, and previous emergency guidance and navigation systems will be given. The third chapter will discuss the requirements of an indoor emergency guidance and navigation system during emergency response and disaster management according to use case studies and requirement analysis. In the fourth chapter, the most commonly preferred shortest path algorithms will be identified, evaluated according some determined criteria, and compared with each other. At the end of the section, an algorithm will be suggested to be utilized in indoor emergency guidance and navigation systems. The fifth chapter will present the vulnerability assessment approach of this study. Finally, in the sixth chapter, a real-time indoor emergency guidance and navigation system will be proposed. The seventh chapter will be concluding the findings of this thesis and make suggestions on future research. In addition to the main text, this study also includes four appendices. Appendix A is about the details of graph theory. Appendix B gives the details of the working mechanisms of Prim’s and Dijkstra’s Shortest Path Algorithms, while Appendix C is about the working mechanism of A* Algorithms. Finally, Appendix D presents an example 2D application of A* Algorithm following a disaster/emergency for better understanding.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the findings of a literature review on guidance and vulnerability assessment approaches, and integrated emergency navigation systems to guide occupants and first responders in facilities after disasters/emergencies. The literature review will have more emphasis on model-based studies and will focus on buildings under the threat of multi-hazard emergencies. The chapter is divided into three main sections. In the first section, an introductory literature review about emergency guidance and navigation systems will be presented. In addition, the concepts about graph theory and shortest path algorithms will be introduced. In the second section, vulnerability related terms will be discussed and current vulnerability assessment approaches will be briefly presented. In the third and final section, the current emergency guidance and navigation systems and approaches will be reviewed.

2.1 Introductory Literature Review

Individuals need guidance and navigation to reach to a target destination from a point selected as origin (Ivin et. al, 2008; Richter and Klippel, 2005). Therefore, studies on navigation are a requirement. Research about navigation is related to several other fields and open to advances (Yuan and Zizhang, 2008; Richter and Klippel, 2005). Advances in programming, communication, and mapping techniques lead to the development of Global Positioning Systems (GPS) that is used to locate and track the movements of mobile objects such as vehicles and human beings (Yuan and Zizhang, 2008). Moreover, there are studies that integrate navigation systems with programs such as Geographic

Information Systems (GIS) and Cellular Automata (CA) to enable utilization of navigation systems to serve for various purposes in various fields. One of these fields, where navigation systems can be employed, is the emergency response and disaster management domain. There are navigation systems for emergency navigation that integrates 2D or 3D GIS with data models (Ivin et. al, 2008; Lee, 2005; Kwan and Lee, 2005; Lee, 2007; Lee and Zlatanova, 2008; Park and Lee, 2008). However, majority of the navigation systems depends on 2D networks. Studies integrating 3D GIS and data models have recently become important. In addition, majority of the emergency guidance and navigation studies have been focused on outdoor environments rather than indoor environments (Meijers et. al, 2005; Pu and Zlatanova, 2005; Kwan and Lee, 2005; Yuan and Zizhang, 2008).

Yuan and Zizhang (2008) groups the reasons why 3D indoor emergency guidance and navigation studies are limited. Firstly, majority of the old buildings have low numbers of floors and they do not have very complex architecture. Thus, indoor emergency guidance and navigation in buildings were not a significant requirement in the past. However, the modern buildings of today, such as schools, hospitals, shopping malls, etc. have complex architecture and high occupancy capacities that developed the need for indoor emergency guidance and navigation during disasters/emergencies. Secondly, there is a lack of required data to establish these systems. Mainly, building plans are prepared via computer-aided design (CAD) systems in 2D environments. This kind of building plans can only include geometric information. Semantic information such as material types, opening direction of doors, purpose of usage of spaces in the buildings, etc. are lacking. Lack of semantic information hampers the establishment of real-time indoor emergency guidance and navigation systems. Third and final item is the inadequacy of currently used 3D data systems in emergency response and disaster management domain. Majority of the navigation systems performs in 2D environments. However, considering the panic environment following a disaster/emergency, navigation should be clear enough to guide any occupant regardless of the condition of the occupant. Thus, 3D navigation is a requirement. Moreover, currently used 3D data systems have drawbacks in terms of multi-purpose and real-time utilization. This is a major problem in developing an effective and in-depth building navigation system.

Emergency response and disaster management domain focused on studies about the indoor emergency navigation systems, especially on evacuation of occupants and guidance of first responders, after the devastating outcomes of 9/11 World Trade Center and 2005 London Subway disasters. The reason of this intensification is the increase in the number of disasters/emergencies such as fires, earthquakes, tsunamis, and terrorist attacks that causes innumerable injuries, mortalities, and economic losses. It is aimed to decrease these losses by offering alternative real-time evacuation paths to the occupants and supplying real-time vulnerability and accessibility information to the first responders considering the conditions that will develop after every different disaster/emergency (Lee and Zlatanova, 2008; Yuan and Zizhang, 2008; Park and Lee, 2008; Lee, 2007).

The basic principle of the emergency guidance and navigation systems depends on shortest path algorithms. The working principles of shortest path algorithms depend on graph theory. Therefore, it would be beneficial for reader to explain the graph theory and shortest path algorithms with the necessary definitions and terms at this point.

2.1.1 Graph Theory and Shortest Path Algorithms

An evacuation path is the shortest possible path between an origin and a target point in distance. To generate the evacuation paths, shortest path algorithms that have the capability to calculate the shortest possible way between two points on a graph network are used (Marcus, 2008; Gross and Yellen, 2006). To explain the concepts about shortest path algorithms better, firstly, graph theory will be briefly explained.

2.1.1.1 Graph Theory

Graph theory is being utilized in several fields. These fields can be fields that require physical networks such as electricity circuit networks, bonding networks between organic molecules, transportation networks, etc. Graph theory can also be utilized for more abstract concepts such as database applications, social networks, and flow chart controls of computer programs (Gross and Yellen, 2006).

Graph theory is firstly suggested by the Swedish mathematician Leonard Euler in 1736 for the solution of Konigsberg Bridge Problem. There were seven bridges connecting two neighboring islands in the city of Konigsberg to each other and to the shores on both sides (Figure 2.1). The Konigsberg Problem was questioning whether it is possible to cross all seven bridges by passing only once from all bridges or not. In Figure 2.1 on the right side, the graph network of this problem is given (Newman et. al, 2006). The points in this figure represent the two islands and the two shores on both sides. Points are connected to each other by lines that represent the bridges. Shortly, graph networks are composed of points, and lines that connect the adjacent points. Points in the network are called nodes, while lines are called edges (Marcus, 2008; Gross and Yellen, 2006). All edges in the graph network are bounded by one or more nodes that limit the edge. These nodes are called the “end points” of the edge. An edge connects the same or different nodes with each other and creates a neighboring (adjacency) relationship (Gross and Yellen, 2006).

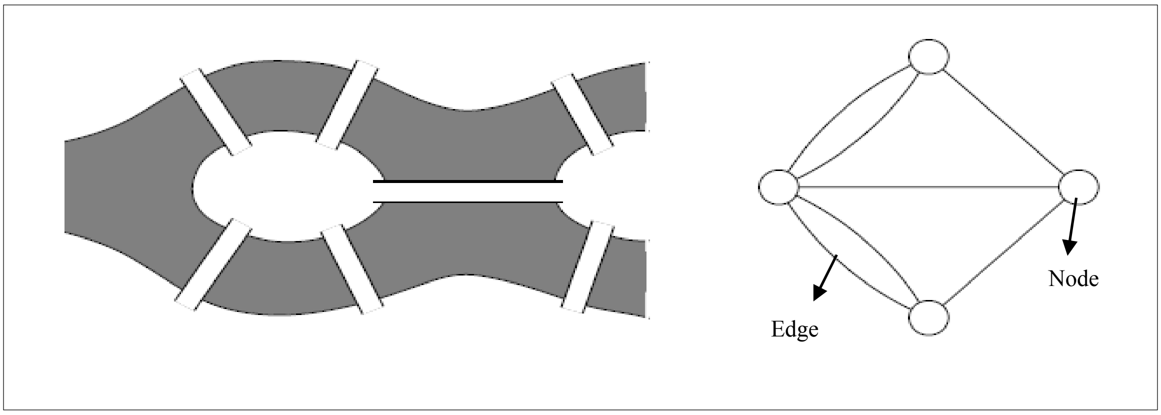

Figure 2.1: The schematic version of the Konigsberg bridge problem (left) and the graph network (nodes and edges) constituted for this problem (Newman et. al, 2006)

The graph network of Konigsberg Problem is composed of four nodes and seven edges. This graph is also known as the Euler's Path. An Euler Path defines a path where all edges in the network have to be crossed. In addition, these edges should be crossed only once (Marcus, 2008).

Each edge on the graph network has a value, which is known as the edge cost. In this study, edge costs will be defined in terms of distances. Shortest paths are calculated according to the edge costs between the nodes. The path giving the total minimum cost between an origin and a target node is the shortest path (Marcus, 2008; Gross and Yellen, 2006).

Mathematically, graphs are composed of two finite sets, which are node sets V(G) and edge sets E(G), and a graph network is a set represented by G = (V,E). The Graph A given in Figure 2.2 can be used for explaining the mathematical structure of graph networks. Graph A is represented as $G_A = (V_A, E_A)$. The graph has four nodes and the node set is represented as $V_A = \{a, b, c, d\}$. There are also four edges and the edge set will be E_A = {ab, bc, cd, da}. The total number of edges that come to and leave the node is called the degree of the node. Node 'a' in Graph A (Figure 2.2) has two edges and the degree of Node 'a' is two (Hartmann and Weigt, 2008).

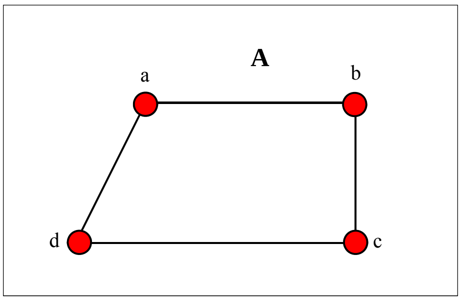

Figure 2.2: Graph A, $G_A = (V_A, E_A)$

The general and mathematical concepts about graph theory are given in this section. More details about the theory can be found in Appendix A. In the next section, shortest path algorithms will be briefly explained.

2.1.1.2 Shortest Path Algorithms

Shortest path algorithms are algorithms that have the capability to calculate the shortest possible way between an origin and a target point in distance (Marcus, 2008; Gross and Yellen, 2006). According to the National Institute of Standards and Technology (NIST) in the USA, shortest path is defined as the problem of finding the shortest possible path that connects two nodes in a graph network. The term "shortest" can be referred as the path that involves the least number of edges, the path that gives the minimum edge cost (i.e. in terms of distance), etc. depending on the desired outcome (Black, 2005). In another definition, shortest path algorithms are defined as the algorithms that are used to determine the optimum paths in the graph networks (Karaş, 2007).

Shortest path algorithms are being used for solving several different problems from various domains including but not limited to problems in vehicle navigation, optimization, work scheduling and critical path finding in Program Evaluation and Review Technique (PERT) charts, robot motion planning, highway engineering, planning of the power lines (Eppstein, 1994).

In this study, shortest path algorithms will be assessed with an emergency response and disaster management point of view. In order to evacuate occupants to safer zones after disasters/emergencies, evacuation paths calculated by shortest path algorithms are being used (Meijers et. al, 2005). Thus, in this study, shortest path algorithms will be used in the real-time indoor emergency guidance and navigation system for buildings under the threat of multi-hazard emergencies.

There are several types of different shortest path algorithms in the literature serving for different purposes and performing under different conditions (e.g. Dijkstra's Algorithm, Prim's Algorithm, A* Algorithms). Thus, the selected shortest path algorithm is important in this study. Details about the shortest path algorithm reviews and selection will be given in Chapter 4 in this thesis.

2.2 Literature Review on Vulnerability and Vulnerability Assessment

Vulnerability in a building is a term used to define the harmful effects of secondary hazards, which are or might be triggered inside the building following a disaster/emergency, on occupants and response teams. Similarly, vulnerability assessment term refers to the assessment of different types of secondary hazards (potential hazards) and its impacts to human, property and business (Lewis and Payant 2003). Vulnerability assessment is also defined as the identification of weaknesses in a system, focusing on defined threats (The National Waterworks of Rural America, 2002). These definitions are constituted with a general emergency management viewpoint rather than a building specific emergency management perspective. To provide such a perspective, this study describes the vulnerability assessment as the identification of the hazardous contents and their locations and determining the potential secondary hazards that can be induced by the interaction of the hazardous contents with the main disaster/emergency. Moreover, the literature review on vulnerability and vulnerability assessment in this thesis will have more emphasis on studies in building-scale.

Most of the previous studies about vulnerability assessment are performed in larger scales (i.e., city or state level) (Cova, 1999; Godschalk, 1991; UCLA Center for Public Health and Disasters, 2006). There are only a few studies that include vulnerability assessment in building-scale (Lawrance Berkeley National Laboratory 2004, Leite et al. 2008; 2009; Leite and Akinci 2011). Lawrance Berkeley National Laboratory (2004) published a report that enhances the understanding of vulnerabilities in buildings caused by chemical, biological, and radiological impacts. The purpose of the report is to develop and test procedures for vulnerability assessment of facilities after chemical or biological attacks, and estimate the consequences of vulnerabilities in facilities following a terrorist attack. Vulnerability issues addressed in the report focused on chemical, biological, and radiological hazardous material releases. The report also included studies on airflows inside the facilities and contaminant transport, evacuation routes and potential safe zones, and decision support activities for first responders to enhance the response operations. The report provides building-specific vulnerability and mitigation advices. However, the focus of the report is on the vulnerabilities in the aftermath of terrorist attacks rather than disasters/emergencies.

Other building-scale vulnerability assessment studies presented a formalized vulnerability representation schema that is aimed to support vulnerability assessment during building emergencies focusing on building system failures and/or malfunctioning (e.g., power outage) that might directly impact a facility and its critical contents (e.g., server computers) (Leite et. al 2008; 2009; Leite and Akinci, 2011). The vulnerability assessment approach of this thesis focuses on the disasters/emergencies and secondary hazards instead of building system failures and/or malfunctioning.

The research about vulnerability and vulnerability assessment in the literature also focus on vulnerabilities due to hazardous material releases, their risks, and mitigation approaches. The 1999 Marmara Earthquake in Turkey is a significant case for hazardous material related vulnerability studies since hazardous material releases following this earthquake affected human lives, economy, and environment negatively (Steinberg et. al, 2004; Cruz and Steinberg, 2005). The results of a survey study carried out after the 1999 Marmara Earthquake pointed out that a great majority of the facilities containing hazardous materials experienced hazardous material releases that caused further threats to people, along with further economic losses (Cruz and Steinberg, 2005). There are several other studies in the literature that investigated the occurrence of hazardous material releases, their potential effects, and mitigation approaches following disaster/emergencies (Reitherman 1982, Prugh and Johnson 1989, ABAG 1990, Selingson et. al, 1996, Lindell and Perry 1997). However, a solely concentrated focus on hazardous material releases will not be preferred in this dissertation. Instead, other causes of vulnerabilities will also be reviewed along with hazardous material releases.

More details about the vulnerability assessment approach of this research can be found in Chapter 5.

2.3 Literature Review on Current Emergency Guidance and Navigation Systems and Approaches

In this section, current emergency guidance and navigation systems and approaches in the literature will be reviewed with more emphasis on studies utilizing BIM tools for automation rather than conventional emergency guidance methods with pre-defined emergency plans and direction signs.

The general tendency in the current emergency guidance and navigation systems and approaches depend on storing and using 3D building data, which can be easily obtained from BIM tools (Yuan and Zizhang, 2008; Lee and Zlatanova, 2008; Park and Lee, 2008; Lee, 2007). In addition, the evacuation paths that will be generated by these systems should be accurate and reasonable (Meijers et. al, 2005). Therefore, the data model and database of these systems are also important. For this reason, current systems focus on databases and data models such as BIM tools, Industry Foundation Classes (IFC), GIS systems, etc. Data models are required to gather the building information, generate the graph network elements, run the shortest path algorithms on these networks, generate the evacuation and guidance paths for occupants and first responders, and visualize these paths on 2D or 3D building plans. Databases, on the other hand, are needed to store all this information. The current studies tend to focus on data model and database studies especially during graph network generation. The following sections will introduce the studies utilizing these databases and data models.

2.3.1 BIM Integrated GIS-Based Studies

In an emergency guidance and navigation system, there are several important aspects. The database and data model of an emergency guidance and navigation system are one of these aspects. Yuan and Zizhang (2008) claims that a 3D real-time indoor emergency navigation can only be achieved with complete and updated building geometry data and semantic building information, vulnerability and accessibility information, and alternative guidance approach that can adapt to the changing indoor conditions. For this reason, they suggested utilization of BIM tools that is integrated with 3D-GIS systems in their indoor emergency navigation system. Here, BIM tools will be employed as the data model of the system as these tools can store and supply the geometric and semantic building data separately at the same time. On the other hand, 3D-GIS systems will be the database for generation of the evacuation paths.

Another study suggesting the utilization of BIM tools with GIS systems is Whiting's (2006) study. In this study, Massachusetts Institute of Technology (MIT) Campus is taken as a pilot application area for real-time inter-building and indoor navigation purposes. Shortest path algorithms are integrated with BIM models of the buildings in MIT Campus for navigation purposes. The proposed data model for the navigation system is composed of geometric, topological, and semantic properties of the buildings that are derived from building plans generated in BIM. Geometric properties of buildings are mainly physical properties such as the coordinate values, containment information (i.e. concert hall is in ground floor), building elements, etc. Topological properties involve the adjacency data of the spaces in and between the buildings. Topological properties are important for shortest path algorithms since these algorithms can only work on topological maps of the buildings. In other words, Whiting has used topological properties to create the graph network for shortest path algorithms to perform. Finally, semantic properties involve the properties that cannot be placed under geometric or topological properties such as the purpose of usage of a room, etc. This study is a good example in terms of establishing an indoor navigation system. The proposed data model includes establishment of graph networks in Extensible Markup Language (XML) format, defining and placing the graph network elements (i.e. nodes and edges) on the building plans, and running of Dijkstra's Shortest Path Algortihm on the generated graph networks. However, details about integrating the generated graph networks with BIM models are not given even if how to use graph networks in software models are explained in details. Another drawback of this study is that the navigation approach is not designed for emergency response and disaster management. Thus, the navigation in case of changing conditions of the buildings are not considered in the scope of the study.

2.3.2 Studies on Establishment of Graph Networks on IFC-Extended BIM Files and Integration of Data in IFC Format with the Proposed Emergency Guidance and Navigation Systems

An important study suggesting utilization of Industry Foundation Classes (IFC) extended BIM models for generation of length-weighted graph networks to calculate the shortest paths in distance is proposed by Lee et. al (2008). In this study, it is proposed that the graph network should be composed of space objects (e.g. corridors, rooms, etc.), doors, and vertical transition locations (e.g. elevators, stairs, etc.). For this reason, it is stated that gathering information in IFC format from the BIM models of the buildings is a significant requirement. The important IFC classes needed for the establishment of graph networks are also discussed in the study. These classes are;

- *IfcSpace:* It is stated that this class is important for identifying the building geometry during graph network generation. There are building elements such as walls, columns, etc. that might limit the movements of occupants. When *IfcSpace* class is identified correctly with its geometric properties, these obstacles will also be avoided. Under this circumstance, focusing on space objects and the links of space objects with each other and doors is important during graph network generation.
- *IfcDoor:* It is stated that this class is important for representation of transitions between spaces. In other words, *IfcDoor* class can be used to understand whether a space is connected to another space. If there is an *IfcDoor* link between two spaces, the nodes of these spaces can be connected to each other.
- *IfcRelSpaceBoundary:* This class identifies the boundaries of space objects.
- *IfcStair:* This class is needed to understand the vertical links between spaces.
- *IfcRamp:* Similar to *IfcStair* class, this class is needed to locate the vertical links between spaces.

- *IfcElevator:* Again, this class is needed to locate the vertical links between spaces.
- *IfcWindow:* In extreme cases, this class can be used as an exit or a transition link.

These mentioned classes should be utilized during creation of the graph networks and running the shortest path algorithms in a navigation system. Thus, these IFC classes will also be considered and used for generation of graph networks of the system proposed in this dissertation. However, in this thesis, it is assumed that elevators are non-accessible after a disaster/emergency for safety reasons. Thus, *IfcElevator* class will not be used.

In another study that is utilizing BIM tools for generation of length-weighted graph networks and calculation of shortest evacuation paths, the details of extending BIM data in IFC format is explained (Lee et. al, 2010). Moreover, key points that should be considered during generation of nodes and edges in the graph network are discussed, especially, the cases when adjacent nodes cannot directly connected to each other via straight edges. The study proposes utilization of concave and convex nodes between two adjacent nodes in such cases and gives the details of this procedure. It is also suggested to establish the graph network of a building using the nodes placed at doors (door nodes). This is suggested for (1) obtaining easier linkage between nodes, (2) avoiding adjacent nodes that cannot be connected via straight edges without using extra nodes (concave and convex nodes), and (3) obtaining more simplified graph networks by having lesser number of nodes and edges. The importance of *IfcSpace* class is also mentioned in this study. The findings of this study can be used during graph network generation studies in an emergency guidance and navigation system.

In a study developed to check the circulation codes of buildings via automated systems, graph networks of buildings and shortest path algorithms are utilized (Eastman et. al, 2009). During establishment of the data model and graph networks for this study, spatial relationships between building elements are required. To fulfill this requirement BIM tools are utilized and data from BIM is extended in IFC format. All spaces, walls, doors, stairs, ramps, elevators, and virtual boundaries between spaces (i.e. when two spaces are adjacent but there are no physical boundaries such as walls, etc. between them) are derived and relationships (i.e. adjacency or containment) between these elements are determined by using the IFC extended BIM data. This study also identified the necessary IFC classes to be used in the data model of the system and Figure 2.3 shows these classes with brief explanations. It can be seen that similar classes (*IfcSpace*, *IfcDoor*, *IfcStair*, *IfcRamp*, *IfcRelSpaceBoundary*) are mentioned again to be used in the data model and this gives hints to the researchers during establishing their own data models.

Minimum modeling requirements for circulation checking.

Modeling element	Description
Space	Space names should be defined on the basis of Space naming conventions of GSA BIM Guide.
Security zone	Security zone should be one of "public", "restricted", and "secure". This information can be defined as property definition for each space.
Door	Is part of wall. Door adjacencies to two spaces used for accessibility checking.
Stair	Use of IfcStair and IfcRelContainedInSpatialStructure. A stair should be contained in a space. Stair may have components such as slab (landing) and flight
Ramp	A ramp should be contained in a space like stairs. Ramp may have components such as flight and slab (landing)
Elevator	Currently, elevator objects are defined through space name. For example, "judges elevator", "prisoner elevator".
Wall	There is no special requirement. Just needed for space boundary.

Figure 2.3: IFC classes to be used in the data model of the Circulation Checking System (Eastman et. al, 2009)

BIM tools is also being used in fire simulation studies. Spearpoint (2007) used IFC extended BIM data to obtain the necessary building information during fire simulation studies. The significance of the data that will be obtained from *IfcSpace* and *IfcRelSpaceBoundary* classes in the data model is mentioned again. Besides these classes, *IfcElement*, *IfcBuildingElement*, and *IfcConnectionGeometry* classes are used in the data model of the fire simulation study.

Returning to indoor emergency navigation systems, Lee (2007) suggested a system that aims to (1) localize the first responders in indoor environments by using 3D-GIS systems, (2) calculate and generate the shortest evacuation paths using Dijkstra's Shortest Path Algorithm and determine the accessibility of these paths for use of occupants, and (3) guide the first responders in the indoor environments. The guidance approach of the mentioned study depends on the human traffic in the building during evacuation. The proposed evacuation system does not depend on shortest evacuation paths but instead, depend on minimum evacuation duration. For this reason, human traffic that might occur during evacuation is tried to be tracked and diverted to alternative paths. The classes that are not available in the IFC extended BIM model of the buildings and their relationships are identified (Figure 2.4). This is the most important outcome of the mentioned study. Although IFC extended BIM models of buildings involve various classes holding necessary building data, some external classes might be needed during establishment of the data model. For example, graph network elements (nodes and edges) are not available among the IFC classes. Thus, these classes should be externally created and integrated with the data model. The attributes (properties), methodologies and relationships of the externally created classes should be determined.

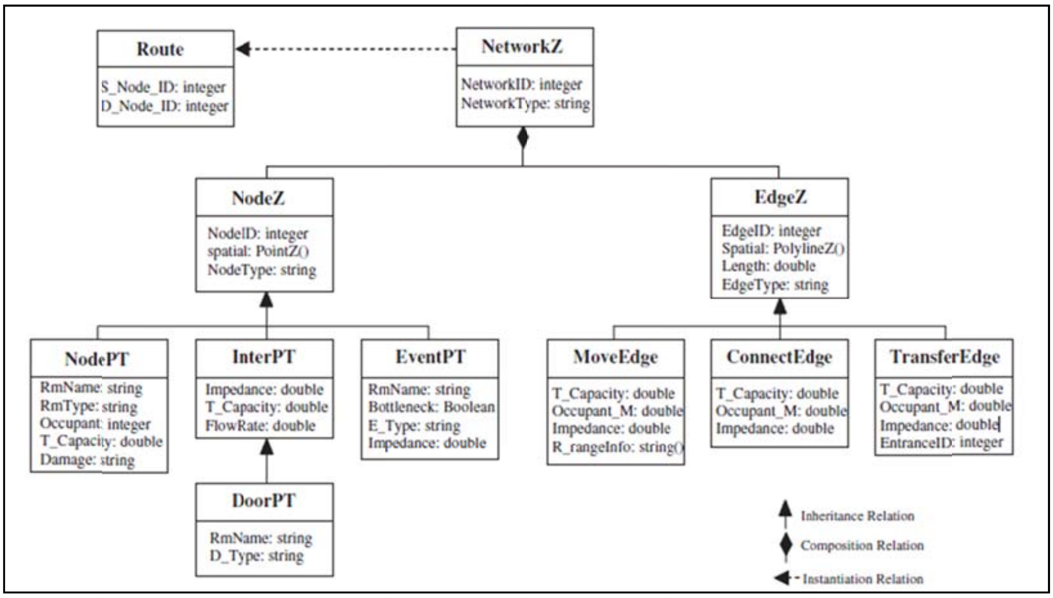

Figure 2.4: The classes and relationships in the data model of Lee (2007) for generation of graph networks

In the light of the findings of Lee (2007) and reviewing these findings, the classes and relationships between these classes can be prepared for the data model of the system proposed in this thesis.

2.3.3 Other Studies

Besides BIM tools, there are other tools that can be utilized in emergency response and guidance systems. One of these tools is Cellular Automata (CA). Park and Lee (2008) proposed a system using CA tools that is capable of defining the space adjacency relations to generate the necessary topological mapping for modeling the indoor environment to achieve emergency guidance and navigation. The aim of the study is to evacuate occupants via personal evacuation paths. Thus, locations of the occupants inside the buildings should be known. For this reason, Radio Frequency Identification

(RFID) technology is used and localization of occupants is achieved although the accuracy of localization is not very dependable.

Integrating localization algorithms with emergency guidance and navigation systems is another research field. Localization algorithms can be used to locate the occupants inside the building and/or to locate the first responders for better guidance of response operations. There are recent studies focusing on localization algorithms in indoor environments (Taneja et. al, 2010a; Taneja et. al, 2010b; Rueppel and Stubbe, 2008). Although the study is not for emergency guidance and navigation, Taneja et.al (2010a) reviewed systems focusing on automated technologies that can be utilized for acquiring field data in construction fields. For this reason, systems depending on RFID tags, GPS tools, indoor localization and tracking technologies, 2D and/or 3D image processing techniques, and sensor monitoring of indoor environments are reviewed and compared with each other. The findings of Taneja's studies about localization and tracking technologies and sensor monitoring of indoor environments can be used for establishing localization algorithms in real-time indoor emergency navigation systems. Similarly, in the emergency guidance and navigation system that will be proposed in this thesis, it will be suggested to monitor the indoor environments by sensors. However, details about integration of sensor data with a BIM-based system are not given in the mentioned study.

Localization studies that focus on emergency response and disaster management are also available in the literature. A BIM-based emergency guidance system is proposed for fire emergencies at Frankfurt Airport (Rueppel and Stuebbe, 2008). The data about the indoor environment will be gathered from systems such as Wireless Local Area Networks (WLAN), ultra wide bands (UWB) radio frequencies, and RFID. Then, these systems will be integrated under a common database and depending on the gathered data, shortest path algorithms will be generated on BIM tools. These shortest paths will be generated for the use of first responders for more effective response operations.

However, the data derived from BIM tools are not in IFC format in this study. Instead, the researchers preferred to use Green Building XML format. Thus, even if there are significant similarities between the mentioned study and this thesis, the mentioned study will have a different data model. In addition, this thesis will not only focus on emergencies due to fire but will have a wider scope in terms of disasters/emergencies.

To sum up the whole literature review chapter; a review on emergency response and disaster management domain, on graph theory and shortest path algorithms, on vulnerability and vulnerability assessment, and on current emergency guidance and navigation systems and approaches are given in details. Now, in the light of all the literature review given in this chapter, the next chapter will be about the requirements of indoor navigation during emergency response and disaster management.

CHAPTER 3

REQUIREMENTS OF INDOOR NAVIGATION DURING EMERGENCY RESPONSE AND DISASTER MANAGEMENT

This chapter presents the studies conducted to determine the requirements of an indoor emergency navigation system during emergency response and disaster management. For this reason, use cases were developed. The purpose of developing the use cases is to describe (1) possible events that may occur in indoor environments following a disaster/emergency, (2) possible triggered threats that may affect indoor environments, (3) flow of events in a building under multiple hazards, (4) behavior of occupants following a disaster/emergency, and (5) working mechanism of emergency navigation algorithms. Based on the developed use cases, the requirement analysis is performed to determine the needs of a real-time indoor emergency guidance and navigation system and common navigation needs. In this study, a real-time indoor emergency guidance and navigation system for buildings under the threat of multi-hazard emergencies is envisioned to be composed of shortest path algorithms to be able to generate evacuation paths and include non-accessible and vulnerable location preventing algorithms. Thus, the determined requirements will be given in three groups: (1) requirements related to shortest path algorithms and graph networks, (2) requirements related to accessibility, and (3) requirements related to prevention of vulnerable locations. Thus, this chapter is divided into four sections. In the first section assumptions and limitations of the use cases will be given. In the second section, the use cases will be introduced. Third section will be composed of requirement analysis of the use cases and the determined requirements will be discussed. The final section is a concluding section for the determination of requirements of indoor navigation during emergency response and disaster management.

3.1 Assumptions and Limitations of Use Cases

Following is the list of assumptions and limitations of use cases:

- An up-to-date data model of buildings (i.e., BIM) that includes information about the building and its content is available.
- An indoor navigation system has been established for the buildings and it generates evacuation routes starting from exit locations of rooms (i.e., doors) and guides occupants through circulation areas in the building (i.e., corridors, stairs).
- Indoor environments of the buildings are monitored by sensors deployed at several predefined locations in the building (e.g., corridors, stairs, and rooms) so that non-accessible and vulnerable locations can be determined.
- There are not any sensors capable of making physical monitoring (i.e. monitoring the collapse of a wall) in room spaces. However, in order to trace the secondary hazards that might occur in the rooms, they will be monitored by chemical sensors (i.e. fire and smoke sensors) that is mandatory to be placed according to fire specifications.
- The impacts of a disaster/emergency are mainly the blockage in indoor environments that prevent occupants from passing through a region and will be examined in two groups: (1) Non-accessible locations (i.e., fully/partially blocked locations) are the ones that are blocked due to the impact of the disaster/emergency and/or secondary hazards. For example, collapse of a wall may block a corridor passage. (2) Vulnerable locations are the ones that contain hazardous materials and threat bearing contents, and have the possibility to cause further injuries and mortalities. They should be avoided during evacuation as

much as possible. For example, post-earthquake fire occurred in a room causes that room to become a vulnerable location as it may cause further damage during evacuation.

- The actors of the use cases are the occupants in the building and the response teams. There are occupants in the building during disaster/emergency in every case.
- Disasters/emergencies trigger secondary hazards and cause the affected building to be under multi-hazard emergencies.
- Elevators will be assumed as non-accessible after the disaster/emergency.
- It is assumed that evacuation paths are offered to the use of occupants via illuminated indicators.
- Occupants are assumed to be capable of following the illuminated indicators and follow the evacuation paths generated for them.
- Regardless of the familiarity of an occupant with the building, it is assumed that every occupant follows the evacuation paths generated for him/her.
- Response teams are assumed to have access to the navigation system via portable computers, hand-held computers, etc.

3.2 Use Cases

Developed use case scenarios will be given in this section.

3.2.1 Use Case Scenario #1

This use case is given to demonstrate the evacuation plan of a complex building following a disaster/emergency.

Flow of Events:

- An earthquake has been reported and although majority of the building is not damaged, some damage has been detected.

- Shortest evacuation paths have been calculated and generated.
- Occupants can follow these paths to reach to safer zones.
- There are two possible exit locations out of the floor in consideration. These are Service Entrance and Canteen Exit (Figure 3.1).
- M1 and M3 stairs have been damaged and they cannot link the floor with other floors.
- Post-earthquake fire has been reported in Room 7. The fire and the smoke due to the fire are rapidly spreading through the corridor.
- Due to the reported fire, occupants located on the north and east sides of the building relative to Room 7, cannot use the corridor that links the Service Entrance with the rest of the building.
- Consequently, the navigation algorithm needs to avoid this vulnerable location and generate the evacuation paths accordingly.
- The current status of the indoor environment in terms of accessibility and vulnerability can be seen in Figure 3.1. This figure also involves the shortest evacuation paths generated by the system. Details about the generation of these paths will be given in the scenario.

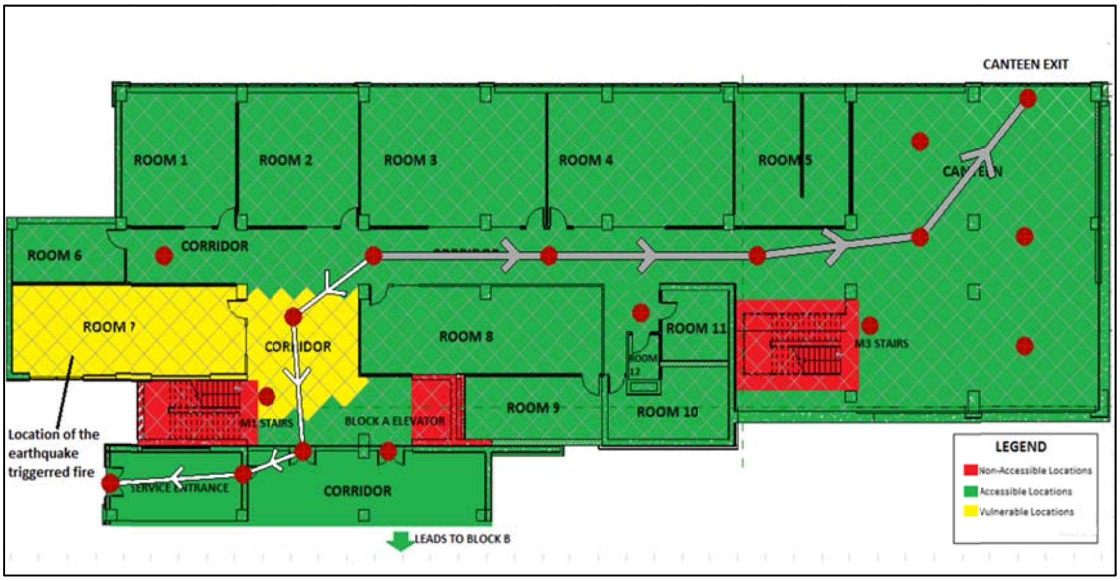

Figure 3.1: Building plan of the ground floor showing accessible and vulnearble locations following the disaster and two alternative evacuation paths generated by the system (Use Case #1)

Scenario:

An earthquake affects the building floor in Figure 3.1. Sensors in the building identifies that the earthquake triggered a fire in Room 7 and caused smoke dispersal through the corridor. Due to safety concerns, elevator is out of order. There are two exit locations from the floor, which are the service entrance and the canteen exit.

An occupant encounters the earthquake and the consequent fire in front of Room 2 and tries to leave the building afterwards. However, the occupant is not familiar with the building and thus, he/she needs guidance for evacuation. At this point, navigation system computes the shortest evacuation path from his/her current location and generates the shortest path shown on Figure 3.1 with white arrows. To avoid the vulnerable locations created by the fire, system generates a second path shown with grey arrows, which is longer but does not pass through vulnerable locations. The occupant follows this new path to leave the building safely.

3.2.2 Use Case Scenario #2

This use case is developed to demonstrate the evacuation plan of a complex building when all possible exit locations are completely blocked following a disaster/emergency.

Flow of Events:

- The building is damaged by an earthquake.
- Shortest evacuation paths have been calculated and generated.
- Occupants can follow these paths to reach to safer zones.
- However, occupants have been blocked in the building and they cannot leave the building with their own efforts. Instead, response teams need to start the response operations to rescue them.
- The only exit from the ground floor of the building is the Main Exit in Block B and due to the damage caused by the earthquake; it cannot be used for evacuation (Figure 3.2).
- M1, M2, and M3 stairs have been completely collapsed and upper floors cannot be accessed. In other words, there are no possible exits from the ground floor.
- Post-earthquake fires have been reported in Room 14, 16, 20, and 23. These fires and the smoke due to these fires are rapidly spreading.
- The current status of the indoor environment in terms of accessibility and vulnerability can be seen in Figure 3.2.

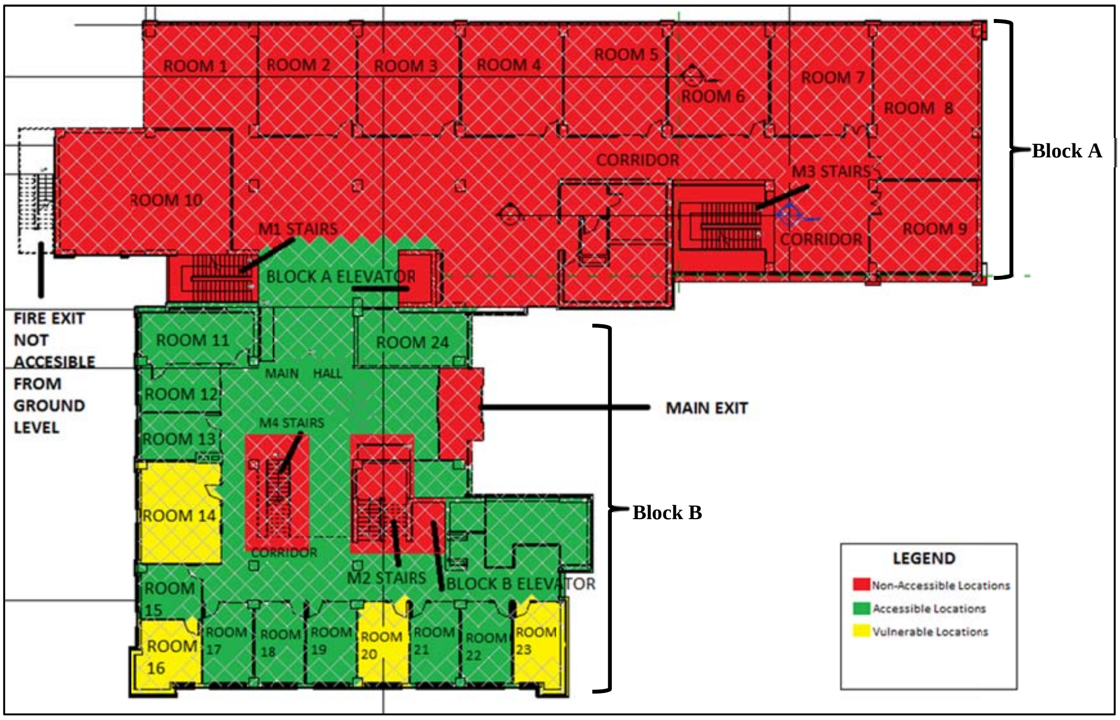

Figure 3.2: Building plan of the ground floor showing accessible and vulnearble locations following the disaster (Use Case #2)

Scenario:

All possible exit locations are completely blocked due to an earthquake. The occupants are spread in the building searching for an exit. Meanwhile, an explosive content creates a vulnerable location in the building. Some occupants are close to that location and unaware of the risk since they lack the vulnerability information. The response team is having difficulties with the response operations since the occupants are apart from each other. At this point, the indoor emergency navigation tool generates evacuation paths that lead all occupants to a relatively safer location (i.e., shelter), thus protecting them from the risks and dangers in the building. Occupants follow these paths to reach to the shelter in the building. The response team reaches the shelter and rescues all occupants immediately before the explosive content causes further damages.

3.2.3 Use Case Scenario #3

Use case #3 is developed to demonstrate the evacuation plan of a complex building when exit locations are partially blocked following a disaster/emergency.

Flow of Events:

- Although majority of the building is not damaged by the earthquake, an earthquake have affected the building.
- Shortest evacuation paths have been calculated and generated.
- Occupants can follow these paths to reach to safer zones.
- There are two possible exit locations out of the floor in consideration. These are the service entrance and the canteen exit (Figure 3.3).
- Since both exit locations are partially blocked, the navigation system will calculate the shortest evacuation path according to the degree of blockage of the exits. In other words, the navigation algorithm will select the safer alternative instead of the shortest one.
- M1 and M3 stairs have been damaged and they cannot link the floor with other floors.
- According to the sensor data, the Service Entrance is 50% blocked due to the collapse of a nearby column.
- According to the sensor data, the Canteen Exit is 75% blocked due to the disturbance generated by the earthquake.
- The navigation system will now run the shortest path algorithm with the safety criteria. The system will check the degree of blockage of both exits and select the safer one even if the evacuation path gets longer.

- The current status of the indoor environment in terms of accessibility and vulnerability can be seen in Figure 3.3.

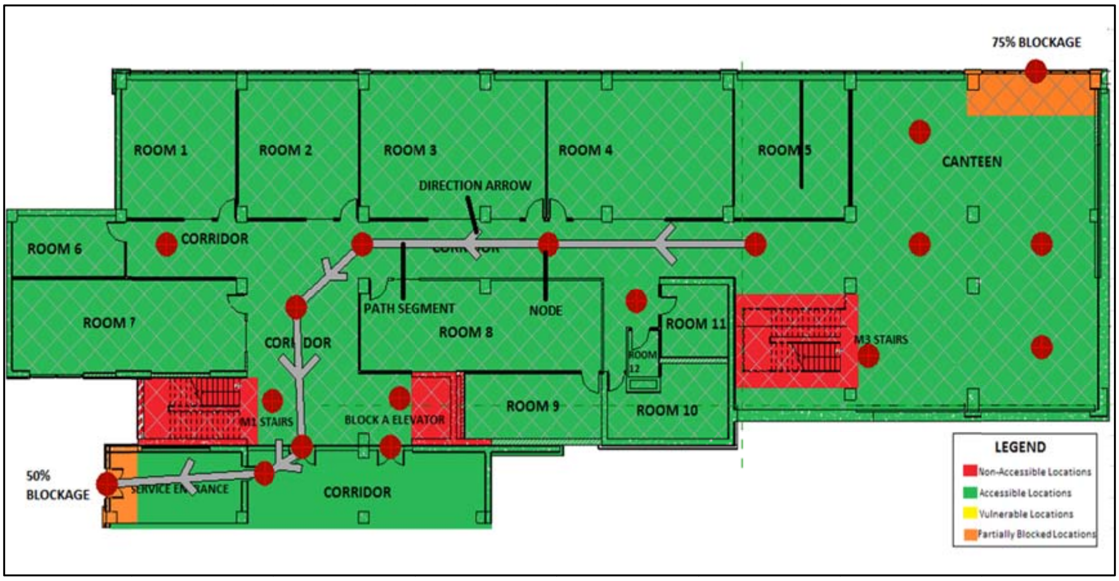

Figure 3.3: Building plan of the ground floor showing accessible locations following the disaster and the evacuation path generated (Use Case #3)

Scenario:

Both of the two possible exits of the building (the service entrance and the canteen exit) are partially blocked after an emergency. An occupant close to Room 5 begins to search for an exit. Meanwhile, the navigation system discovers that the exit that is closer (the canteen exit) has a higher blockage ratio than the further exit (the service entrance). Therefore, the system generates an evacuation path towards the further exit with the lower blockage ratio.

3.2.4 Use Case Scenario #4

Use case #4 is developed to demonstrate the evacuation plan of a complex building when vulnerable locations cannot be avoided.

Flow of Events:

- An earthquake has affected the building but majority of the building is not damaged seriously.
- Shortest evacuation paths have been calculated and generated.
- Occupants can follow these paths to reach to safer zones.
- There are two possible exit locations out of the floor in consideration. These are the service entrance and the canteen exit (Figure 3.4).
- Since evacuation paths leading to exit locations are passing through vulnerable locations, the navigation system will perform iterations to select the less risky path for guidance. These iterations will be based on the damaging potential of the secondary hazards causing these location to become vulnerable.
- M1 and M3 stairs have been damaged and they cannot link the floor with other floors.
- A fire is reported in Room 7 due to the damage in the electricity system and the fire is spreading towards the corridor. The smoke from the fire is being aspirated to the elevator opening.
- Room 11 is used as chemistry laboratory. Thus, the laboratory contains various hazardous contents that have high risk of explosion.
- The navigation system will now run the shortest path algorithm with a vulnerability assessment approach. The system will check the risk levels of both vulnerable locations and select the safer one even if the evacuation path gets longer.

- The current status of the indoor environment in terms of accessibility and vulnerability can be seen in Figure 3.4.

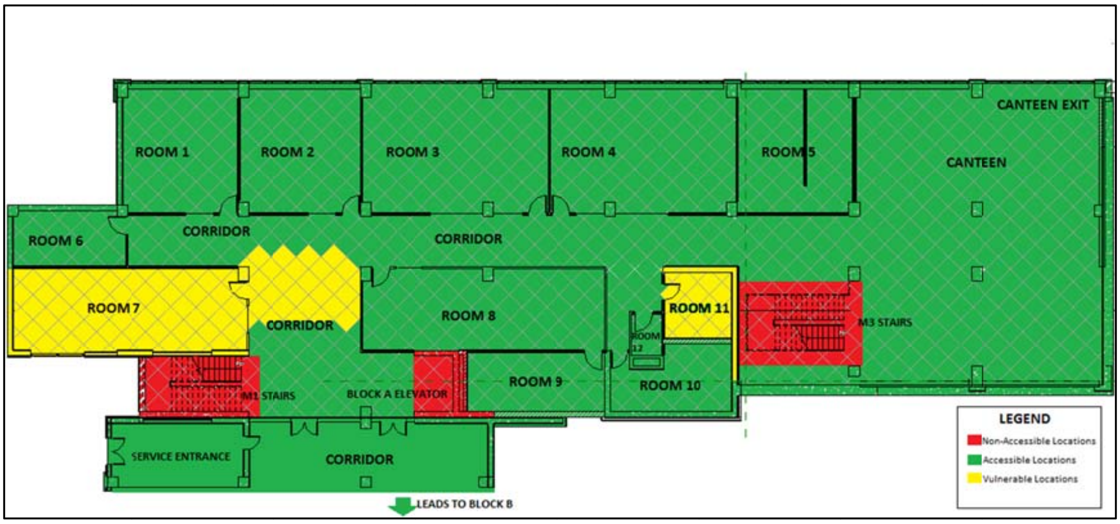

Figure 3.4: Building plan of the ground floor showing accessible and vulnerable locations following the disaster (Use Case #4)

Scenario:

An earthquake triggers consequent threats that affect the indoor environment (fire and possibility of explosion) and evacuation paths cannot avoid these vulnerable locations. Evacuation path of an individual has two alternatives: (1) guiding the individual through a fire, (2) going through a chemistry laboratory with high possibility of explosion. In this case, navigation algorithm performs guidance based on the predefined vulnerability risk ranking, which prioritizes all possible hazardous contents and secondary hazards according to the risks possessed. The risk is the possibility of hazardous contents and secondary hazards to cause injuries and mortalities. This ranking need to be prepared according to the literature review and interviews with response teams (e.g., fire fighters) and the results will be integrated with the navigation algorithm. In this scenario, the system identifies that a vulnerable location due to a fire is less preferable than a vulnerable location caused by explosion possibility. Therefore, the evacuation path that guides the individual through explosive storage area is selected.

3.3 Requirement Analysis

The requirement analysis is performed to determine the needs of an indoor navigation system and, common navigation needs based on the use cases developed. The determined requirements are given in three groups: (1) requirements related to shortest path algorithms and graph networks, (2) requirements related to accessibility, and (3) requirements related to prevention of vulnerable locations.

3.3.1 Requirements Related To Shortest Path Algorithms and Graph Networks

Shortest path algorithms and graph networks are significant elements of an emergency guidance and navigation system. Therefore, requirements related to shortest path algorithms and graph networks are also very important. These requirements, which are derived from the identified use cases, are given in this section.

3.3.1.1 Requirement #1

The first requirement is about the establishment of graph networks that shortest path algorithms will work on. Graph networks have two main elements; nodes and edges. Edges cover the distance between adjacent nodes and connect them. However, the distance between adjacent nodes should be determined and standardized. Thus, a maximum and a minimum distance value should be set for the distance between two adjacent nodes. These distances should be determined according to the coverage areas and other limitations of the sensors that are used for monitoring the indoor environment.

Reasons:

The distance between two adjacent nodes should not be very large. As the area to be monitored by the sensors increases, blockages or vulnerabilities cannot be detected effectively. The main reason of this is the sensor coverage areas. Sensors have a maximum range and beyond that limit, they cannot acquire data. In addition, the accuracy of the acquired data decreases as the area to be covered by the sensor increases. This leads to a decrease in the accuracy and safety margins of the evacuation paths.

The distance between two adjacent nodes cannot be very small either. As the distance between two adjacent nodes decrease, the number of iterations needed for calculating the shortest path increases since the number of nodes and edges in the area to be monitored increases.

All spaces will be represented by one node in the graph network and each node will be monitored by sensor(s) to detect any blockage and/or vulnerability in the space. These sensors need to be connected to sensor mainboards so that they can send the required indoor environment data to the navigation system. When the distance between two adjacent nodes increases, the area to be monitored by the sensors increases. Consequently, the number of sensors required to gather accurate and complete data from that space increases. However, sensor mainboards have a maximum sensor holding capacity depending on the type of the sensors and mainboard. Thus, sensor mainboard limitation is another aspect that needs to be considered during determining the distance between two adjacent nodes in the graph network.

Considering all these, maximum and minimum distance values between adjacent nodes should be determined considering the sensor coverage areas and sensor mainboard limitations.

Suggested Solution:

The number of sensors that can be attached to a sensor mainboard and the coverage area of a sensor are limited. Thus, the building should be divided into building sub-parts to reduce the areas. Sub-parts cannot be larger than sensor coverage areas since sensors cannot retrieve data beyond their coverage areas. The sub-parts can be created according to the building structure. For example, a sub-part area (space) can consist of 4 columns, 2 or more structural or non-structural bounding walls, a slab, a ceiling or a suspended ceiling, and other non-structural units (e.g., cupboards). With this solution, the building will be divided into sub-parts such as corridor parts, lobby parts, etc. An example building sub-part can be seen in Figure 3.5. For each sub-part that is not larger than the sensor coverage areas, sensors will be attached to one mainboard located in that building sub-part.

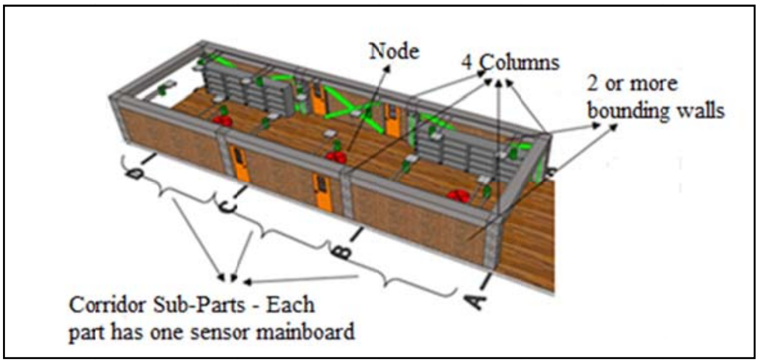

Figure 3.5: An example building sub-part (example to corridor sub-parts)

There can be cases when it is not possible to define building sub-parts and place nodes within the limits of sensor mainboards and coverage areas. In such cases, the distance between two adjacent nodes will be taken as 5 meters. This distance can be taken as an optimum value to obtain accurate sensor measurements. There are two aspects that are considered during determination of the 5 meters value, which are (1) the appropriate distance for accurate sensor measurements, and (2) sensor efficiency. Firstly, sensor measurements are not reliable below a certain distance value (i.e. 1 meter). On the other hand, the coverage areas of sensors are not very large either. Thus, it is decided that the distance between two adjacent nodes should be smaller than 6,4 meters for obtaining better sensor data. This 6,4 meters value is the coverage area for the ultrasonic distance measurement sensor that is planned to be used for monitoring the collapsed building elements such as walls in the real-time indoor emergency guidance and navigation system. Secondly, sensor efficiency should be considered. Sensor efficiency can be explained as monitoring the maximum number of spaces (nodes) with the minimum number of sensors. Considering these two aspects, it can be claimed that taking the distance between two adjacent nodes as 5 meters when building sub-parts cannot be generated is a reasonable assumption.

3.3.1.2 Requirement #2

The second requirement states that alternative evacuation paths should also be calculated and ready to be used in need.

Reason:

During the evacuation process, there can be events that cannot be predicted and/or monitored by the real-time indoor emergency guidance and navigation system. For example, a blocked location may not be sensed by the sensor network and can be classified as accessible even if it is not, or a vulnerable location may be classified as safe while it is not. Such an event may hamper the usability of the generated evacuation path.

Suggested Solution:

Alternative evacuation paths should also be calculated and must be readily available for use in need.

3.3.1.3 Requirement #3

Third requirement related to shortest path algorithms and graph networks states that each floor should have its own evacuation routes.

Reason:

Organization of the evacuation and adapting to changes in the indoor environment are complex activities for the emergency guidance and navigation system. Changes in the accessibility and vulnerability conditions of the indoor environments will also alter the evacuation paths. In case of such changes on a building floor, it is an easier procedure for the navigation algorithm to calculate a new evacuation path only for the floor where conditions have changed, instead of making calculations for the whole building.

Suggested Solution:

To decrease this complexity, each floor should have its own evacuation routes. For example, a person at the second floor during a disaster/emergency should be guided to the shortest path that leads him/her to the stairs to the first floor. After arriving at the first floor, the navigation for this person should start from the stairs on the first floor and should be calculated separately for the first floor.

3.3.2 Requirements Related To Accessibility

Accessibility in the indoor environments is another very important aspect during evacuation and emergency response. Non-accessible locations are blocked locations following a disaster/emergency or a secondary hazard. Along with vulnerable locations, non-accessible locations are the main determinants of evacuation path generation. Evacuation paths will be calculated and generated according to the accessibility information that is obtained from the sensor measurements. In addition, responders will be notified about the accessible and non-accessible locations in the building so that they can organize their response operations accordingly. Therefore, the requirements of a real-time indoor emergency guidance and navigation system related to accessibility should be determined from the identified use cases. The determined requirements related to accessibility are given in this section.

3.3.2.1 Requirement #4

The fourth requirement is a general requirement that suggests that the navigation algorithm should avoid non-accessible locations and exits during determination of the evacuation paths.

Reason:

The navigation algorithm should not guide the occupants or response teams to non-accessible locations and exits to ensure the evacuation of the building following a disaster/emergency.

Suggested Solution:

Nodes of non-accessible locations and exits should be defined as "closed nodes" in the navigation algorithm to prevent guidance to such locations.

3.3.2.2 Requirement #5

The blockage percentage of a space (building sub-part) or an exit under consideration should be determined.

Reason:

Buildings are tend to be damaged following a disaster/emergency. However, the damaged location may not become completely non-accessible and may still be used for evacuation. Such an event can be detected by sensors.

Suggested Solution:

The blockage percentage of an area can be determined by sensors. By using the data coming from different sensors and interpreting them with some approaches (i.e. using decision trees), the real-time indoor emergency guidance and navigation system can determine the blockage percentage of a space or an exit. Blockage percentage is, in other words, the degree of accessibility of a location in the building. For example, an exit location may be only 10% blocked which may indicate that the exit can still be used for evacuation. By assigning a blockage percentage to that exit, improved evacuation paths can be generated.

3.3.2.3 Requirement #6

The final requirement related to accessibility states that when all exit locations are partially/fully blocked, a guidance approach generating multiple evacuation path alternatives depending on the blockage percentages of the exit locations should be available. Such an approach should be developed and integrated to the system.

Reason:

When there is no/partial exit out of a building, occupants tend to panic and spread around the building to find their own way out. Such an event may increase the response duration of rescue teams since they need to locate all the occupants in the building during response operations.

Suggested Solution:

When all the exits are completely blocked, all occupants should be guided to a safe location (e.g., shelter) until the response teams arrive.

If all the exits are partially blocked, the navigation algorithm should be able to select the path with lower blockage percentage even if the evacuation path gets longer. However, guidance to a distant exit with a relatively low blockage percentage (e.g., lower than 50%) would be unnecessary since evacuation would probably be possible from an exit that has blockage percentage less than 50%.

3.3.3 Requirements Related To Prevention of Vulnerable Locations

Vulnerable locations are the last aspect that should be considered during evacuation and emergency response. Vulnerable locations contain hazardous and threat bearing contents, and possess the risk of causing further injuries and mortalities due to the disturbance generated by a disaster/emergency. Both occupants and responders should be warned about the vulnerabilities in the indoor environments. Vulnerable locations should be taken into consideration by means of appropriate avoiding algorithms during evacuation path generation. Responders should be informed about the vulnerabilities to support their decision-making and planning processes during response operations. Therefore, the requirements of a real-time indoor emergency guidance and navigation system related to prevention of vulnerable locations should be determined from the identified use cases. The mentioned requirements are given in this section.

3.3.3.1 Requirement #7

The first requirement related to prevention of vulnerable locations is that the navigation algorithm should be able to avoid vulnerable locations and consider the risk levels of these locations in extreme cases; for example, when all possible evacuation paths pass through vulnerable locations.

Reason:

Vulnerable locations may cause further injuries and mortalities during evacuation. The navigation algorithm should be able to avoid vulnerable locations due to safety reasons. Similarly, the algorithms should also be able to select the safest vulnerable location according to the potential risk levels in extreme cases where there are multiple vulnerable locations that cannot be avoided. For example, the navigation algorithm should be able to decide which path is safer to use when there is a vulnerable location due to a fire and a vulnerable location due to a possibility of explosion.

Suggested Solution:

A method should be integrated with the navigation algorithm to avoid evacuation through vulnerable locations and the risk levels of vulnerable locations should be predefined and prioritized. By increasing the cost (i.e., distance value) of an edge between two adjacent nodes by a risk value, a vulnerable location prevention mechanism can be integrated with the navigation algorithm.

3.3.3.2 Requirement #8

The last requirement states that when vulnerability levels or vulnerable locations of indoor environment changes, the navigation algorithm should adapt the evacuation paths to the changes accordingly.

Reason:

During a disaster/emergency situation, a building’s indoor environment can change rapidly and a blockage/vulnerability may occur. For example, a fire can spread to larger areas or a location with possibility of explosion may explode and these conditions will be sensed.

Suggested Solution:

The navigation algorithm should be able to regenerate the evacuation paths according to the up-to-date data under changing indoor environment.

3.4 Summary of the Chapter

There is a need for a navigation approach to be used during and after disasters/emergencies by occupants for achieving more effective evacuation process and by first responders for achieving more effective response operations. This need is even more significant when the architectural complexity of the buildings and possible secondary hazards are considered.

The first step in the establishment of such a system or approach is determining the requirements. For this reason, multiple use cases related to disasters/emergencies are developed for complex buildings. Afterwards, these use cases are identified and examined to determine the requirements by conducting requirements analysis. The determined requirements have been grouped under three main items; (1) related to shortest path algorithms and graph networks, (2) related to accessibility, and (3) related to prevention of vulnerable locations. Some of the key requirements provided in this study can be listed as determining the blockage percentages, using methods for alternative evacuation path generation depending on the blockage percentages and performing vulnerability risk ranking to select the safest evacuation alternative.

The results of the requirement analysis can be used for establishing a real-time indoor emergency guidance and navigation system and/or approach.

CHAPTER 4

REVIEW, COMPARISON, AND EVALUATION OF THE SHORTEST PATH ALGORITHMS FROM AN EMERGENCY RESPONSE AND DISASTER MANAGAMENT POINT OF VIEW

This chapter presents the studies for selection of the shortest path algorithm to be utilized in the real-time indoor emergency guidance and navigation system for buildings under the threat of multi-hazard emergencies. Indoor emergency guidance studies aims to guide the occupants to safer zones during and after disasters/emergencies by generating evacuation paths that avoid non-accessible and vulnerable locations to decrease the harmful effects of secondary hazards. To achieve this, shortest path algorithms are being used in indoor emergency guidance and navigation systems. Several different shortest path algorithms that have different performances, limitations, and capabilities are available in the literature. These differences are due to the purpose of utilization of the algorithms. In other words, different shortest path algorithms serve for different purposes. Thus, a shortest path algorithm should be selected for utilization in the navigation system. For this reason, similar research on indoor emergency guidance and navigation has been examined and the most commonly preferred shortest path algorithms in the literature have been identified. Then, the identified algorithms have been further examined with an emergency response and disaster management point of view. For this reason, several criteria have been set related to the performance and capabilities of the algorithms. These pre-defined criteria have been determined considering the requirements of the real-time indoor emergency guidance and navigation studies that are determined in the previous chapter. According to the findings of this examination, identified shortest path algorithms have been compared with each other and their performance and capabilities have been evaluated. Finally, an algorithm is selected to be utilized in the system that will be proposed in this thesis.

This chapter is divided into three sections. The first section will be an introductory section that gives brief information about the most commonly preferred shortest path algorithms, their properties, performances, and capabilities. In the second section, the evaluation criteria of the shortest path algorithms will be given. At the end of this section, these algorithms will be compared with each other. The final section is a concluding section explaining the selection of the shortest path algorithm that will be utilized in the system that will be proposed in this thesis.

4.1 Review of the Shortest Path Algorithms

Computing shortest paths in networks is an important task and choosing the most appropriate algorithm among numerous shortest path algorithms is a significant activity (Zhan and Noon, 1998). Shortest path problems are basic problems in network analysis, especially for optimization purposes (Cherkassky et. al, 1993). Calculation of shortest paths is a requirement for many applications related to transportation (navigation) (Golden, 1976).

In this dissertation, guidance of occupants will be achieved by integrating the shortest path algorithms with the data derived from BIM model of the buildings. For this reason, depending on the building related data (i.e. floor plans, location of building elements) derived from BIM, graph networks of the buildings will be prepared and a shortest path algorithm will be run on these graph networks to calculate and generate the shortest evacuation paths. Thus, a shortest path algorithm should be decided for utilization in the navigation system.

Although shortest path algorithms are similar in theory, depending on the purpose of utilization, there are differences in their performances and capabilities. At this point, the most commonly used shortest path algorithms in the literature will be identified with an emergency response and disaster management point of view. The identified shortest path algorithms are (1) Prim's Algorithm, (2) Dijkstra's Algorithm, (3) Bellman-Ford Algorithm, and (4) A* Algorithms. Properties, working mechanisms, and limitations of the identified algorithms will be discussed in the rest of this section.

4.1.1 Prim's Algorithm

Prim's Algorithm is a shortest path algorithm that performs on a weighted and connected graph network. This algorithm aims to calculate the minimum spanning tree rather than calculating the shortest path between an origin and a target point. A tree is a loopless connected graph network and there is only one edge between two adjacent nodes in a tree. Minimum spanning tree is the tree that connects all the nodes of a graph network from the shortest way (the path that has the minimum cost). The main purpose of the Prim's Algorithm is to find the minimum spanning tree, not to find the shortest path. For this reason, the algorithm stores the edge with the minimum cost and selects the next node according to the cost of the possible edges. This process repeats itself until all nodes of the graph network are connected to each other (Marcus, 2008; Gross and Yellen, 2006; Cormen et. al, 2009).

An example to demonstrate the working mechanism of the Prim's Algorithm is given in Appendix B. In that example, a small-scaled graph network that is composed of 5 nodes and 8 edges is given and the calculation methodology of the algorithm for determination of the minimum spanning tree is explained.

Park and Lee (2008) preferred using Prim's Algorithm in a system, which depends on Cellular Automata, that is capable of defining the space neighborhood relations to perform necessary topological analysis for modeling the indoor environment during emergencies. In other words, relations, properties, and effects on each other of neighboring spaces are defined so that, the indoor environment can be modeled following a disaster/emergency. In addition, occupants are planned to be evacuated via personal evacuation paths that will be generated for every individual. To achieve this, RFID technology is used in determination of the locations of the occupants inside the building. However, the accuracy of localization is a significant drawback in the system. Returning to the considerations about Prim's Algorithm, the algorithm has a major drawback compared to Dijkstra's Algorithm. This drawback will be explained in the next section while discussing the Dijkstra's Algorithm.

4.1.2 Dijkstra's Shortest Path Algorithm

Dijkstra's Shortest Path Algorithm, which is proposed by Edgar Dijkstra in 1959, is the most popular and for most cases, the best solution giving shortest path algorithm (Karaş, 2007). There are various versions of Dijkstra's Algorithm available in the literature with small variations such as "Basic Dijkstra's Algorithm", "Dijkstra Naive Implementation", and "Dijkstra Fibonacci Heap". The basic principles of these various algorithms are the same. The differences are in the performance of the algorithms. These differences are as small as in milliseconds. In other words, the only difference between various versions of the Dijkstra's Algorithm can be realized in milliseconds while obtaining the solution (Zhan and Noon, 1998). The timesaving in milliseconds is generally required for the massive computer programs. Although this algorithm will be used after disasters/emergencies to generate evacuation paths and time is very critical, timesaving in milliseconds will not give a significant contribution in this study. Thus, application of the general principles of Dijkstra's Algorithm will be sufficient for this study.

The working mechanism of Dijkstra's Algorithm is very similar to Prim's Algorithm. Both algorithms calculate the minimum spanning tree in the graph network to obtain the shortest paths. Still, there are differences between these two algorithms. Prim's

Algorithm calculates the shortest path according to the minimum edge cost between the current node and its adjacent nodes. On the other hand, Dijkstra's Algorithm try to keep the total edge cost at minimum value (Cormen et. al, 2009). In other saying, Dijkstra's Algorithm finds the shortest paths and minimum spanning tree according to the total distance taken from the origin point. Prim's Algorithm only stores the edge cost between the current node and its adjacent nodes. Thus, previous iterations are not stored. Calculations are done according to the node the algorithm is currently on. This phenomenon helps Dijkstra's Algorithm to give better results compared to Prim's Algorithm.

Despite the mentioned advantages, Dijkstra's Algorithm also has some drawbacks. When there are directed edges in the graph network, the performance of the Dijkstra's Algorithm is negatively affected. Directed edges limit the selection options of the algorithm, which affects the performance of the algorithm negatively. Another drawback occurs when there are edges with negative costs. The algorithm does not give consistent results when there are edges with negative costs in the graph network (Marcus, 2008). However, this problem is not significant for this study. The edge costs will be in terms of distance and consequently, there will not be any edges with negative costs.

The similarity of the working mechanisms of Prim's and Dijkstra's Algorithms are stated earlier. Thus, the example given to demonstrate the working mechanism of the Prim's Algorithm in Appendix B also applies for demonstrating the working mechanism of the Dijkstra's Algorithm. Therefore, the example given in Appendix B is also valid for understanding the working mechanism of the Dijkstra's Algorithm.

When the studies in the literature are reviewed, it can be seen that the most commonly preferred shortest path algorithm is the Dijkstra's Algorithm. Ivin et. al (2008), Karaş (2007), Lee (2007), and Richter and Klippel (2005) utilized Dijkstra's Algorithm in their studies about navigation systems based on 3D GIS. Yuan and Zizhang (2008) also preferred to use Dijkstra's Algorithm in their study that enables 3D indoor navigation by integrating navigation systems with BIM tools.

4.1.3 Bellman-Ford Algorithm

Bellman-Ford Algorithm is developed to recover the drawback of the Dijkstra's Algorithm in the presence of edges with negative costs. Bellman-Ford Algorithm and Dijkstra's Algorithm can said to be the same except that Bellman-Ford Algorithm can give accurate results with negative costs. However, the edge costs will be in terms of distance and cannot have negative values. Therefore, it can be said that there is no need to prefer Bellman-Ford Algorithm to Dijkstra's Algorithm for this study.

4.1.4 A* Algorithms

A* Algorithms are one of the most popular algorithms used for path finding. Compared to other mentioned algorithms, A* Algorithms have the following advantages (Amit, 2010):

- Capable of finding the shortest paths on larger graph networks (on larger areas).
- Can generate more flexible paths (easy to regenerate when the conditions change)
- Have better obstacle prevention mechanism. (considering the blockages that may occur in indoor environments following a disaster/emergency, this property is very important)
- Solution mechanism depends on heuristic methods.

A* Algorithms are generally preferred in gaming industry and navigation in virtual environments. Although it is popular in virtual environments, A* Algorithms are not preferred as much as Dijkstra's Algorithm in real life navigation systems since creation of the graph network for the A* Algorithms is a very troublesome process. For this reason, programmers do not prefer to use A* Algorithms in real life navigation systems

(Amit, 2010). Hence, there are not many studies in the literature utilizing A* Algorithms for navigation purposes. However, the flexibility and obstacle prevention properties can be advantageous during generation of evacuation paths following disasters/emergencies since non-accessible and vulnerable locations can be easily avoided.

Use of heuristic methods, provided that the predicted values are accurate, makes A* Algorithm perform faster than other shortest path algorithms. Besides knowing the total minimum edge cost used in the calculations of Dijkstra's Algorithm, if the location of the target point is also known and the distance between the origin and the target locations is predicted accurately, A* Algorithm will generate the shortest path in the fastest manner (Lester 2005; Amit, 2010). However, contributions, as small as milliseconds, are not very significant in this study. Another issue is that the predictions made in heuristic methods should be precise. If the predicted distance value is larger than the real value, the algorithm will not be able to generate consistent results and might generate paths that are not really the shortest (Lester 2005; Amit, 2010). To understand the concept explained in this paragraph, one might need to know the working mechanism of the A* Algorithms. For this reason, grounding on the studies of Lester (2005) and Amit (2010), the working mechanism of the A* Algorithms is explained on an example in Appendix C. In addition, in Appendix D, an example A* Algorithm application in 2D environment during emergency response and disaster management is given. In this application, the evacuation paths generated by using the A* Algorithms can be seen and the changes in the evacuation paths after the disaster/emergency (flexibility and obstacle prevention mechanisms of the algorithm) can be observed.

4.2 Comparison and Evaluation of the Shortest Path Algorithms

There are numerous studies about the performances of shortest path algorithms (Glover et. al, 1985; Gallo and Pallottino, 1988; Cherkassky et. al, 1993; Zhan and Noon, 1998). However, it is difficult to claim one shortest path algorithm being superior to others

(Zhan and Noon, 1998). The studies comparing the performances of shortest path algorithms cannot claim that their findings are applicable for all kinds of shortest path problems. This situation will also apply for the shortest path algorithm selection that will be made at the end of this chapter.

One of the most comprehensive evaluations of different shortest path algorithms is performed by Cherkassky et. al (1993). This study is a milestone in studies about shortest path algorithm evaluation. In that study, 17 different algorithms have been evaluated and their performances are compared with each other. The performance of algorithms is determined according to the solution duration and accuracy. Although it is stated that the findings of the study can vary and cannot be applied to all shortest path problems, the findings pointed out that Dijkstra's Algorithm is the best performing shortest path algorithm on graph networks that does not have any edges with negative costs. Zhan and Noon (1998) have also evaluated 15 of the algorithms evaluated by Cherkassky et. al (1993) in real road networks. Their findings have also suggested utilization of Dijkstra's Algorithm for calculation of shortest paths in real road networks. On the contrary, there is limited number of studies selecting other algorithms than Dijkstra's. For example, Golden (1976) claims that under certain circumstances Bellman-Ford Algorithm is better than Dijkstra's Algorithm. Therefore, considering the uniqueness of the shortest path problem in this thesis, evaluation criteria should be determined and an evaluation should be conducted. For this reason, six evaluation criteria have been determined. These criteria and the reason of determining such criterion will be discussed in the next section.

4.2.1 Determination of Shortest Path Algorithm Evaluation Criteria

The shortest path problem faced during emergency response and disaster management activities in buildings is a unique problem. Determination of the shortest evacuation paths according to the graph network of the building may require different approaches than determination of the shortest path in a road network. For this reason, considering the requirements of an indoor emergency guidance and navigation system, six criteria have been determined to be used during evaluation of the performance of the shortest path algorithm. Some of these criteria are obtained from the previous evaluation studies in the literature while some of them are unique criteria determined only for this study. These criteria are as follows:

- **Solution Duration (Speed):** Majority of the studies in the literature evaluated and compared the shortest path algorithms according to their problem solving durations (Glover et. al, 1985; Gallo and Pallottino, 1988; Cherkassky et. al, 1993; Zhan and Noon, 1998). Considering time is critical during evacuation of occupants and response operations, solution duration can be set as a criterion for shortest path algorithm selection.
- **Obstacle Prevention:** As discussed during review of the most commonly preferred shortest path algorithms, some algorithms are superior to others in obstacle prevention. This is a significant property since there may be obstacles (blockages and vulnerable locations) in indoor environments following disasters/emergencies. Thus, the generated shortest evacuation paths should be taken these obstacles into account and avoid them as much as possible during generation of these paths.
- **Obtaining Shortest Path Guarantee:** Occupants should be evacuated from the building affected by the disaster/emergency as soon as possible to avoid harmful effects of secondary hazards. In other words, they should be guided to safer zones via shortest evacuation paths. Thus, the algorithm should calculate the shortest paths under every condition so that the occupants do not lose critical time during evacuation.
- **Working between Pre-Defined Points:** Some shortest path algorithms can work when the origin and target points are given to the algorithm. However,

determining the origin and/or target points may not always be possible during emergencies. For example, the selected exit location might be blocked. Thus, the algorithm should be capable of generating the shortest evacuation path without externally determining the origin and target locations. In other words, evacuation paths can be generated regardless of the conditions of the indoor environment.

- **Reliability:** The results obtained from the shortest path algorithms should be reliable. Under some conditions, algorithms fail to generate accurate and/or consistent results. For example, Dijkstra's Algorithm cannot give consistent results when graph networks include edges with negative costs. Considering the conditions of the emergency guidance and navigation system, reliability of the algorithms should be checked.
- **Use of Heuristic Methods:** Use of heuristic methods can be advantageous since it enhances the solution duration of the algorithms (Lester, 2005; Amit, 2010). Thus, algorithms using heuristic methods are also better in terms of solution duration.

According to these criteria, the most commonly preferred shortest path algorithms reviewed in this thesis will be compared with each other. Table 4.1 summarizes the results of this comparison depending on the review of algorithms given earlier in this chapter. According to Table 4.1, solution duration of shortest path algorithms can be 'Sufficient' or 'Not Sufficient'. Also, a shortest path algorithm can have obstacle prevention, obtaining shortest path guarantee, working between pre-defined points, reliability, and use of heuristic methods abilities, which will be represented with 'Yes' or 'No' values in Table 4.1.

The 'Sufficient*' value located in 'Solution Duration' criterion of A* Algorithms represents that A* Algorithms calculate the shortest paths faster than other algorithms given that the predicted distance values are accurate during utilization of heuristic methods. Similarly, 'Yes**' values located in 'Obtaining Shortest Path Guarantee' criterion of Dijkstra's and Bellman-Ford's Algorithms represent that these algorithms have this property considering the graph network conditions in this thesis. However, in general, none of the shortest path algorithms can have this property.

Table 4.1: Comparison of shortest path algorithms

NAME of the ALGORITHM	Prim's Algorithm	Dijkstra's Algorithm	Bellman-Ford Algorithm	A* Algorithm
CRITERIA				
1) Solution Duration	Sufficient	Sufficient	Sufficient	Sufficient*
2) Obstacle Prevention	Yes	Yes	Yes	Yes
3) Obtaining Shortest Path Guarantee	No	Yes**	Yes**	No
4) Working between Pre-Defined Points	No	No	No	Yes
5) Reliability	No	No	No	No
6) Use of Heuristic Methods	No	No	No	Yes

4.3 The Selected Shortest Path Algorithm

According to Table 4.1, it can be seen that Prim's Algorithm is the least favorable algorithm. Dijkstra's Algorithm and Bellman-Ford Algorithm is similar according to this comparison. However, as stated earlier, the only difference between these two algorithms is that Bellman-Ford Algorithm can give consistent results when graph networks have edges with negative costs while Dijkstra's Algorithm cannot. Since edge costs are in terms of distances, negative costs are not possible. Thus, there is no reason to select Bellman-Ford Algorithm instead of Dijkstra's. A* Algorithms can be said to be the best among these algorithms depending on the solution duration, use of heuristic methods, and better obstacle prevention mechanisms. However, this is not correct since these algorithms have significant drawbacks. These drawbacks are (1) problems faced during creation of the graph networks for A* Algorithms and (2) problem of working between pre-defined points. In emergency cases, selection of origin and target points may not always be possible. Thus, from Table 4.1, it can be concluded that Dijkstra's Algorithm will be the best solution for the shortest path problems in emergency guidance and navigation system.

CHAPTER 5

VULNERABILITY ASSESSMENT APPROACH

This chapter will suggest an approach for the vulnerability analysis that should be performed in a real-time indoor emergency guidance and navigation system. Such systems cannot achieve effective evacuation and response operations without considering the secondary hazards, hazardous contents, and vulnerabilities. The chapter will be composed of two main sections. In the first section, a vulnerability approach will be presented considering the hazardous contents, secondary hazards, and standoff distances. The second section will give an approach about vulnerability risk ranking. At the end of this section, the vulnerability assessment approach will be summarized.

5.1 Vulnerability Assessment Approaches in the Literature

In this study, vulnerability assessment is defined as the identification of the hazardous contents and their locations and determining the potential secondary hazards that can be induced by the interaction of the hazardous contents with the main disaster/emergency. Vulnerable locations will be determined according to the results of the vulnerability assessment.

There are numerous causes of vulnerabilities. The vulnerabilities that can occur in a building depend on many parameters involving but not limited to building type, building's utilization purpose, disaster/emergency type and magnitude, and variety of hazardous materials in the building. Therefore, vulnerability assessment studies inclined on determination of the hazards in the buildings, content-hazard relationships, secondary hazards and their impacts (Leite et. al, 2008; Leite et. al, 2009; Leite and Akinci, 2011). These studies aim to improve the response process by focusing on identification of vulnerable locations and the potential vulnerable locations (e.g. a location with a possibility to explode is not vulnerable yet, but has the potential to become vulnerable), identification of the hazardous contents that cause vulnerable locations, and determination of their impacts. Leite and Akinci (2011) proposed a vulnerability representation schema following disasters/emergencies to improve the vulnerability assessment process with a facility management point of view. In other words, the study aims to determine the important contents in a facility (e.g. server computers) and the vulnerability that might occur in the facility due to a threat (e.g. power outage). Although the aim of the mentioned study is different from the aim of this thesis, it is a good example of determining the hazardous contents in the building and their impacts on occupants.

US Environmental Protection Agency (1987) has examined the vulnerability assessment process under three items as; (1) determination of hazards, (2) vulnerability assessment, and (3) risk analysis. In the first step, which is determination of hazards, the location, magnitude, and cause of the hazards are determined. However, the mentioned study focuses only on the chemical hazardous contents. In the second step, identification of vulnerable locations, critical points, and conditions of the occupants affected from these vulnerabilities are being examined. Finally, in the risk analysis, the occurrence probabilities of hazards and the significance of their impacts are determined.

Another study that can be used as a basis for the proposed vulnerability assessment approach in this chapter is the Hazard Risk Assessment Instrument prepared by UCLA Center for Public Health and Disasters (2006). The process in the Hazard Risk Assessment Instrument can be interpreted in four steps as; (1) the probability of occurrence of disasters/emergencies, (2) the significance of the disasters/emergencies, (3) assessment of the result and assigning the risk levels, and (4) risk analysis. The first step, which aims to calculate the probability of occurrence of disasters/emergencies, ranks the disasters/emergencies in a scale from “0” to “4” considering the number of occurrence of each disaster/emergency in a given area for a specific period (e.g. last 25 years). “0” is used for the least probable disasters/emergencies while “4” is for most probable ones. The second and third steps are similar steps aiming to assess two items. These items are human factor (e.g. number of mortalities, injuries, people in need of a hospital, etc.) and society factor (e.g. usable water potential, number of evacuated buildings, number of health professionals that can serve, etc.). These parameters are also ranked in a scale from “0” to “4”. The final step is the risk analysis and this step combines all the rankings made in previous steps to reveal a vulnerability assessment outcome.

The vulnerability assessment approach in this thesis can said to be a combination of US Environmental Protection Agency (1987) and UCLA Center for Public Health and Disasters (2006). The proposed vulnerability assessment approach will also have four steps as; (1) identification and determination of hazardous contents and secondary hazards, (2) determination of standoff distances, and (3) identification of vulnerable locations, and (4) vulnerability assessment.

5.2 Proposed Vulnerability Assessment Approach

The first step in vulnerability analysis is the identification and determination of hazardous contents and secondary hazards. There are many studies in the literature on determination of the hazardous contents in the buildings, their impacts and impact areas, and secondary hazards that might be caused due to these contents. Moreover, there are studies aiming to create a list of hazardous materials (e.g. list of hazardous chemicals in buildings) (Evans et. al, 2005; Jones and Bukowski, 2001). Besides hazardous contents, other causes of vulnerabilities such as power lines, etc. are also considered in vulnerability approaches (Evans et. al, 2005; Leite et. al, 2008). These studies can be used as reference to identify and determine the hazardous contents and secondary hazards in indoor environments. Moreover, interviews with experts about hazardous materials, secondary hazards, emergency response, and disaster management should be conducted to prepare the list of hazardous contents and secondary hazards in indoor environments. However, such a study requires a very comprehensive study and it is not included in the scope of this thesis.

The second step of vulnerability assessment is the determination of the standoff distances of the identified hazardous contents and secondary hazards. There are several sources that can be used to determine the standoff distances. Emergency Response Guidebook (ERG) (2008) developed by the joint work of U.S. Department of Transportation, Transport Canada, the Secretariat of Transport and Communications of Mexico, and Centro de Información Química para Emergencias of Argentina is one of these documents. In addition, Material Safety Data Sheets (MSDS) of the chemicals provide information about the hazardous health effects and the potential secondary hazards (e.g. explosion, fire) that might be caused by them. Thus, they can be used for determining the secondary hazards caused by the hazardous contents and the impact of the hazardous contents. Shortly, data about the standoff distances can be gathered from legislations, guidebooks, and MSDS. Then, the gathered data can be validated by interviews with experts in the related domains. However, this is another research that should be conducted in details and it is not included in the scope of this thesis.

Knowing the hazardous contents, the secondary hazards that can be caused due to these contents, and the standoff distances, vulnerability conditions in the building can be determined and vulnerable locations can be identified in the third step. For example, upon explosion of an explosive content, the area to be identified as “vulnerable” is known since the standoff distance of that content is known.

Finally, vulnerability assessment can be finalized and the results can be obtained in the fourth step. The nodes of the graph network in the vulnerable locations will be assumed as "closed" nodes and they will not be involved in the shortest path calculations. Another suggestion to represent the vulnerability assessment results is to assign penalty points to the nodes of the graph network in vulnerable locations to represent the level of vulnerability. The details about how to assign these penalty points to the vulnerabilities can be found in the next section.

5.3 Vulnerability Risk Ranking

The real-time indoor emergency guidance and navigation system should also consider cases when it is not possible to avoid evacuation paths from passing through vulnerable locations. In other words, both evacuation alternatives of an individual might pass through vulnerable locations. In such cases, the vulnerability assessment algorithm should decide which path is safer to select. For this reason, the risks possessed by the hazardous contents and the risk levels of secondary hazards should be determined and be available in the system. For example, the system can be able to choose an evacuation path between an alternative that passes through a vulnerable location due to fire and another alternative that passes through a vulnerable location due to a possibility of explosion depending on the risk levels of these incidents. To achieve such a ranking among various vulnerabilities (hazardous contents and secondary hazards), opinions of experts in the emergency response and disaster management domains should be obtained. An example vulnerability risk ranking approach can be seen in Table 5.1. In this table, the hazardous contents are separated into two as contents that cause minor hazards and major hazards. There can be numerous different ways of ranking the risk levels of hazardous contents and secondary hazards. In addition, the hazardous contents in this table are not validated. Shortly, this table is only given as an example to enhance the understanding of the vulnerability risk ranking logic.

Table 5.1: An example vulnerability risk ranking approach

RANKING GROUP	HAZARDOUS CONTENTS
Hazardous Contents that Might Cause Minor Hazards	Red Phosphorus, Naphthalene, Coal Dust, Hydrogen Peroxide, Perchloric Acid, Sodium-Potassium Nitrate, Chlorate, Perchlorate, Calcium Carbonate, Chromic Acid, Ammonium Nitrate
Hazardous Contents that Might Cause Major Hazards	LPG, Argon, Acetylene, Nitrogen, Formic Acid, Phosgene, Hydrogen Fluoride, Chlorine, Perfume, Fuel Oil, Toluene, Ethyl Acetate, Solvent, Paints, Magnesium, Sulphur, White Phosphorus, Aluminum Dusts, Organic Peroxide, Sulfuric Acid, Nitric Acid, Potassium Hydroxide, Sodium

The outcomes of the vulnerability risk ranking can be reflected to the emergency guidance and navigation system by penalty points assigned to the nodes. Different hazardous contents and secondary hazards will have different risk levels. Thus, according to the risk level of the incident, penalty points can be given to the nodes. An example of penalty point assignment approach can be seen in Table 5.2. In this table, penalty points are assigned to some of the secondary hazards according to their risk levels. The risk ranking of secondary hazards in this table is not validated. Shortly, it is given as an example only to enhance the understanding of the penalty point assigning logic. Normally, shortest path algorithms calculate the evacuation paths according to the distance between nodes. These penalty points will increase the distance between nodes artificially. For example, 100 penalty points will double the real distance between two nodes, while 60 points will increase the distance by 60%. As the distance between the vulnerable node and other nodes increase and considering that the algorithm aims to select the shortest alternative, vulnerable locations (nodes) can be avoided. However, the aim of this thesis is not conducting such studies but, to suggest a vulnerability approach only.

Table 5.2: An example of penalty point assignment approach for secondary hazards

SECONDARY HAZARD	PENALTY POINT
Fire	100
Massive Explosion	60
Natural Gas Leakage	60
Minor Explosion	40
Electricity Leakage	20
Flooding	20

To summarize the chapter shortly, a vulnerability assessment approach is suggested. The activities to be performed for this approach are (1) identifying and determining the hazardous contents in the building and secondary hazards that can be caused, (2) determining the standoff distances of hazardous contents and secondary hazards, (3) identifying the vulnerable locations, and (4) representing the results of vulnerability assessment. The results of vulnerability assessment can be represented either by setting the nodes in vulnerable locations as non-accessible or by determining the vulnerability risk ranking of various vulnerabilities and assigning penalty points to the nodes in the vulnerable locations according to their risk levels.

CHAPTER 6

PROPOSED SYSTEM FRAMEWORK

The preliminary studies before proposing the real-time indoor emergency guidance and navigation system for buildings under the threat of multi-hazard emergencies have been given so far as; (1) the requirements of the system, (2) shortest path algorithm to be utilized in the system, and (3) vulnerability assessment approach of the system. Now, the proposed system framework can be introduced to the reader. Thus, this chapter will be divided into two main sections. In the first section, the proposed system overview will be given. The second section will be a discussion section about the system.

6.1 Overview of the Proposed System Framework

The proposed system framework is summarized by using Integration Definition for Function Modeling (IDEF0) method, which is one of the most commonly used process modeling methods in the literature. IDEF0 is a method that presents the data flow, system control, and functional flow of the processes in various working areas, production and enterprise activities graphically in different levels of details. IDEF0 diagrams model the processes, the inputs and outputs, system controls, and mechanisms while giving the relationships of all these components with each other (Defense Acquisition University, 2000). The IDEF0 diagram of the proposed system framework is given in Figure 6.1. This diagram shows all the inputs and outputs of the system explaining which functions can be performed by the system, what is the scope, aim, and methodology of the system, what can the system do at what stage, and which inputs are utilized and what kind of outputs are given by the system.

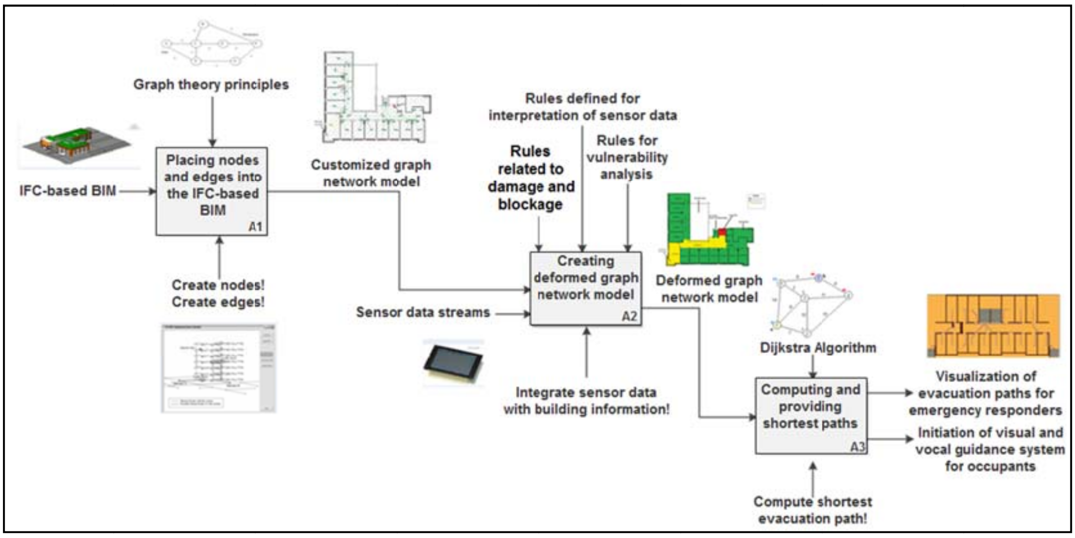

Figure 6.1: Proposed system framework

The real-time indoor emergency guidance and navigation system proposed in this thesis (Figure 6.1) has three main steps:

- A1 (Step 1) – Placement of nodes and edges into the IFC based BIM model
- A2 (Step 2) – Creating the deformed graph network model
- A3 (Step 3) – Computing and providing the shortest paths

Shortly, in the first step, the graph network of the building is created using the IFC based BIM model of the building. Then, in the light of the data coming from sensors that monitor the indoor environment, the damage status of the building following a disaster/emergency is obtained. Using this data, vulnerability assessment is performed by using the approach proposed in Chapter 5. Combining the graph network, the sensor data, and the results of the vulnerability assessment, deformed graph network of the building is obtained in the second step. Finally, in the third step, Dijkstra's Shortest Path Algorithm will be run on the deformed graph network of the building to calculate the real-time shortest paths for users of the system (occupants and first responders). These steps will be explained in details in below sections.

6.1.1 A1 (Step 1): Placement of Nodes and Edges into the IFC based BIM Model

The first step of the system aims to generate the graph network of the building. For this reason, using the IFC based BIM model of the building, graph network of every floor of the building is generated so that, shortest path algorithms can be run to generate the evacuation paths.

6.1.1.1 IFC Based BIM

BIM models of the buildings involve all the information needed to generate the graph networks such as building geometry, floor plans, locations of building components (i.e. columns, walls), spaces in the indoor environments, their relationships with each other, etc. The BIM models of the buildings can be prepared by using tools such as Autodesk REVIT, ArchiCAD, etc. Then, the data in these BIM models are exported in IFC format. Exporting the building related information in IFC format helps the system to overcome the interoperability problems and to attach the external classes, which can be generated in other programming languages (e.g. Java), required for the generation of the graph networks. Shortly, IFC based BIM models are the starting point of the system that supplies all the building related information and helps attaching the external classes to the system.

6.1.1.2 Graph Theory Principles

Using the data stored in BIM files exported in IFC format, graph networks of the buildings should be established. However, the IFC structure does not have all the necessary classes to create the networks. Thus, the IFC structure should be extended depending on the graph theory principles. In other words, classes related to graph theory (i.e. node classes, edge classes) should be externally added to the system in this step.

6.1.1.3 Creating Nodes and Edges

After extending the IFC structure by adding the necessary classes, the elements of graph networks can be created. Thus, this process states that nodes and edges are created to obtain the graph networks.

6.1.1.4 Customized Graph Network Model (Output)

After nodes and edges are created and placed into the IFC based BIM models, the output will be customized graph network model of the building. This output will be utilized as an input for the functions in the second step.

6.1.2 A2 (Step 2): Creating Deformed Graph Network Model

The second step of the system aims to generate the deformed graph network of the model following a disaster/emergency. The sensors deployed at several different locations in the building will monitor the indoor environments to give accessibility and vulnerability information to the system. Then, using the information coming from the sensors, the customized graph network model of the building will be updated so that the indoor environment conditions can be reflected to the system. In other words, the system can realize the accessibility and vulnerability conditions of the nodes and edges in the customized graph network of the building and consequently, generate the deformed graph network model so that (1) the damage caused by the disaster/emergency can be monitored, (2) secondary hazards in the indoor environments can be distinguished, and (3) the risks related to damage, secondary hazards, and hazardous contents in the building can be foreseen.

6.1.2.1 Customized Graph Network Model (Input) and Sensor Data Streams

Customized graph network models created in the first step will be used as the input of the second step.

The second input for this step is the sensor data streams. The sensors that have different capabilities (e.g. ultrasonic distance measurement sensors, smoke and fire sensors) will monitor the indoor environments to give accessibility and vulnerability information to the system. Cameras and image processing functions will also be used to increase the accuracy and reliability of the sensor data. With these data streams, incidents such as blockages, collapses, secondary hazards, etc. can be distinguished.

6.1.2.2 Rules Related to Damage and Blockage and Rules for Vulnerability Analysis

Data streams coming from sensors and camera systems in the building are in raw format (e.g. 0-1 format) and they should be interpreted to understand the accessibility and vulnerability conditions in the building. In addition, the same spaces (nodes and edges) might be monitored with more than one sensor and camera at the same time. In such cases, data coming from several sensors and camera should be combined with each other so that, the conditions of the space can be realized. Interpretation and combination of sensor data streams will be done by assigning threshold value to each sensor and the rules related to damage and blockage are these threshold values. Using these threshold values, the system can interpret and combine the sensor data streams and understand if the space is accessible or not, and vulnerable or not.

The rules for vulnerability assessment should be set to evaluate the vulnerability information coming from the sensors. Hazardous content information of the building derived from IFC based BIM files are combined with sensor data streams to assess the risk levels of the vulnerabilities. Moreover, especially in case of multiple vulnerabilities in the building, the vulnerability assessment algorithm will prioritize the vulnerabilities by performing a vulnerability risk ranking iteration according to their risk levels. The results of the assessment will be used to avoid vulnerable locations during generation of evacuation paths while the risk ranking will be used when none of the alternatives of an evacuation path can avoid passing through such locations. The risk ranking will select the least risky alternative and make the evacuation path pass through that location.

6.1.2.3 Integration of Sensor Data with Building Information

After the system interpreted the sensor data streams and utilized that data in vulnerability assessment algorithms, it is time for making decisions for nodes and edges. The system should decide whether a node and/or an edge will be included in the shortest path calculation process or not depending on the accessibility and vulnerability conditions of the node/edge. For this reason, the interpreted sensor data should be integrated with the customized graph network model of the building.

6.1.2.4 Deformed Graph Network Model (Output)

After integrating the sensor data with the customized graph network of the building, the customized graph network becomes updated according to the current conditions in the indoor environment. The new updated graph network is called the deformed graph network model since the non-accessible and vulnerable nodes and edges are eliminated from the network. Deformed graph network model of the building is the outcome of the second step and will be the input for the third step, where shortest paths will be calculated and generated.

6.1.3 A3 (Step 3): Computing and Providing the Shortest Paths

The third and final step of the system aims to compute and generate the shortest evacuation paths calculated by the shortest path algorithms that will be run on the deformed graph network models of the buildings. The generated paths will be provided to the occupants via vocal and/or visual guidance to achieve an improved evacuation process and to the first responders via devices such as hand-held computers, etc. to achieve more efficient response operations.

6.1.3.1 Deformed Graph Network Model (Input)

All the information (e.g. accessibility and vulnerability of a node and/or an edge) will be used to run the shortest path algorithms and compute the evacuation paths. For this reason, the deformed graph network model of the building will be used as an input at this step.

6.1.3.2 Dijkstra’s Algorithm

Dijkstra’s Shortest Path Algorithm was suggested as the algorithm to be utilized in the real-time indoor emergency guidance and navigation system. Therefore, this algorithm will be run on the deformed graph network model of the building to calculate the evacuation paths.

6.1.3.3 Computation of the Shortest Evacuation Paths

Finally, the shortest evacuation paths can be calculated according to the data derived from the deformed graph network model of the building.

6.1.3.4 Initiation of Visual and Vocal Guidance System for Occupants and the Visualization of Evacuation Paths for Emergency Responders

The generated evacuation paths should be provided for the usage of occupants during evacuation. For this reason, visual and/or vocal systems should be employed to transmit these evacuation paths to the occupants. In addition, evacuation paths should also be visualized for the first responders by devices such as hand-held computers, etc. to inform them about the conditions in the building, damage status, and vulnerabilities.

6.1.4 Other Features of the System

In the light of the proposed framework and considering the capabilities of the system, the general working mechanism of the proposed real-time indoor emergency guidance and navigation system can be realized. At this point, other details related to the proposed system will be given.

The system monitors the indoor environment via sensors. In other words, indoor environment data (i.e. accessibility and vulnerability conditions of the system) is dependent to sensor data. Therefore, the sensor data flow, which involves the gathering the indoor environment data and transferring it to the system, is an important task. The details of the sensor data flow can be seen in Figure 6.2.

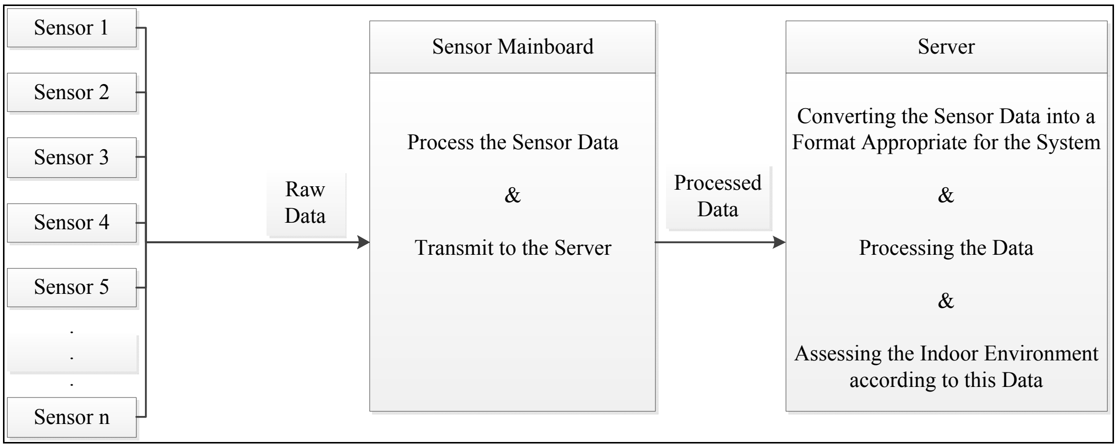

Figure 6.2: Sensor data flow

Shortly, the raw data obtained by various sensors (i.e. in binary format) is transferred to the sensor mainboards. There will be numerous sensor mainboards that will collect the data from the sensors in the building. Then, this raw data is processed and transmitted to the server located in a safe location in the building. The processed data in the server is converted to a format that is usable by the system (i.e. IFC format). Then, this data is further processed for assessment of the conditions in the indoor environment such as degree of accessibility and/or vulnerability of a building sub-part.

The sensors will transmit the data to the servers via wireless local area networks as can be seen from Figure 6.3. Every building that has the real-time indoor emergency guidance and navigation system should have its own server machine for data collection. In other words, the system will be unique for every building not only in terms of software and graph network model, but also in terms of data flow and transfer mechanisms. Using the indoor environment data derived from the sensors, the server computer will have the necessary algorithms to perform the vulnerability assessment and to generate shortest evacuation paths.

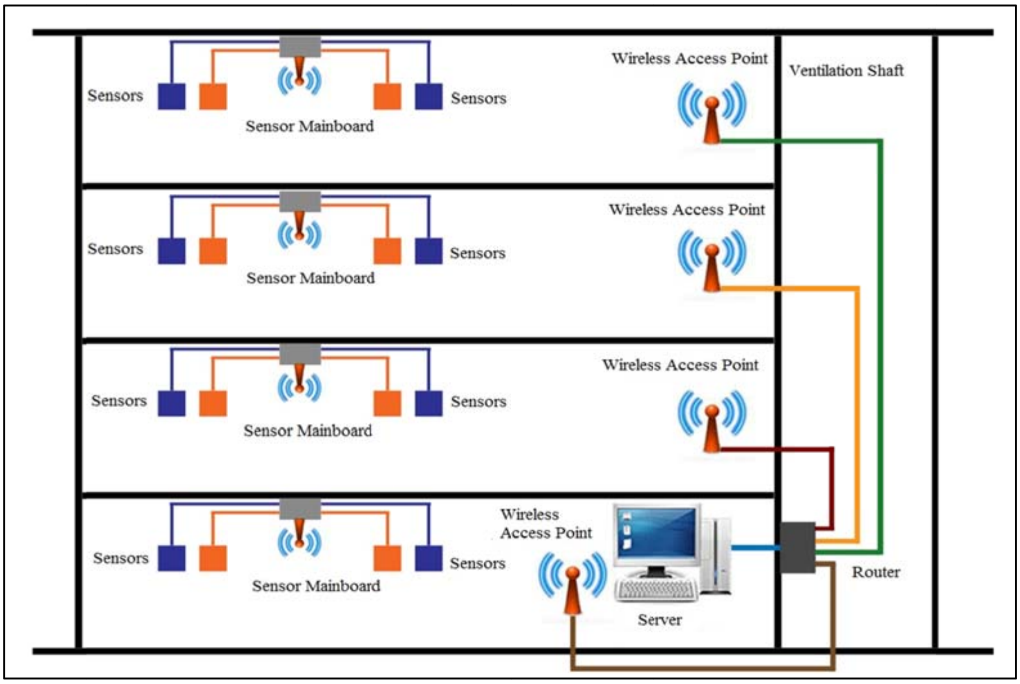

Figure 6.3: Sensor data transfer to server via WLAN and system hardware

6.3 Discussions on the Proposed System Framework

The proposed system derives building related information in IFC format from BIM models of the buildings. Then, different types of sensors, which are placed at various locations in the building, supplies information about the conditions in the indoor environment. However, the sensor data should be interpreted to integrate it with the IFC based BIM. For example, cable sensors give data in binary format, where 0 value is used for damaged building elements and 1 value is used for non-damaged ones. However, such sensors do not give how a building element is collapsed (i.e. totally collapsed or partially collapsed). Ultrasonic distance measurement sensors give distance values and in case of a building element monitored by this sensor collapses, the distance value will change. Considering all these, the data coming from sensors in different formats and with different meanings should be interpreted. Such interpretation can be based upon model experiments and setting threshold values according to the results of these experiments. With this, when the sensor threshold value is exceeded, it will state that the building element is damaged. If not, the building element will be assumed to be non-damaged.

Moreover, spaces being monitored by more than one sensor should be taken into further consideration. In some cases, different sensors can give conflicting information about the same space. For example, cable sensor might state that the building element is damaged while ultrasonic distance measurement sensor states the otherwise. For this reason, reliability of each type of sensor should be determined by experiments. Depending on the reliability results from the experiments, measurements of each sensor should be combined with some reliability coefficient determined from these experiments and the decision about that space should be made accordingly.

Finally, the system knows the accessibility and vulnerability conditions of the building and can generate the deformed graph network model of the building to reflect these conditions. Then, shortest path algorithms can run on these networks and calculate the evacuation paths. These paths will then be given to the occupants and the first responders for utilization during emergencies.

Shortly, the proposed system framework aims to give a new and combined approach using IFC based BIM files, sensors, and vulnerability assessment algorithms. The main goals of the system are to improve the evacuation process of occupants by supplying them visual and/or vocal guidance during emergencies and to increase the efficiency of response operations of first responders by supplying them visual guidance and necessary information during response operations.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

This chapter aims to conclude the research and the main findings of the study by highlighting the importance of the proposed real-time indoor emergency guidance and navigation system integrated with BIM, IFC, sensors, shortest path algorithms, and vulnerability assessment approach.

Following a disaster or an emergency, there is a need for a navigation approach to guide first responders and occupants in a blocked indoor environment because of the complex architecture of buildings and various threats that may occur. Therefore, two main goals of the study are identified as follows:

- Proposing a system for guidance of occupants from facilities under the threat of multi-hazard emergencies
- Proposing a system for first responders to enhance the decision-making and planning processes of the response operations by supplying them the necessary building related information, real-time accessibility and vulnerability conditions of the building

To achieve these goals, a system framework has been proposed. There are several similar studies proposing such systems in the literature (Yuan and Zizhang, 2008; Lee and Zlatanova, 2008; Park and Lee, 2008; Lee, 2007) and these studies generally focus on the system itself and the software model to be produced. However, several other aspects should also be considered during studies about indoor emergency guidance and navigation systems. Thus, in this research, the following studies, which are less observed in the literature, have been conducted to consider these aspects:

- Determination of requirements of indoor navigation during emergency response and disaster management
- Review, comparison, and evaluation of the shortest path algorithms from an emergency response and disaster management point of view
- Proposing a comprehensive vulnerability assessment approach

In other words, this study was undertaken as the initial part of an ongoing research project that aims to develop a real-time indoor emergency guidance and navigation system integrated with BIM, IFC, sensors, shortest path algorithms, and vulnerability assessment approach.

The initial aim of the study is to determine the requirements of indoor navigation during emergency response and disaster management. For this reason, four use case scenarios related to disasters/emergencies have been developed for complex buildings to demonstrate (1) the possible events that may occur in indoor environments following a disaster/emergency, (2) the possible triggered threats that may affect indoor environments, (3) the flow of events in a building under multiple hazards, (4) the behavior of occupants following a disaster/emergency, and (5) the working mechanism of emergency navigation algorithms. Using the developed use cases, a requirements analysis has been performed and eight main requirements have been identified. These requirements are collected under three groups as follows:

- Requirements related to shortest path algorithms and graph networks
- Requirements related to accessibility
- Requirements related to prevention of vulnerable locations

Some of the major requirements provided in this study can be listed as determining the blockage percentages, using heuristic methods for alternative evacuation path generation depending on the blockage percentages and performing vulnerability risk ranking to select the safest evacuation alternative.

Determination of requirements of indoor navigation during emergency response and disaster management study provides a basis for further studies that aim to create a navigation approach and an indoor emergency navigation system.

Navigation systems generally use shortest path algorithms in their calculations. Similarly, shortest path algorithms are also being used in indoor emergency guidance and navigation systems. There are numerous different algorithms used for calculation of shortest paths. Thus, an individual has to select an algorithm among numerous alternatives and use for the solution of the shortest path problem faced. However, there is not much emphasis on the shortest path algorithm to be utilized in emergency guidance and navigation systems.

In the light of these, the second foremost objective of the study is to suggest utilization of the most appropriate and best solution-giving shortest path algorithm among several algorithms for indoor emergency guidance and navigation systems. For this reason, the most commonly preferred algorithms in the literature for the solution of shortest path problems have been identified. The identified algorithms are (1) Prim's Algorithm, (2) Dijkstra's Algorithm, (3) Bellman-Ford Algorithm, and (4) A* Algorithms. The advantages and disadvantages of the identified algorithms have been reviewed according to their properties, performances, and limitations.

Considering the requirements of the indoor emergency guidance and navigation systems, six evaluation criteria have been determined for comparison of the algorithms. Some of these criteria are obtained from the previous evaluation studies in the literature while some of them are unique criteria determined only for this study. These criteria are as follows:

- Solution Duration (Speed)
- Obstacle Prevention Capability
- Obtaining Shortest Path Guarantee
- Working between Pre-Defined Points
- Reliability
- Use of Heuristics

The algorithms have been compared with each other using these criteria with an emergency response and disaster management point of view. The outcomes of the comparison pointed out that utilization of Dijkstra's Algorithm for solution of shortest path problems faced during generation of evacuation paths in indoor environments following disasters/emergencies.

One major drawback of the findings of studies about shortest path algorithms is that, the algorithm suggested to be utilized may not always be the most appropriate and best solution-giving one for all shortest path problems. It should not be forgotten that every shortest path problem is different from the other and they have different conditions. Therefore, the suggestion made in this research may not give the same outcomes for other shortest path problems.

Nevertheless, studies on shortest path algorithms to suggest utilization of the most appropriate and best solution-giving algorithm among several algorithms for indoor emergency guidance and navigation systems will be a guiding study for researchers aiming to conduct studies about evacuation of occupants and/or guidance of first responders following disasters/emergencies.

The third objective of this research is to propose a comprehensive vulnerability assessment approach that can be integrated with the indoor emergency guidance and navigation systems. Vulnerable locations in the building following a disaster/emergency should be avoided during evacuation of occupants to decrease the harmful effects of secondary hazards and hazardous contents on human health. In addition, by informing the first responders about the vulnerabilities determined as an outcome of vulnerability assessment, it is possible to increase the effectiveness of the response operations. Therefore, it can be claimed that vulnerability assessment is an important component of emergency guidance and navigation systems.

There are several vulnerability assessment studies in the literature (Evans et. al, 2005; Jones and Bukowski, 2001; Leite et. al, 2008, Leite et. al, 2009; Leite and Akinci, 2011; US Environmental Protection Agency, 1987; UCLA Center for Public Health and Disasters, 2006). However, majority of them lacks the emphasis of building-scale analysis with an emergency response and disaster management point of view. Nevertheless, these can be referenced for proposing a vulnerability assessment approaches following disasters/emergencies. Therefore, this thesis aims to propose a comprehensive vulnerability assessment approach to fill the gap in the literature.

The activities to be performed for this approach are as follows:

- Identifying and determining the hazardous contents in the building and secondary hazards that can be caused
- Determining the standoff distances of hazardous contents and secondary hazards
- Identifying the vulnerable locations
- Representing the results of vulnerability assessment

The results of vulnerability assessment can be represented either by setting the nodes in vulnerable locations as non-accessible or by determining the vulnerability risk ranking of various vulnerabilities and assigning penalty points to the nodes in the vulnerable locations according to their risk levels. By representing the results of vulnerability assessment to the system (via graph networks), it can be possible to avoid vulnerable locations during evacuation.

One major drawback of the findings of the studies about vulnerability assessment approach development is that, the proposed approach is not validated. Instead, it depends on the literature findings and can be considered as a combination of similar studies in the literature prepared to achieve a comprehensive approach.

Finally, in the light of all these studies, a real-time indoor emergency guidance and navigation system integrated with BIM, IFC, sensors, shortest path algorithms, and vulnerability assessment approach has been proposed.

The proposed system derives building related information in IFC format from BIM models of the buildings, combines it with the real-time indoor environment data (accessibility and vulnerability) derived from sensors, and generates the deformed graph network model of the building to reflect the current accessibility and vulnerability conditions of the building. Then, shortest path algorithms can run on these networks and calculate the evacuation paths. These paths will then be given to the occupants by visual and/or vocal systems and to the first responders by visual systems during disasters/emergencies. In addition, necessary information during response operations will be supplied to first responders via visual systems.

The future works include the creation of indoor emergency guidance and navigation systems and tools which are capable of generating evacuation paths, considering the accessibility and vulnerability in the indoor environment. In addition, an application to a pilot building can be made to observe the advantages and disadvantages, strengths and drawbacks, and possible problems of the system.

To conclude the research, although there are some drawbacks, this study can be a guideline for researchers aiming to create indoor emergency guidance and navigation systems. Using the findings of the study and the proposed framework, it is possible to develop systems that can decrease the injuries and mortalities by achieving effective evacuation and improved response operations.

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APPENDIX A

IMPORTANT TERMS IN GRAPH THEORY

In this chapter, important terms related to graph theory, which are thought to be significant to understand the shortest path studies better in this thesis, will be defined and explained in details. The information given in this chapter is based on the studies of Bender and Williamson (2005), Hartmann and Weigt (2008), Gross and Yellen (2006), and Marcus (2008). This chapter will be divided into four main sections. The first section will introduce the terms about edges and edge directions. The second section explains the terms about the graph networks while the third section describes the terms about the paths. The final section will describe the terms related to graphs and matrices.

A.1 Terms about the Edges and Edge Directions

- **Parallel Edges:** If more than one edge is limited with (connected to) the same endpoints, these edges are said to be parallel edges. Parallel edges should be present in a graph network that will be used for navigation purposes following a disaster/emergency because there may be blocked locations. For example, if two nodes in the graph network of the building is connected with only one edge, the shortest path algorithm cannot generate any paths when that edge is blocked. However, if there are parallel edges between two nodes, the algorithm can continue its path generation efforts through parallel edges in case of a blockage. Thus, parallel edges are required in the graph networks to avoid blockage problems.

- **Loops:** If an edge ends at the starting point, that edge is said to be making loops. In other words, looping edges return to the starting point. In an evacuation path, looping edges will not be desired. Therefore, looping edges should be avoided in graph networks.
- **Directed Edges and Directed Graphs (Digraphs):** Edges can have direction arrows that indicate the direction of the edge from the origin point to the destination point and such edges are called directed edges. Directed edges can only work on the direction of the arrow and movement in the opposite direction is not possible. Graphs composed of directed edges only are called directed graphs or digraphs. The direction (node) arrow points the head or top node, and the other node is called the tail. Graph A in Figure A.1 is a directed graph since all edges have direction arrows. Node "a" on the Edge "ab" is the tail node and the Node "b" is the head node. Directed edges limit the movement in one direction. Although in some cases limiting the movement in one direction can be useful (for edges that leads to nodes at dead ends), directed graphs will have half the path possibilities compared to undirected graphs because of this limitation. This might affect the alternative path generation ability of the shortest path algorithms negatively since path possibilities are limited. Hence, use of directed graphs are not suggested for use in evacuation path generation.

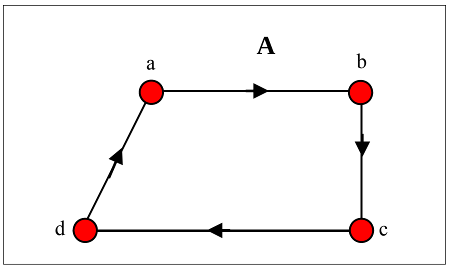


Figure A.1: A directed graph example (Graph A)

- **Undirected Edges and Undirected Graphs:** Undirected edges do not have direction arrows and movement on both directions is possible. In undirected graphs, none of the edges has direction arrows. Figure A.2 is an undirected graph example. In this graph, Edge ab and Edge ba represents the same path but different directions. The iteration alternatives increase in undirected graphs since there are more options. Thus, the iteration time of the shortest path algorithm will increase when the graph is undirected. This may decrease the performance of the algorithm.

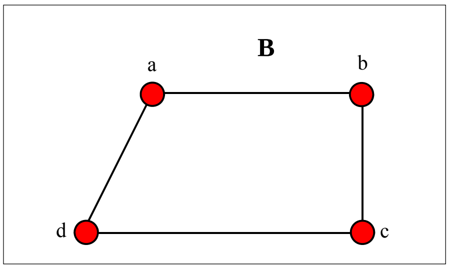


Figure A.2: An undirected graph example (Graph B)

- **Mixed Graphs:** Mixed graphs are the graphs that have both directed and undirected edges. The Graph C in Figure A.3 is a mixed graph example. During preparation of the graph network of the building, considering the conditions and architecture of the indoor environment, it might be better to have directed and undirected edges for better algorithm performance.

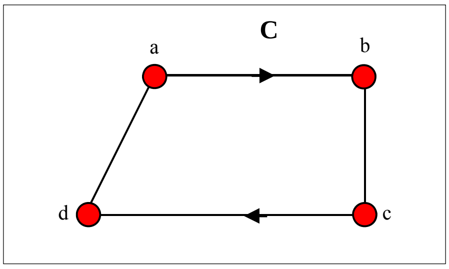


Figure A.3: A mixed graph example (Graph C)

A.2 Terms about the Graph Networks

- **Simple Graphs:** Graphs that have no parallel or looping edges are called simple graphs. Graphs A, B, and C given in previous figures (Figure A.1, Figure A.2, and Figure A.3) are examples to simple graphs. The solution generated by the shortest path algorithm will always be a simple graph. However, a simple graph will not always be the shortest path in the graph.
- **Weighted Graphs:** If all edges in the graph have weights (costs), that graph is called a weighted graph. The edge costs can be in terms of distance, length, price, time, etc. Graph D given in Figure A.4 is a weighted graph. The numbers written on the edges represents the edge costs. In this study, the graph networks will be weighted graph since the shortest paths will be determined according to the total distance. The distance information will be gathered from the floor plans derived from the BIM model of the buildings.

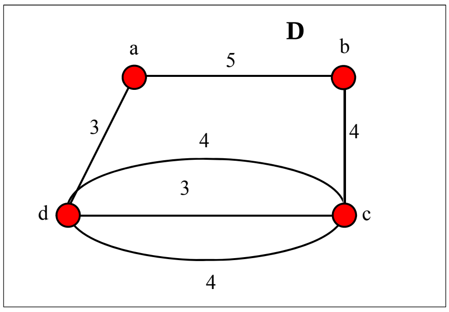


Figure A.4: A weighted graph example (Graph D)

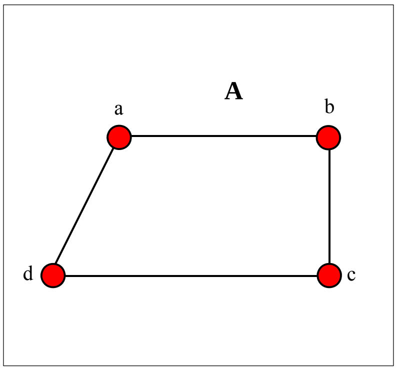
- **Connected Graphs:** If all nodes in the graph network are connected to each other with edges, that graph network is called connected graph. In other words, if one can pass through all the nodes without lifting the pen, that graph is a connected graph. In connected graphs, disconnections between nodes are not allowed. However, this does not mean that every node should be connected with all nodes in the network. A node can be connected indirectly to another node (connection after passing through a second node). An indoor navigation system should be ready for all kinds of events after a disaster/emergency. When the nodes in the graph network are all connected to each other, the shortest path algorithm is more likely to adapt to the various conditions that might occur following a disaster/emergency since there will be more path options as there are more edges in the graph network.
- **Disconnected Graphs:** All graphs that are not connected graphs are called disconnected graphs. There will be disconnections in this kind of graph networks. Disconnected graphs are undesired in this study considering the advantages of connected graphs.

A.3 Terms about the Paths

- **Paths:** Paths represents the set of a series of nodes and edges. The purpose of creating the graph network of a building is to generate the paths (shortest evacuation paths for this study). Paths start with an origin node and ends at a target node. During the movement between the origin and the target nodes, a series of nodes and edges might be passed that form the paths. For example considering the Graph A given in Figure A.1 previously, assume that a path will start from Node "a" and ends with Node "a" again. The path will then follow Edge ab to reach Node b, Edge bc to reach Node c, and Edge cd to reach Node d, and finally Edge da to reach Node a. Thus, the path will be {a, ab, b, bc, c, cd, d, da, a}.
- **Length of a Path:** The length of a path is the total number of edges involved in the path. If an edge is used for repeated times, these edges are included in this number every time they are used. For example, the path that is listed as {a, ab, b, bc, c, cd, d, da, a} passes through four edges. Hence, the length of that path is four.
- **Simple Path:** If all nodes and edges are used only once in the path, that path is called simple path. Simple paths connect the origin node and the target node directly and do not pass from the same node/edge for a second time. Simple paths will be useful during evacuation since they will directly guide the occupants to safer zones (target). In fact, all shortest paths are already simple paths. However, all simple paths are not shortest paths.
- **Cycles:** Cycles are the paths that return to the origin node. Such paths are not desired in graph networks that will be used in emergency navigation systems. However, cycles cannot be avoided in graph networks. Thus, determining the exit nodes in the graph network will become an important task to avoid cycles in the networks.

A.4 Terms about the Graphs and Matrices

- **Adjacency Matrix:** If two nodes can be connected to each other with edges directly, these nodes are adjacent to each other. Adjacency matrices are the matrices that lists the adjacent nodes. Adjacent nodes in the table are represented by the value of "1" and other are represented by "0" value. These matrices are required by the computer programs to understand the adjacency of nodes in the graph network. An adjacency matrix for a graph network can be seen in Figure A.5. For example, Node a and Node b are adjacent to each other. Thus, they will have a value of "1". However, Node a and Node c are not adjacent and their value will be "0" in the matrix.



	a	b	c	d
a	0	1	0	1
b	1	0	1	0
c	0	1	0	1
d	1	0	1	0

	ab	bc	cd	da
a	1	0	0	1
b	1	1	0	0
c	0	1	1	0
d	0	0	1	1

Figure A.5: **Left:** An undirected graph (Graph A), **Middle:** Adjacency Matrix of Graph A, **Right:** Incidence Matrix of Graph A.

- **Incidence Matrix:** This matrix shows the relations between nodes and edges. If a node have the edge in the matrix, it will have the value of "1", otherwise it will be "0". For example, Node a has Edge ab and Edge da. Thus, the appropriate cells in the incidence matrix will hold the value of "1" for these edges. Other edges for Node a will get "0" value. Moreover, incidence matrices show the degree of node. The summation of the rows, gives the degree of that node. For example, Node a has a degree of 2 (Figure A.5). These matrices are required by the computer programs to understand which nodes are connected to each other by which edges in the graph network.

APPENDIX B

WORKING MECHANISM OF PRIM’S ALGORITM/DIJKSTRA’S ALGORITHM: AN EXAMPLE

The working mechanisms of Prim’s Algorithm and Dijkstra’s Algorithm are very similar. Hence, the working mechanisms of both algorithms will be explained on the same example. The graph network in Figure A.1 is taken as an example network. The example network is composed of 5 nodes (Nodes A, B, C, D, and E) and 8 edges that connect these nodes. Each edge has a cost value in terms of distance.

The aim in this example is to reach every node in the network from the shortest possible way starting from Node A. Thus, Node A is taken as the origin node and it is marked with a yellow sign in Figure B.1. Marking the nodes and edges is important because it is not possible to return to marked nodes and edges. In other words, an individual cannot pass through a node or an edge that is marked for the second time.

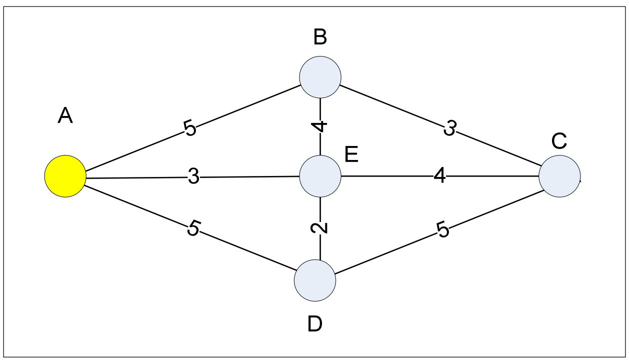


Figure B.1: Graph network example

The main principle of shortest path algorithms is calculating the shortest possible way between two adjacent nodes. Therefore, both algorithms will select the edge with the minimum cost between two adjacent nodes. The cost of the Edge AB is equal to the cost of the Edge AD, which is 5 meters. On the other hand, the cost of the Edge AE is 3 meters. Hence, the algorithm will select the Edge AE to start with and reach to Node E. As a result, Edge AE and Node E are marked since they are used once. Figure B.2 shows this first iteration schematically. Total cost is 3 at the end of first iteration.

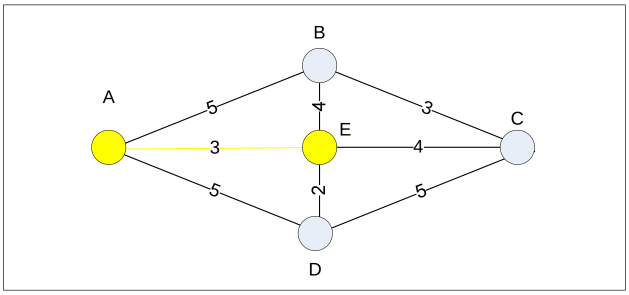


Figure B.2: First iteration of the algorithm

In the second iteration, the second node to be reached will be selected according to the minimum edge cost. This time the algorithm is at Node E. Checking the edges that connect Node E with other nodes in the graph network, it can be seen that Edge EB and Edge EC are 4 meters, and Edge ED is 2 meters. Edge EA is marked and it cannot be used in this iteration. Among these three alternatives, the edge with the minimum cost is Edge ED that takes the algorithm to Node D. Thus, Edge ED and Node D are marked. Figure B.3 shows the second iteration schematically. Total cost was 3 before this iteration. Adding the cost of this iteration, which is 2, the total cost at the end of second iteration becomes 5.

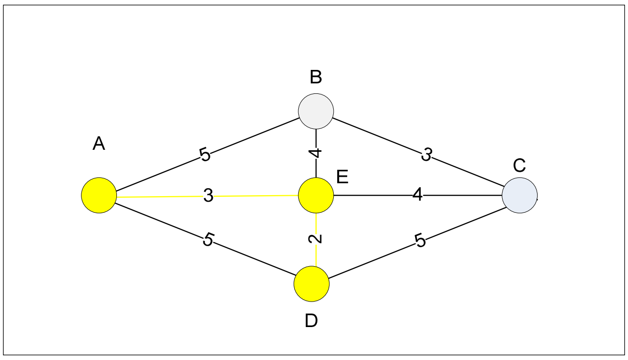


Figure B.3: Second iteration of the algorithm

In the third iteration, the next node should be reached from Node D. Since Node A is marked, there is no need to try to reach to that node using Edge DA. Edge DE is also marked. Hence, the only option is reaching to Node C using the Edge DC that has a cost of 5. With this option, the total cost becomes 10. However, this is not correct. If this path was selected and the algorithm comes to Node C, in the next iteration that is performed to reach Node B, the algorithm would have selected Edge BC that has a cost of 3. Considering the total movement from Node D, to reach Node B, the cost would be 8. On the other hand, Node B can also be reached from Node E that has a cost of 4 (cost of Edge EB). Following this, to reach Node C from Node B, the cost is 3 (cost of Edge BC). Consequently, the total cost is now 7, which is smaller than the previous alternative that had a cost of 8. As a result, the algorithm will use Edge EB to reach Node B instead of using Edge DC to reach Node C. Then, Edge EB and Node B are marked. After second iteration, the total cost was 5. Since Edge EB has a cost of 4, the total cost becomes 9. The third iteration is shown in Figure B.4 schematically.

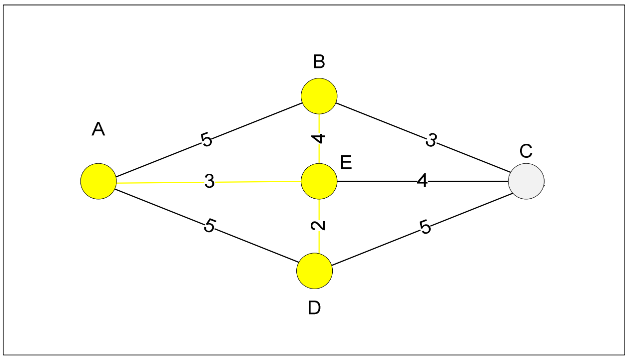


Figure B.4: Third iteration of the algorithm

The last iteration will be performed to reach to the last node, Node C. As explained in the previous iteration, the only option is Edge BC that has a cost of 3. Thus, the total cost of the minimum spanning tree in this example is 12. Figure B.5 demonstrates the final iteration.

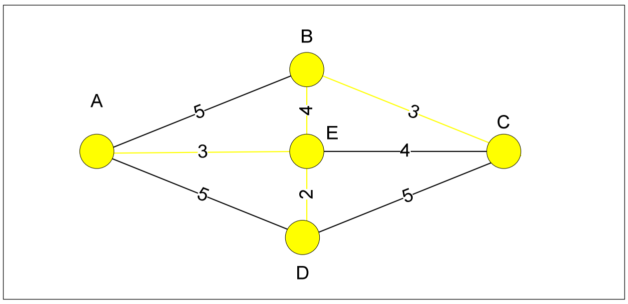


Figure B.5: Fourth iteration of the algorithm

According to these iterations, the minimum spanning tree obtained by running Prim's Algorithm and Dijkstra's Algorithm will be the tree shown in Figure B.6. The minimum spanning tree will reach to every node in the network.

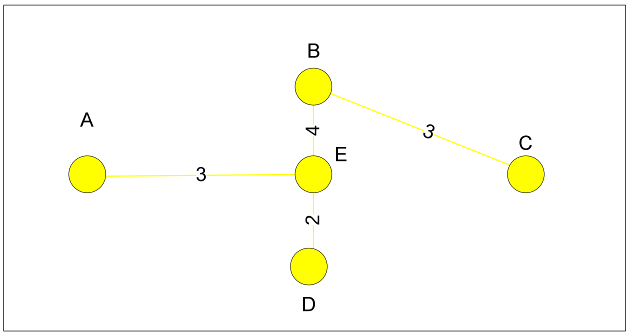


Figure B.6: The minimum spanning tree for the network

APPENDIX C

WORKING MECHANISM OF A* ALGORITHMS: AN EXAMPLE

The working mechanisms of A* Algorithms can be summarized in five steps.

Step 1:

The first step for A* Algorithms to perform is dividing the area (space) into smaller pieces. This is similar to preparing graph networks for other shortest path algorithms.

There are several different methods for dividing the areas. For simplicity, the area in the given example will be divided into equivalent squares. The whole area and the equivalent squares constituted in the example can be seen in Figure C.1. Suppose that the origin is Point A and the target destination is Point B in this example. The three black squares in the figure represent the non-accessible locations in the area. Other squares are assumed to be accessible.

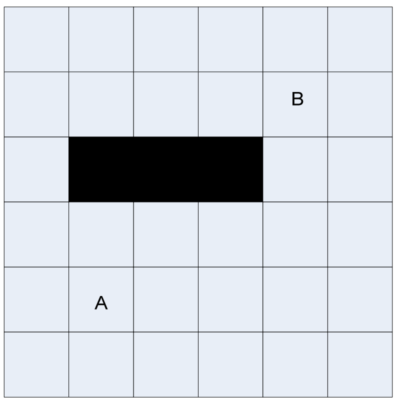


Figure C.1: The area for the A* Algorithm example

Step 2:

In the second step, search for the shortest path is started and the neighboring squares are included to the "available squares list (open list)".

The search for the shortest path to reach Point B starts from the origin point (Point A). The neighboring squares of the square that holds Point A will be placed into the available squares list. The square that holds Point A will be called the "parent square". Direction arrows will be drawn to the squares in the available squares list and these arrows will be heading to the parenting square. The direction arrows of the squares in the available squares list will be represented by red arrows while the arrows of the squares that are not in the list will be represented by black arrows. The whole phenomenon explained in this paragraph is demonstrated in Figure C.2.

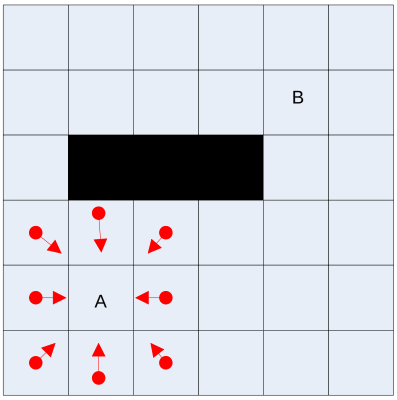


Figure C.2: List of available squares neighboring the square holding Point A and their direction arrows

Step 3:

In the third step, the next square to be selected will be determined. For this reason, the equation "F = G + H" will be used. Here, "G" is the real distance value that represents the distance between the origin and the target locations. “H” is the predicted distance value between the origin and the target. It is obtained by using heuristic methods. The H value prediction is a very important task. As the predicted distance becomes closer to the real distance, the iteration and calculation speed of the A* Algorithms will improve. In addition, if the predicted value is larger than the real value, the guarantee of obtaining the shortest path between the origin and target points is lost. Thus, predicting the distance is a critical task.

There are several different heuristic methods used for predicting the “H” value. Manhattan Method and Diagonal Shortcut Method are among the most commonly preferred methods. The “H” values predicted by using Manhattan Method are generally very close to the real values. Thus, it can be said that A* Manhattan Algorithm has high iteration and calculation speeds. This property of the Manhattan Method brings it one-step forward than the other methods. For this reason, to solve the example given here about A* Algorithms, Manhattan Method will be used. However, in some cases (especially, when the distance between the origin and the target increases), “H” value predicted by using Manhattan Method can be larger than the real value, which hampers the guarantee of obtaining the shortest path.

In Manhattan Method, the movement (passing to the next square) should be either horizontal or vertical. Diagonal movements are not preferred. Thus, diagonal movements have an extra penalty cost. In this example, the cost of horizontal and vertical movements is 10 meters while the cost of diagonal movements is 14 meters (with extra penalty values). Since diagonal movements are not allowed in Manhattan Method, to reach to Point B from Point A, three vertical and three horizontal movements (total of six movements with 10 meters cost) should be done. Thus, the distance between A and B will be 60 meters (Figure C.2). In the light of these, the “H” values will be predicted for the squares that are in the available squares list of the square that holds Point A.

After predicting the "H" value, it will be summed with "G" value (the real distance value) and an "F" value will be obtained. The square that has the lowest "F" value will be selected as the next square to be moved. The selected square will be taken out of the available squares list and will be appointed as the new parent square. Since the parent square have changed, the available squares list should be updated accordingly.

Figure C.3 demonstrates the selection when the parent square is the square that holds Point A. The values in the squares are in terms of distance. The numbers on the bottom left of the squares are "G" values, the numbers on the bottom right of the squares are "H" values, and the values on the top are "F" values. The square with the minimum "F" value has a value of 54 meters. Therefore, that square is selected as the next square and it is taken out of the available squares list. It becomes the new parent square and two new squares are added to the available squares list accordingly.

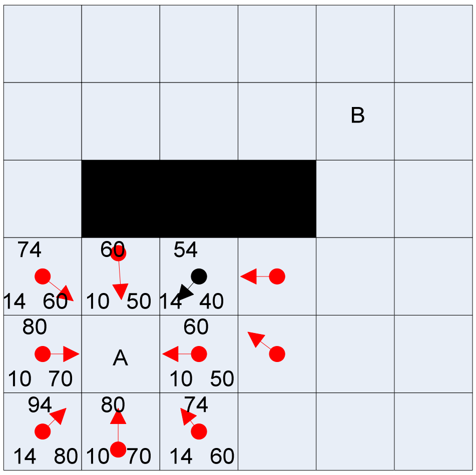


Figure C.3: Iteration and selection procedure of A* Algorithm (Manhattan Method)

Step 4:

The iteration and selection procedure explained in Step 3 will be repeated until the target square is reached. There is an important point to be taken into consideration during these repetitions. When a new square is selected, that square should be taken out of the available squares list and new squares should be added to the list according to the selected square (new parent square).

Step 5:

When the target square is reached, the arrows showing the directions in the selected squares are connected with each other until the origin square. With this, shortest path between the origin and the target is obtained.

APPENDIX D

AN EXAMPLE A* MANHATTAN ALGORITHM APPLICATION IN 2D ENVIRONMENT DURING EMERGENCY RESPONSE AND DISASTER MANAGEMENT

In Figure D.1, the floor plan of a building can be seen with the evacuation paths generated by the A* Manhattan Algorithm before a disaster/emergency. Dotted lines represents the evacuation paths for occupants, brown lines represent the walls, grey sections represent the stairs (exits from the floor), and white squares represent the nodes on that floor. The evacuation paths that are generated for every node on the floor guide the occupants to the closest stair for exit. In other words, occupants are evacuated from the shortest possible way.

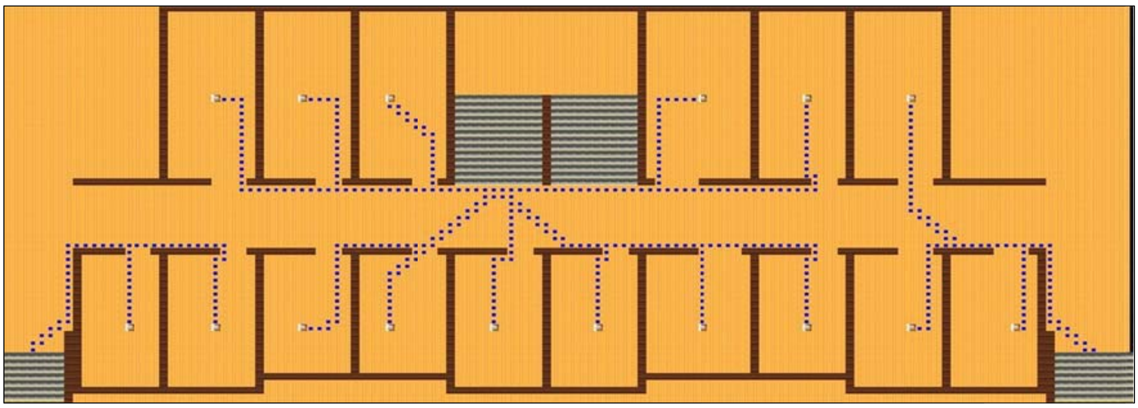


Figure D.1: Floor plan of a building with the evacuation paths generated by the A* Manhattan Algorithm (before a disaster/emergency)

Figure D.2 shows the same floor plan after a disaster/emergency affected the building. The building is damaged by the disaster/emergency. It is assumed that the access between the rooms on the left side of the floor and the stairs in the middle and right sections of the floor are lost. The A* Manhattan Algorithm regenerates the evacuation paths according to the changed conditions. The alterations in the evacuation paths can be observed from Figure D.2.

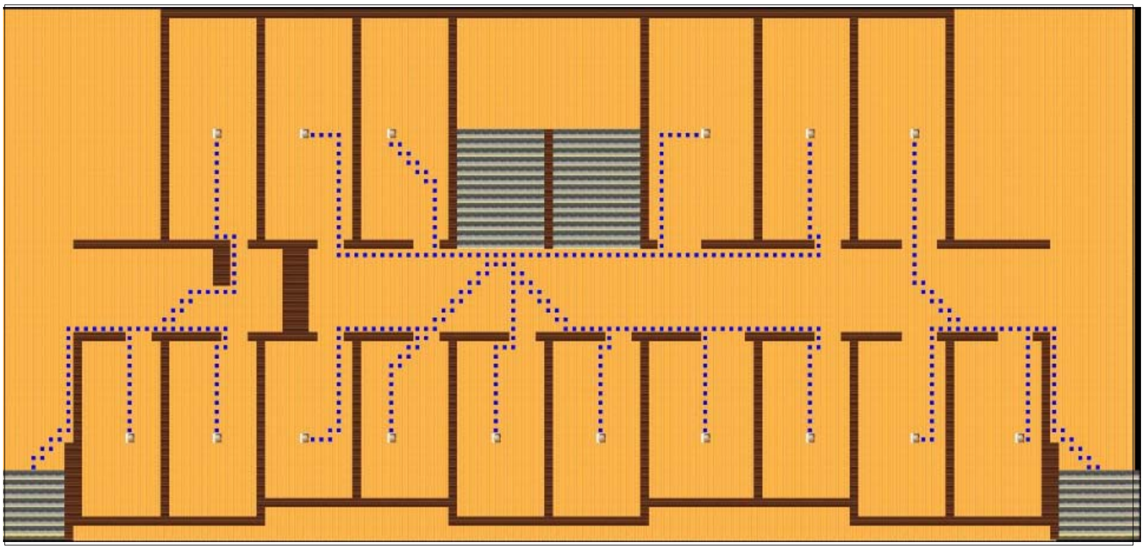


Figure D.2: The same floor plan after a disaster/emergency with the regenerated evacuation paths by the A* Manhattan Algorithm