A COMMUNICATION SYSTEM TO SUPPORT EVACUATION ROUTE IN THE BUILDING CONSTRUCTION PROJECT

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สมจินตนา แขนงแก้ว : ระบบสื่อสารเพื่อสนับสนุนเส้นทางอพยพในโครงการก่อสร้างอาคาร. (A COMMUNICATION SYSTEM TO SUPPORT EVACUATION ROUTE IN THE BUILDING CONSTRUCTION PROJECT) อ.ที่ปรึกษาหลัก : รศ. ดร.นพดล จอกแก้ว, อ.ที่ปรึกษาร่วม : รศ. ดร.ธนิต ธงทอง

ตลอดระยะเวลาที่ผ่านมา พบว่า การเกิดเหตุการณ์ฉุกเฉินในโครงการก่อสร้าง ส่งผลกระทบทำให้คนงานก่อสร้างและผู้ที่เกี่ยวข้องได้รับบาดเจ็บและเสียชีวิตจำนวนมาก เนื่องจากลักษณะของโครงการก่อสร้างอยู่ในรูปแบบพลวัต ในปัจจุบันรูปแบบการจัดการเพื่อสนับสนุนเส้นทางอพยพในโครงการก่อสร้าง จัดอยู่ในรูปแบบสถิตและไม่มีปฏิสัมพันธ์ เช่น แผนอพยพในรูปแบบ 2 มิติ ไม่สามารถแสดงเส้นทางอพยพที่เหมาะสมได้ทันที รวมถึงการติดตั้งป้ายทางออกฉุกเฉินที่ไม่ชัดเจนและแสดงเส้นทางอพยพที่ไม่ถูกต้อง เนื่องจากลักษณะของโครงการก่อสร้างที่เปลี่ยนแปลงตามแผนงานก่อสร้าง และพบว่าแผนการอพยพปัจจุบันมีข้อจำกัดและจำเป็นต้องมีการปรับปรุง แบบจำลองสารสนเทศอาคารและเทคโนโลยีความจริงเสมือนเสริม สามารถแสดงเส้นทางอพยพ ตำแหน่งทางออกในรูปแบบ 3 มิติและสามารถอัพเดทความคืบหน้าของโครงการก่อสร้างได้ ดังนั้นงานวิจัยนี้มีวัตถุประสงค์เพื่อนำเสนอระบบสื่อสารที่สนับสนุนเส้นทางการอพยพ โดยคำนึงถึงลักษณะของโครงการก่อสร้างแบบพลวัต จากการศึกษาพบว่า ระบบสื่อสารเพื่อสนับสนุนเส้นทางการอพยพ ทำให้คนงานก่อสร้างและผู้ที่เกี่ยวข้องสามารถรับรู้ข้อมูลในการอพยพ เช่น เส้นทางอพยพที่เหมาะสม ตำแหน่งทางออก เสียงและสัญลักษณ์บอกทิศทาง ระยะทางจากตำแหน่งปัจจุบันถึงทางออก รวมถึงหลีกเลี่ยงสิ่งกีดขวางในโครงการก่อสร้าง เป็นต้น งานวิจัยนี้ได้ทำการตรวจสอบความถูกต้องของระบบสื่อสารเพื่อสนับสนุนเส้นทางอพยพจากการร่วมประเมินและทดสอบจริงของวิศวกรจำนวน 3 คน นักศึกษาฝึกงานจำนวน 4 คนและคนงานก่อสร้างจำนวน 5 คน ผ่านเทคโนโลยีแบบจำลองสารสนเทศอาคาร เทคโนโลยีความจริงเสมือนเสริมและโครงการก่อสร้างจริง จากการทดสอบพบว่า ระบบสื่อสารเพื่อสนับสนุนเส้นทางอพยพสามารถนำเสนอข้อมูลอย่างถูกต้องตามลักษณะของโครงการก่อสร้างได้

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In the past decade, emergencies have occurred in construction projects, directly influencing injuries and casualties due to the dynamic nature of construction. Currently, the practice of developing evacuation routes for most construction projects is presented in a static and non-interactive manner. This involves a two-dimensional evacuation plan that cannot provide a real-time evacuation route. Furthermore, some emergency signs are unclear and do not provide the correct evacuation routedue to construction activities not aligning with the construction progress. Therefore, conventional evacuation plans have limitations and require improvement. Building Information Modeling (BIM) and Augmented Reality (AR) can present the evacuation route position of exit in a three-dimensional and can update the construction work following the construction progress. The objective of this research is to develop a communication system to support the evacuation route in a dynamic nature to assist construction workers and staff in accessing evacuation information such as appropriate evacuation route exit voice and arrow direction distance from the current location to the exit and obstacle avoidance in the construction project. In addition, to validate the proposed system approach, the case study uses Building Information Modeling (BIM) and Augmented Reality (AR), and a real construction project is executed. Moreover, three engineers, four trainees, and five construction workers participated in evacuating the proposed system. The result indicated that the proposed system could provide the correct evacuation route following the dynamic nature of the construction project.

Field of Study:	Civil Engineering	Student's Signature ....
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Introduction

1.1 Background

1.1.1 Communication system in construction projects

Communication is the heart of implemented projects (Taleb et al., 2017). The construction process requires collaboration between people, and the contractor should be able to communicate in a clear (Tessema, 2008) and understandable platform between the receiver and sender (Ahmed et al., 2021). Communication is one of the most critical factors contributing to success because of the numerous parties involved in working together and addressing the issues occurring on projects (Safapour et al., 2019). In general, communication is based on a two-way exchange of information. Just providing (sending) information is not communicating, except in some uncommon situations where the receiver has nothing to do with delivering the service (Goh et al., 2014).

Construction is a high-hazard industry comprising a wide range of construction activities. The construction phases record high accidents compared to other phases. Because the characteristics of construction projects are extremely complex and often take place in an uncontrolled, unprepared, and dynamic environment where each project goes through several phases leading to completion (Sardroud, 2012), continuously changed workplaces, the number of occupants, spaces, and evacuation routes change from one day to another (Daour, 2018). In addition, evacuation conditions in the construction phases differ from the other phases, and the disasters are becoming diverse (Min-Yuan Cheng, 2016), making it challenging to predict the appropriate evacuation routes.

The construction project is a fragmented and dynamic sector with a project-based nature. This means many stakeholders operate in frequently changing relationships (Hoezen et al., 2006).

An essential key to effective emergency response is a communication system that can replay accurate information quickly. In order to achieve effective communication and be reliable, information should exist only once rather than be duplicated unnecessarily, communications equipment must be used, procedures developed, and personnel trained. However, the current communication system in a construction project is a non-interactive system of communication between the owner, contractor, consultants, and other parties that uses email, drawings (CAD), phone calls, WhatsApp, and site meetings (Ahmed et al., 2021). According to OSHA statistics (2001), various emergencies may necessitate swift evacuation on a construction project, including severe or unexpected weather, earthquakes, and partial building collapse. Additionally, it is crucial to ensure that evacuation plans are robust enough to handle unforeseen events.

Meanwhile, in the current practice, the construction project has one party responsible for monitoring and controlling the safety of the construction project. However, in an emergency, that party cannot control the communication system with stakeholders and provide the information to evacuate from the hazardous area directly and in real-time, which leads to injuries and casualties. However, the current communication system is not appropriate for the dynamic nature of the construction project and cannot provide the information for daily evacuation. Therefore, the current practice requires adequate information access to enhance the interactive communication system among the involved participants in the construction project.

1.1.2 Evacuation route in Construction Projects

Generally, construction site environments have many temporary works and continuously changing workplaces, meaning the number of occupants, spaces, and evacuation routes change from one day to another (Daour, 2018). Furthermore, evacuation routes cannot identify locations due to continuously evolving workplaces and obstructed hallways from materials and equipment. The lack of identification of evacuation routes on-site frequently results in additional cost growth schedule delays during construction phases (Jungsik Choi, 2014). However, for the common evacuation routes in construction projects, the drawings were usually guided in two-dimensional (2-D) views to explain hazardous areas and evacuation routes, as shown in Figure 1.1. Common users cannot interpret the drawings quickly, understand their position within the building, and select appropriate evacuation routes (Kun-Chi Wang, 2014). In addition, recent relevant research has identified the cause of a high proportion of emergency casualties as a direct link with the delayed evacuation service of the facility (Fahy, 2001), which the lack of real-time information updates can cause, such as building users in an emergency cannot get the real-time location evacuation route (Bin Wang, 2014). Thus, to reduce the number of injuries and fatalities from emergencies in the construction project, it is essential to prepare a communication system based on real-time information that may improve the decision-making process and provide real-time access to information for evacuating and guidelines to direct construction workers and staff to evacuate as fast as possible from the hazardous location.

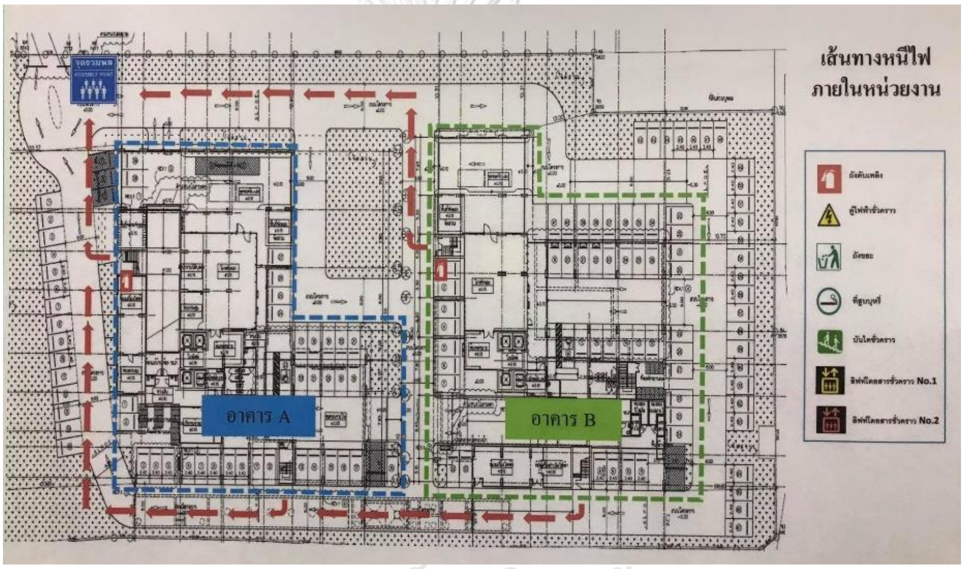


Figure 1.1 Evacuation routes in construction project

In the past decade, researchers have made significant progress in the development of technologies and tools for managing emergency evacuation in construction projects and improved by researchers (Shiau, Lu, and Chang, 2014; Choi, Choi, and Kim, 2014; Wang et al., 2014; Wehbe and Shahrour, 2017; Feng and Kamat, 2012; Adjiski, Despodov, and Serafimovski, 2017; Rüppel and Schatz, 2011; Cheng et al., 2016; Chen et al., 2016). Information technology, especially visualization technologies, has been developed and widely used in construction projects to increase safety. The primary goal is to prepare the communication system using tools, such as visualization technologies, to evaluate and provide guidelines to help construction workers and staff evacuate from hazardous locations. Furthermore, using innovative technology can improve the communication of safety information among project participants. (Petcharat Limsupreeyarat, 2012).

1.2 Problem Statement

1.2.1 Need to manage evacuation safety

In recent years, with the rapid increase in high-rise buildings, the harm of high-rise building fires to lives and properties has become serious (Chen Haitao, 2012). According to statistics from 2012 to 2018, the Bangkok Fire and Rescue Department responded to an estimated average of 889 reported structure fires per year (Department of Alternative Energy Development and Efficiency, 2021). Many high-rise building fires occurred during this period and caused severe damage to the construction project. The construction project is characterized by its dynamic nature and physically demanding tasks, which have the number of occupants, spaces, and routes changing over time depending on the project work schedule. These characters may pose increasing risks and be more dangerous and severe.

According to the current practice, in most construction projects, fire exit signs and evacuation routes are not adapted according to the dynamic nature of the construction project. Construction workers and staff use their experience and intuitive understanding of changing workplace conditions (Soltani et al., 2002). For example, material handling is one of the construction activity must be used to become acquainted with the movement of materials and goods from one location to another, which leads to a high risk of human errors in the decision-making process of selecting the appropriate evacuation route in the construction project, in case of a new construction worker, who does not have the experience and understanding with the position in the construction project. However, the construction industry follows site-specific fire safety planning practices, which must be reviewed and updated regularly (Choe & Leite, 2017). Consequently, the current fire evacuation plan is not updated with the construction work schedule and environment. In addition, being stuck by an object obstructed by materials and equipment, as shown in Figure 1.2, is one of the four fatalities when fire accidents occur in the construction stages. These causes of fire accidents lead to injuries or the fatalities of construction workers and staff when a fire occurs in construction projects.

Figure 1.2 An object obstructed by materials and equipment in the construction project.

For example, on April 1, 2020, at the construction site at the New Phetchaburi Road fire, 37 construction workers got stuck and could not find the evacuation route while they waited for help from firefighters for around 30 minutes to move away to their destination and one construction worker was injured; on August 31, 2020, in the construction project at Srinakarin road fire a construction worker was injured, as shown in Figure 1.3

Figure 1.3 Fire accident at the construction project (JS100 Radio, 2021)

The damages can be found in the construction project and the number of dead or injured workers involved in the cases. Therefore, evacuating people to a safety zone in most emergency management is crucial to prevent loss of life and property from fire occurring in the construction project (Guo Li, 2013).

1.2.2 The real-time and actual site conditions that influence users in the decision-making

Emergency guidance plans, such as exit signs and evacuation route maps, are present in a static way of expression (Ma et al., 2017) to explain hazardous areas and evacuation routes. These emergency guidance plans cannot interpret the drawings quickly, and there is poor visibility. Meanwhile, for high-rise buildings, which are complex structures with many exits, different fire exits directly affect the evacuation route options (Lim & Rhee, 2010), and it is difficult to understand their exact position within the building. Moreover, laws and regulations indicate that all fire exit signs and access ways must be marked by approved signs readily visible from any direction of exit access; every sign must be located in such a way that it is readily visible and of the correct size, distinctive colour, and design to provide contrast with decorations, interior finish, or other signs.

Moreover, the convention evacuation plan also has limitations, and it still needs to be improved. Most construction projects have emergency exit signs, but these emergency signs are not enough to reach a safe place and are not installed in every position on every floor. Some fire exit signs were unclear and could not be modified according to the construction progress, which could have resulted in construction workers and staff not knowing the appropriate evacuation route. Furthermore, fire exit signs and evacuation plans may show the shortest route to the assembly point, but these routes are not considered risk locations, such as the obstacle location. Therefore, the current emergency guidance plans cannot provide the appropriate fire evacuation routes and must be improved.

In addition, material handling is one of the construction activities that requires familiarity with and experience of construction workers and staff with the route and information of the storage location. Thus, if construction workers and staff are unfamiliar with the route, they risk losing and not getting updated information on evacuation routes, leading to work delays, injuries, or fatalities. However, in the current construction project, the evacuation route is presented in the two-dimensional drawings (2-D drawing), and the route has not been updated following the daily construction work schedule.

According to the Ministerial Regulation on the Standard for Administration and Management of Occupational Safety, Health, and Environment concerning Fire Prevention and Control, B.E. 2555 (A.D. 2012), section 30, employers should arrange for all employees to undergo fire drills and practice to evacuated at least once a year. Furthermore, construction toolbox talks are brief (10 - 15 min) at the beginning of the work shift on Monday morning to discuss a specific health and safety topic with a group of construction workers. A construction toolbox talk is traditional and potentially impactful for supervisor safety communication in construction (Olson et al., 2016). For example, a construction toolbox for fire safety could refresh people’s knowledge about how fires start, what types of fire hazards are present on the construction site, and how to minimize the risks in workplaces. In contrast, the construction characteristics and environment are dynamic, meaning the fire evacuation route will change daily, and real-time data cannot be provided for construction workers and staff. The difficulty in determining the appropriate evacuation route is because construction workers and staff may not investigate how to evacuate as fast as possible within the prescribed time. Furthermore, a lack of accurate and immediate guidance severely affects the evacuation.

In this research, a new communication system can effectively support the evacuation and material handling route in the dynamic nature of the construction project, which directly influences the evacuation route and work schedule and can impact evacuation performance. Moreover, the problem of the construction project has a non-interactive communication system as real-time communication will be solved by proposing a new communication system that can efficiently reduce potential hazards in the construction project by automatically generating appropriate evacuation routes as an effective tool is needed to support decision-making and enable common users, who were construction workers and staff to perceive and understand information clearly and efficiently for evacuation purposes to assist common users in the evacuation process. Meanwhile, this tool could advance the construction sector and benefit a project with accelerated on-site training and communication with all parties involved, from the owner to the construction workers. A new communication system can observe evacuation guidance representing information such as voice and arrow directions for evacuation guidance, virtual green line, exit, distance from the current location to the exit, and the appropriate evacuation route in the construction project. Consequently, the problem with the current evacuation plan is that it is not updated with the construction work schedule and environment, and being stuck by an object obstructed by materials and equipment would be improved by providing the appropriate evacuation route via the mobile application.

1.3 Research Objectives

Objectives of this dissertation are:

1) To develop a communication system to support the evacuation route in a dynamic nature.

2) To enhance a system that can be used to generate the appropriate evacuation route.

1.4 Scope of Study

Scope of study in this dissertation are:

1) The construction project type was building projects in the construction phases.

2) The tools used to develop a system were visualization techniques, which are Building Information Modeling (BIM) and Augmented Reality (AR).

1.5 Research Methodology

The research methodology employed in this research is as follows:

1) A review of the previous literature related to fire accidents in construction projects and fire emergency procedure.

2) A review of previous literature related to visualization technology in construction. Visualization technology should transform and enhance information in real-time for construction workers and staff associated with evacuation in the construction project. Building Information Modeling (BIM) and Augmented Reality (AR) and the advantages and limitations of these technologies were identified.

3) Building construction projects are surveyed to investigate the current evacuation management regarding the evacuation route in the construction project. Walkthroughs and direct interviews were applied to collect data. Additionally, photography and video recordings, such as the construction environment, construction activities, and emergency exit location, were also implemented and analyzed to examine the potential evacuation improvement.

4) Design the proposed system concept from the literature review and observed data.

5) Design a prototype system for guidelines for construction workers and staff to improve decision-making, provide the information for evacuating from the hazard location, and experiment with the prototype system in the laboratory and construction project.

6) Verify and validate the proposed system and identify the system limitations.

7) Summarize and discuss the results.

1.6 Research Contribution

The contributions of this research comprise the following:

1) The output will be a new communication system considering the evacuation route, voice and arrow directions, and obstacle avoidance.

2) The algorithm developed for the evacuation system can be used in the dynamic nature of the construction project.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a literature review of related studies. The contents are divided into ten sections. First, the definition of real-time is described. In the second, the general emergency procedures of the building are described. In the third section, the general emergency procedure of the building is described. The fourth section reviews the type of evacuation of the high-rise building. In the fifth section, the average speed of the evacuee is reviewed. In the sixth section, communication of the procedure is reviewed. In the seventh section, regulations relating to the evacuation plan are reviewed. This section contains rules, regulations, and guidelines for evacuation procedures. In the eighth section, the current practice guide construction project. Next, visualization technology employed to enhance communication is described. This section is divided into Building Information Modeling (BIM) and Augmented Reality (AR). The last section is the research gap.

2.2 Definition of Real-Time

Real-time systems have been defined as predictably fast enough for use by processes being serviced (Dodhiawala et al., 1989); there is a strict time limit by which a system must produce a response, regardless of the algorithm employed (O'Reilly & Cromarty, 1985); the ability of the system to guarantee a response after a domain defined fixed time has elapsed (Laffey et al., 1988); and a system designed to operate with a well-defined measure of reactivity (Georgeff & Ingrand, 1989).

2.2.1. Four aspects of Real-time performance

While speed is indeed fundamental to real-time performance, speed alone is not real-time. The four aspects of real-time performance are:

- Speed
- Responsiveness

- Timeliness
- Graceful adaptation

2.3 General emergency procedures of the building

In an emergency within a building, locating the nearest exit or alternative routes is crucial if the primary one is obstructed. Except for a hostage crisis, where a stay-in-place strategy is vital, the optimal action is to vacate the hazardous area while conditions remain favorable. Unwarranted use of emergency phone calls may delay the delivery of vital resources to the most vulnerable locations. In general, do not use the elevators; even if it is safe to use them, elevators will be needed by authorized personnel to evaluate people with disabilities and children. No one can use elevators during emergencies such as a fire or structural damage. Most people use the stairs to evacuate during an emergency evacuation, causing congestion.

2.4 Type of evacuation of the building

According to the National Fire Protection Association (Kobes, Helsloot, De Vries, & Post, 2010), buildings with a height of more than 75 ft (approximately 23 m) are defined as high-rise buildings. In contrast, the definition of high-rise buildings in Thailand is similar. According to the definition of the Thailand Building Control Act B.E. 2535 (1992), the height of the high-rise building is over 23 meters.

Evacuation in an emergency is a crucial problem in a building, as many occupants are in a limited amount of space. The evacuation process in buildings can be divided into two parts: horizontal evacuation and vertical evacuation. Typically, the structure of buildings is complex and confusing, with many turns and obstacles. It is not easy for evacuees to find an exit to the staircases. In an internal evacuation, route choice strongly influences the time cost and final evacuation efficiency (Ding et al., 2021).

2.4.1. Horizontal evacuation

There are three typical behaviors involved in horizontal emergency wayfinding: perception of guidance, leader–follower behavior, and heading behavior. The details of each behavior are described:

(1) Perception of guidance

As evacuation signs are crucial information indicators for indoor evacuation, pedestrians engage with these signs and make evacuation decisions after processing the signals (Chu et al., 2015),(Kobes, Helsloot, De Vries, Post, et al., 2010). The interaction process between pedestrians and signs can be divided into three phases: perceiving the sign, detecting the sign, and following the sign (Xie et al., 2007). Various factors influence this interaction process, including objective features of the signs, cognitive abilities of pedestrians, building environments, and so on (Filippidis et al., 2006).

(2) Leader–follower behavior

Most individuals are followers during an evacuation (Cornwell, 2003), (Johnson, 2005). They often hesitate to react to danger initially, preferring to wait for others to take the lead. Practical guidance from a leader can significantly improve evacuation efficiency. The choice of evacuation direction is closely tied to leader and follower behavior. In complex high-rise buildings, choosing the wrong escape direction can waste valuable evacuation time and potentially lead to fatalities. Investigating the dynamics of leader-follower formations and opinion spread is crucial for enhancing evacuation management and promoting efficiency.

(3) Herding behavior

Herding behavior pertains to individuals in high-pressure situations who are influenced by group dynamics, abandoning their personal views to align with the majority. This behavior is blind, with pedestrians lacking an exact leader to follow. Route choices emerge from the group rather than specific evacuees. In contrast, leader-follower groups can opt for a different exit from the entire group. This distinction between leader-follower behavior and herding behavior is crucial.

2.4.2. Vertical evacuation

Egress choices encompass stairs, evacuation elevators, and other modern evacuation aids, with individuals exhibiting diverse behaviors during evacuations based on these options. Traditionally, stair evacuation is not only the conventional but also the recommended method in most buildings. Nevertheless, with the growing height of high-rise structures, the likelihood of staircase congestion increases if occupants opt for stairs during evacuation. Additionally, in high-rise buildings, relying solely on stairs for evacuation can result in pedestrian fatigue, particularly for those on higher floors, thus diminishing the efficiency of crowd evacuation.

(1) Evacuation behavior in stairs

In vertical staircases, pedestrian flow characteristics often differ from horizontal evacuations, and the discrete steps can limit evacuation speed. Moreover, except for spiral steps, every two stairs need to be connected by a platform, requiring individuals to navigate side turns, resulting in a slower pace. Numerous scholars have focused on the evacuation speed in staircases.

(2) Merging behavior

Merging behavior occurs on the stair landings of high-rise buildings when occupants enter the stairwell and blend with downstream crowds—the location, flow, and local density of merging notably impact evacuation speed. Merging behavior on each floor of the staircase platform holds significance in the evacuation of high-rise buildings. Pedestrian behavior influences the speed of pedestrian flow, consequently affecting the overall evacuation time.

2.5 Average speed of the evacuee

Much previous research has analyzed the evacuee's average speed with different sizes of singles and pedestrian groups, which showed that both step time and step width for groups with larger sizes are significantly higher during descending movements (Fu et al., 2020). Köster et al. (2019) found that pedestrians are generally slower upstairs than downstairs when on the stairs only, while the situation is opposite when on the landing. Kretz et al. (2018) tested evacuees' speed on the stairs at two different slopes: 35.1°and 22.2°. The average speeds of the evacuees from previous research are shown in Table 2.1. (Kretz et al., 2008)

Table 2.1 Average speed of the evacuee in the references

Source	**Mean Velocity (m/s)**	**Age**	**Gender**	**Slope**	**Distance**
Fruin (1971) (Fruin, 1971)	0.60	Over 50	Female	26.5°& 31.9°	1st floor
	0.67	Over 50	Male		
	0.67	30–50	Female		
	0.76	30–50	Male		
	0.88	Under 30	Female		
	1.01	Under 30	Male		
Averill et al. (2005)	0.20	(Averill et al., 2005)			
Galea (2012)	0.29				
Kretz et al. (2008) (Kretz et al., 2008)	0.90 (0.58-1.44)			22.2°	
Yeo & He (2009) (Yeo & He, 2009)	0.42		Male	Vertical travel speed	Short stair
	0.36		Female		
Choi et al. (2014) (Choi et al., 2014)	0.83	23.4	Male	32.5°	50 floors
	0.74	23.4	Female	32.5°	50 floors

2.6 Communication of the procedure

According to the Construction Safety Association of Ontario (2003), in order to be effective, an Emergency Response Procedure must be communicated to all site personnel. The following activities should be considered:

(1) Review the procedure with new site subcontractors and new workers to ensure that it covers their activities adequately.

(2) Review the procedure with suppliers to ensure that it covers any hazards that the storage or delivery of their material might create.
(3) Review new work areas in operating plants with the owner/client to ensure new hazards are identified and covered in the procedure.
(4) Review the procedure with the Joint Health and Safety Committee or Health and Safety Representative regularly to address new hazards or significant changes in site conditions.
(5) Post the procedure in a conspicuous location.

The Emergency Response Procedure for a construction project must continuously undergo review and revision to meet changing conditions.

2.7 Regulations relating to the evacuation plan

Nowadays, there are many evacuation plan rules, regulations, and guidelines. The details of the rules, regulations, and guidelines are as follows:

2.7.1. Managing health and safety in construction, Construction (Design and Management) Regulations 2015

a) Regulation 30 (Emergency procedures)

1) Where necessary in the interests of the health or safety of a person on a construction site, suitable and sufficient arrangements for dealing with any foreseeable emergency must be made and, where necessary, implemented, and those arrangements must include procedures for any necessary evacuation of the site or any part of it.

2) In making arrangements under paragraph (1), account must be taken of---

- The type of work for which the construction site is being used;
- The characteristics and size of the construction site and the number and location of places of work on that site;
- The work equipment being used;
- The number of persons likely to be present on the site at any one time

  - The physical and chemical properties of any substances or materials on, or likely to be on, the site

3) Where arrangements are made under paragraph (1), suitable and sufficient steps must be taken of---

  - Each person to whom the arrangements extend is familiar with those arrangements, and
  - The arrangements are tested by being put into effect at suitable intervals.

b) Regulation 31 (Emergency route and exits)

1) Where necessary, in the interests of the health or safety of a person on a construction site, a sufficient number of suitable emergency routes and exits must be provided to enable any person to reach a place of safety quickly in the event of danger.

2) The matters in regulation 30(2) must be taken into account when making provision under paragraph (1).

3) An emergency route or exit must lead to an identified safe area as directly as possible.

4) An emergency route or exit and any traffic route giving access to it must be kept clear and free from obstruction and, where necessary, provided with emergency lighting so that it may be used at any time.

5) Each emergency route or exit must be indicated by suitable signs.

2.7.2. Occupational Safety and Health Standards (OSHA) (1970)

a) Standard Number - 1910.38

1) Standard Number - 1910.38(a)

  - An employer must have an emergency action plan whenever an OSHA standard in this part requires one. The requirements in this section apply to each such emergency action plan.

2) Standard Number - 1910.38(b)

- An emergency action plan must be in writing, kept in the workplace, and available to employees for review. However, an employer with ten or fewer employees may communicate the plan orally to employees.

3) Standard Number - 1910.38(c)(2)

- An emergency action plan must include, at a minimum, procedures for emergency evacuation, including type of evacuation and exit route assignments.

4) Standard Number - 1910.38(e)

- An employer must designate and train employees to assist in a safe and orderly evacuation of other employees.

5) Standard Number - 1910.38 (f)(1)

- An employer must review the emergency action plan with each employee covered by the plan when the plan is developed or the employee is initially assigned to a job.

6) Standard Number - 1910.38 (f)(2)

- An employer must review the emergency action plan with each employee covered by the plan when the employee's responsibilities under the plan change.

7) Standard Number - 1910.38 (f)(3)

- An employer must review the emergency action plan with each employee covered by the plan when the plan is changed.

b) Standard Number – 1910 Subpart E App

1) At the time of an emergency, employees should know what type of evacuation is necessary and what their role is in carrying out the plan. In some cases where the emergency is

very grave, total and immediate evacuation of all employees is necessary. In other emergencies, a partial evacuation of nonessential employees with a delayed evacuation of others may be necessary for continued plant operation. In some cases, only those employees in the immediate area of the fire may be expected to evacuate or move to a safe area, such as when a local application fire suppression system discharge employee alarm is sounded. Employees must be sure that they know what is expected of them in all such emergency possibilities that have been planned in order to ensure their safety from fire or other emergencies.

2) The designation of refuge or safe areas for evacuation should be determined and identified in the plan. In a building divided into fire zones by firewalls, the refuge area may still be within the same building but in a different zone from where the emergency occurs

c) Standard Number - 1918.100

1) Standard Number - 1918.100(b)(1)

- Emergency escape procedures and emergency escape route assignments.

2) Standard Number - 1918.100(d)

- The employer shall establish the types of evacuation to be used in emergency circumstances.

d) Fact Sheet – Evacuating High-Rise Buildings

1) Do not lock fire exits or block doorways, halls, or stairways.

2) Regularly test all backup systems and safety systems, such as emergency lighting and communication systems, and repair them as needed.

3) Develop a workplace evacuation plan, post it prominently on each floor, and review it periodically to ensure its effectiveness.

4) Identify and train floor wardens, including backup personnel, who will be responsible for sounding alarms and helping to evacuate employees.

5) Conduct emergency evacuation drills periodically.

6) Establish designated meeting locations outside the building for workers to gather following an evacuation. The locations should be a safe distance from the building and in an area where people can assemble safely without interfering with emergency response teams.

7) Identify personnel with special needs or disabilities who may need help evacuating and assign one or more people, including backup personnel, to help them.

8) Ensure that during off-hour periods, systems are in place to notify, evacuate, and account for off-hour building occupants.

9) Post emergency numbers near telephones.

2.7.3. Ministerial Regulation Prescribing the Standard for Administration and Management of Occupational Safety, Health and Environment for Construction work B.E. 2551 (A.D.2008)

a) Clause 18

1) The Employer shall not permit his employees to reside in any building built during the construction work or in the construction area except when the Employer provides safety measures and receives written approval from an engineer.

2) Designate the entry and exit and pathway leading in the residences without passing the Dangerous Zone; set up special safety measures for the Employees in case the pathway passes through the Dangerous Zone; and establish preventive measures against material falloffs from high areas.

b) Clause 28

1) The Employer shall provide fire exits and staircases, including the symbolic sign of a fire exit on every floor of the building being built during the construction period, and shall not permit any materials, machinery, or other stuff to barricade the fire exit and staircases.

2.7.4. Ministerial Regulations Prescribing Standards for Management, Management and Operations on Occupational Safety, Health and Working Environment Regarding Fire Prevention and Suppression B.E. 2555 (2012)

a) Clause 8

1) Employers must provide at least two fire escape routes on every floor of the building, which can safely evacuate all employees working at the same time to a safe location within no more than five minutes.

2) The fire escape routes from the point where the employees work to a safe location must be free from obstructions.

Figure 2.1 Keep fire exits clearly signed and free from obstructions (HSE, 2010)

2.7.5. Occupational Safety and Health Administration

a) eTools Evacuation Plans and Procedures: Emergency Action Plan - Evacuation Elements

Most employers create maps from floor diagrams with arrows that designate the exit route assignments. These maps should include locations of exits, assembly points, and equipment such as fire extinguishers, first aid kits, and spill kits that may be needed in an emergency. Exit routes should be:

- Clearly marked and well-lit.
- Wide enough to accommodate the number of evacuating personnel.
- Unobstructed and clear of debris at all times.
- It is unlikely to expose evacuating personnel to additional hazards.
- For more information on exit routes, required height and widths, door access, and hinges.

2.7.6. Health and Safety Executive 168 – Fire safety in construction

a) Section 252

1) Escape routes need to be clearly indicated by proper signs.

b) Section 253

1) Signs need to be large enough so that they can be clearly seen and positioned where they are least likely to be obstructed or obscured by smoke.

c) Section 306

1) Some emergencies may require total evacuation of the site, for example, where it comprises a single high-rise structure. Some emergencies may require only partial evacuation, for example, where a series of separate structures is present on the site.

2) Some emergencies may require evacuation of adjacent premises. Give careful thought to ensuring that the emergency arrangements are appropriate and capable of achieving the desired goal.

d) Section 307

1) All people on site understand any procedures.

2) Ensure procedures are communicated to everyone, taking into account the changing workforce, the transient nature of construction workers, and any personnel who may have difficulty understanding written or spoken instructions.

e) Section 308

1) All emergency plans need to be clear, unambiguous, and known to all who are on the site.

2.8 The current practice guide construction project

Construction projects have many hazards that construction workers and staff will encounter. Fire is one accident that does not occur as frequently as other accidents. Fires on construction sites cause significant property loss and can be deadly. NIOSH's National Traumatic Occupational Fatality (NTOF) database reported 220 deaths due to fire and 354 deaths due to explosion from 1980-1995 in construction, an average of 36 fire and explosion deaths per year. In order to prevent the number of injuries and fatalities from fire accidents in construction projects, developing a site-specific fire prevention and inspection policy can minimize the potential for fires to be implemented during construction phases.

2.8.1 Fire escape and evacuation training

Fire escape and evacuation training is one of the working group's annual activities, aiming to educate construction workers and staff about workplace safety, health, and environment and allow them to practice appropriate fire evacuation. There are five steps of fire escape and evacuation training, including the following:

(1) Teach prevention by recognizing fire hazards, which trains employees not only how to identify fire risks in the workplace but also how to respond to them.

(2) Train employees on fire response.

(3) Develop comprehensive evacuation plans.

(4) Perform regular fire drills.

(5) Test and maintain fire safety equipment.

2.8.2 Toolbox Talks in Construction

Toolbox talks are short presentations or discussions to the workforce on a single aspect of health and safety. Toolbox talks are a traditional and potentially impactful form of supervisor safety communication in construction (Olson et al., 2016). Many topics covered in toolbox talks, such as first aid, confined spaces, using equipment, tools and appliances, personal protective equipment, electrical safety, falling objects hazards, and emergency and rescue procedures.

As part of emergency and rescue procedures, toolbox talks would present the understanding of why evacuation procedures are essential in the construction project, to discuss with the construction workers where to get information on evacuation procedures for the workplace, and what to do in an emergency and understand their role.

Figure 2.2 Toolbox Talks in Construction (Engineering, 2019)

2.9 Visualization technology employed to enhance communication

Visualization technology is an effective communication tool (SangUk Han, 2009) for fire safety management in construction projects. The advantages of visualization techniques are as follows: displaying complex data easily understandable, identifying the hazard area visually, enabling decision-making, and interactions between staff and engineers to solve problems. For this reason, the following visualization techniques are applied in construction projects.

2.9.1 Building Information Modeling (BIM)

Building Information Modeling (BIM) is defined as a modeling technology and associated set of processes to produce, communicate, and analyze building models (Eastman, 2011). Building Information Modeling (BIM) is recognized as an excellent platform for exchanging information and visualization, playing an essential role in transforming industry collaboration and replacing traditional construction methods. The emergence of multiple applications that can directly use and exchange information between stakeholders provides opportunities to enhance communication between industry stakeholders within the project collaboration (Goh et al., 2014). Building Information Modeling is considered relevant as a collaborative communication tool because of its ability to share ideas and visualize the project better than the traditional method. It can eventually improve collaborative communication among project participants (Melzner et al., 2015), (Svalestuen et al., 2017), as shown in Figure 2.3. Furthermore, all the stakeholders' communication problems can be solved by employing Building Information Modeling (BIM), which integrates process chains and manages all information.

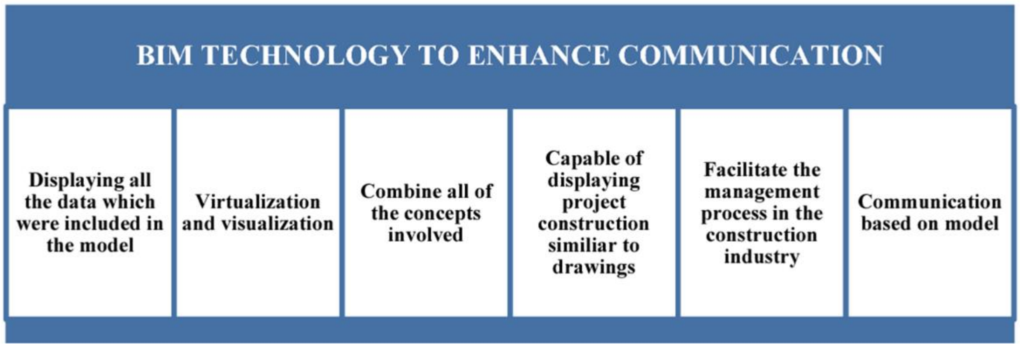
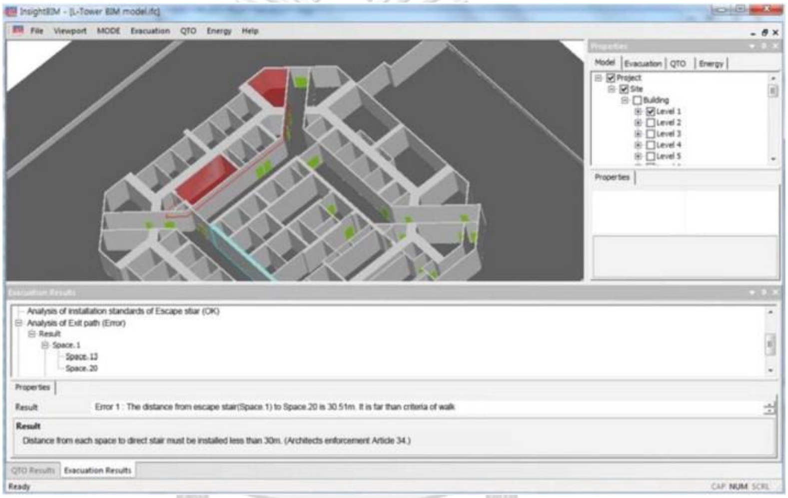


Figure 2.3 BIM Technology to Enhance Communication (Goh et al., 2014)

In the past decade, researchers have made significant progress in the development of Building Information Modeling (BIM) as a tool for developing a communication system to evacuate in construction projects, including the following:

Shiau, Lu, and Chang (2012) proposed Building Information Modeling (BIM) integrated with sensors and monitors to construct a fire control system. When the sensor is activated, the system can instantly show the floor and room plan of the fire point in the 3-D model and connect to monitors assigned to watch the suspected fire area to determine the authenticity of the fire alarm.

Choi, Choi, and Kim (2014) proposed that Building Information Modeling (BIM) integrated with regulation checking processes called InSightBIM-Evacuation for a high-rise building and a complex building design had high priority and are critical for adequate disaster prevention systems and egress routes. They used it to verify evacuation regulation check results. The results show that the system could provide expansion possibilities for various disciplines that can be verified.



Analysis of installation standards of Escape stiar (OK)
Analysis of Exit path (Error)
Result
Space.1
Space.13
Space.20

Result: Error 1 : The distance from escape stair(Space.1) to Space.20 is 30.51m. It is far than criteria of walk

Result
Distance from each space to direct stair must be installed less than 30m. (Architects enforcement Article 34.)

Figure 2.4 Result of checking for escape stairs installation and exit routes (exit route error)
(Jungsik Choi, 2014)

Wang et al. (2014) proposed a disaster prevention management module based on Building Information Modeling (BIM) that connected the module with the fire simulation software as Fire Dynamic Simulator (FDS) to generate the escape route according to the 3-D functions of BIM and predict the time to evacuation the safety of personnel. The results show that a disaster prevention management module could enhance the standard of fire safety educational training and apply it to a high-tech facility to test its feasibility.

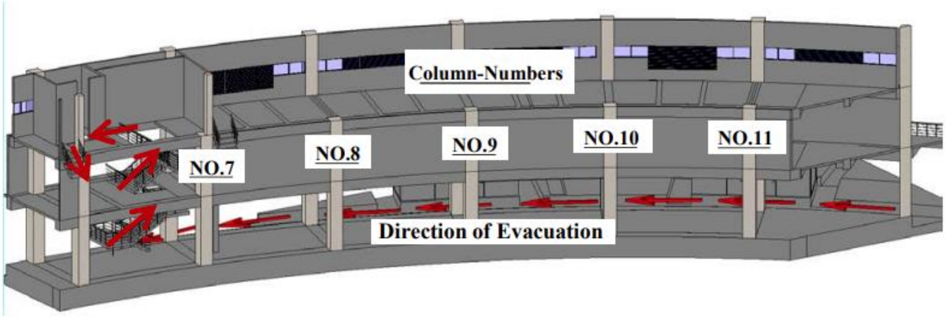


Figure 2.5 Escape directional map (Wang et al., 2014)

Kim and Lee (2019) proposed a framework to automatically analyze, generate, and visualize the evacuation paths of multiple crews in 4D BIM, considering construction activities and site conditions at the specific project schedule. This research develops a prototype that enables users to define parameters for pathfinding, such as workspaces, material storage areas, and temporary structures, to identify the accessible evacuation paths automatically. The results show the secured evacuation paths in the 4D BIM environment, allowing users to organize the automatically generated evacuation paths. (Kim & Lee, 2019)

Ma and Wu (2020) proposed a fire emergency management system (FEMS) that combined Building Information Modeling (BIM) and building user behavior decisions to improve fire emergency management effectiveness. The results show that the system realized the dynamic monitoring of building fire, the judgment of fire category, the users' location, and the ability to view fire points in a 3-D Model and could plan optimal action routes according to different building user decisions. (Ma & Wu, 2020)

Wehbe and Shahrour (2021) proposed an intelligent fire evacuation system that combined Building Information Modeling (BIM) and intelligent technologies to improve occupants' safety during fire evacuations. The system provided the capacities as follows: early fire detection, the evaluation of environmental data, the identification of the best evacuation path, and information for occupants about the best evacuation routes. The results show that the system's capacities and benefits could identify the evacuation route with the accurate distance needed to evacuate safely.

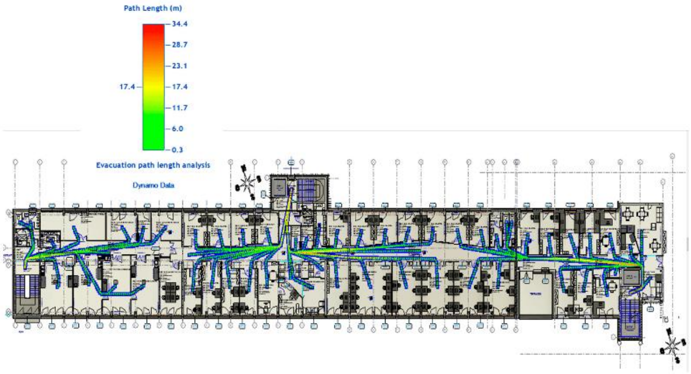


Figure 2.6 BIM visualization for evacuation paths (Wehbe & Shahrour, 2021)

Deng et al. (2021) proposed a framework for assisting emergency evacuation navigation in a fire scenario, mainly including indoor positioning and rescue route planning by integrating Building Information Modeling (BIM) and computer vision. It only needs real-time images to implement the automatic generation of the rescue route, which is cheap and convenient. The result indicates that the rescue route generated by the proposed framework is secure and reasonable. (Deng et al., 2021)

Tongthong et al. (2023) propose a framework to assess the fire extinguisher installation plan (FEIP) and recommend the locations of fire extinguishers based on Building Information Modeling and Game engine by considering the dynamic nature of construction. The results show that the prototype that enables the users to define the parameters for the fire extinguisher installation plan exists, as well as appropriate locations of fire extinguishers and unsafe areas.

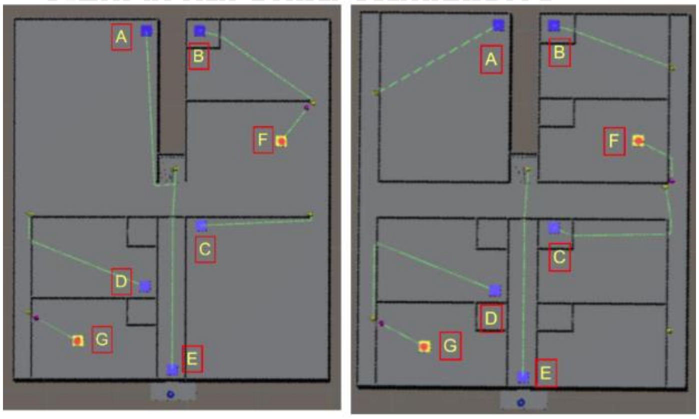


Figure 2.7 The generated fire extinguisher installation plan (Tongthong et al., 2023)

2.8.2 Augmented Reality (AR)

Augmented Reality (AR) is a technology or an environment where the virtual information created by a computer is superimposed onto the user's view of a real-world scene (Petcharat Limsupreeyarat, 2012) through a display device. This technology allows for visualization of the real environment. It is applied computer-generated with a digital augmentation overlay, being a highly visual and interactive method with digital content such as text, images, 3-D models, and sound to the real world after simulation (Yunqiang Chen, 2019). Augmented Reality (AR) is a subset of the Mixed Reality (MR) range of the Reality-Virtuality (RV) continuum. The Mixed Reality (MR) definition by Milgram and Colquhoun (1999) is a special class of Virtual Reality (VR) related technologies for creating environments wherein real world and virtual environments are presented together in a single display.

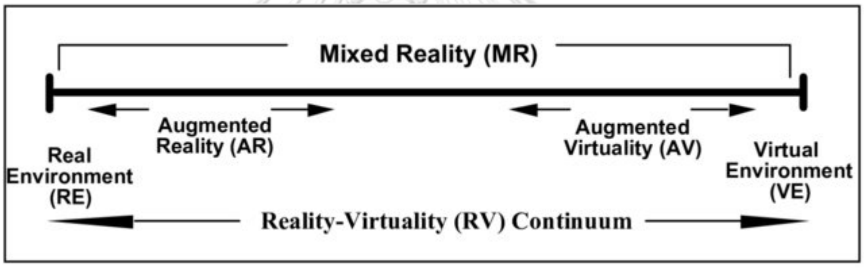


Figure 2.8 Definition of Mixed Reality (MR) in terms of the Reality – Virtuality Continuum (Paul Milgram, 1999)

Figure 2.8 describes that a Reality-Virtuality continuum refers to the spectrum of classes of substances offered in any particular case. It spans from the Real Environment (RE) on the left to the Virtual Environment (VE) on the right. On the left side, the described environment comprises only real objects and contains what is observed through a conventional video display unit of a Real Environment (RE) scene. On the right side, described environments comprise only virtual objects, such as a conventional computer graphics simulation (Merve Yavuz, 2021).

Augmented reality (AR) is an altered form of reality in which computer-generated content is superimposed on the user's real-world views, allowing digital assets to be added to their physical environment through display devices such as smartphones, tablets, and Hololens (Softtek, 2021). Therefore, Augmented reality (AR) can enhance the user's perception with visual discovery, which in turn is defined as a technology that fulfils a user's curiosity about the world around them by giving them information and relevant content when objects and images in the field of view are selected (Peddie, 2017).

Azuma (1997) classified two ways to accomplish augmentation: optical or video technologies. A see-through HMD is one device used to combine real and virtual. Optical see-through HMDs work by placing optical combiners in front of the user's eyes. The user can see virtual images bounced off the combiners from head-mounted monitors. The user can look directly through the combiners to see the real world—a conceptual diagram of optical see-through HMDs, as shown in Figure 2.9.

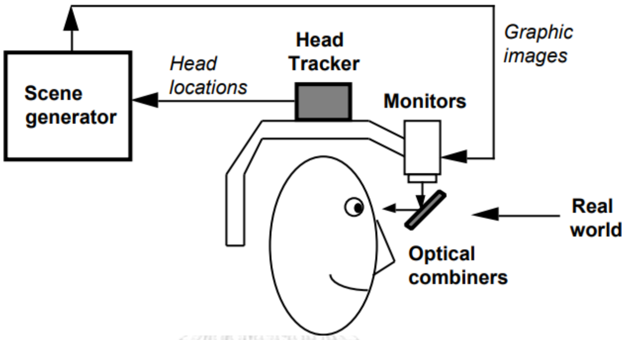


Figure 2.9 Optical optical see-through HMDs conceptual diagram (Azuma, 1997)

HMDs combine a closed-view HMD with one or two head-mounted video cameras in part of video see-through. The video cameras provide the user's view of the real world by combining the video cameras with the graphic images created by the scene generator, blending the real and virtual. The result is sent to the monitors in front of the user's eyes in the closed-view HMDs—a conceptual diagram of see-through video HMDs, as shown in Figure 2.10.

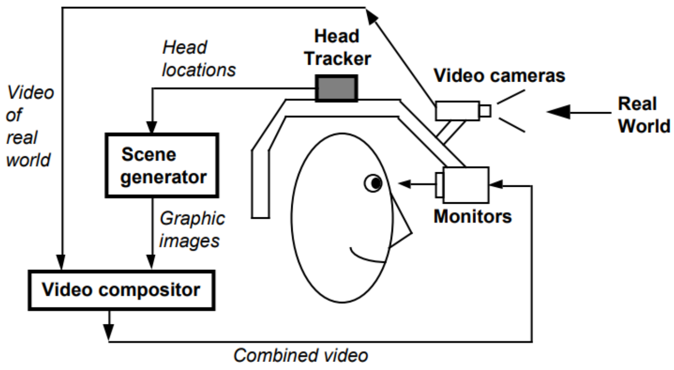


Figure 2.10 Video see-through HMDs conceptual diagram (Azuma, 1997)

Augmented Reality (AR) is a promising technology for improving information visualizations directly on construction sites (Julia Ratajczak, 2019). Currently, Augmented Reality (AR) can be classified into two categories: triggered, which are paper or object markers, GPS location, dynamic augmentations of objects and complex augmentation, and view-based augmentation, which are indirect augmentation and non-specific digital augmentation (Amanda EDWARDS-STEWART, 2016). This technology allows users to interact with real and virtual objects by overlaying digital information and 3-D objects on real objects, improving decision-making and providing real-time access to information. The details of Augmented Reality (AR) types are presented in Table 2.2. Furthermore, some researchers provided that classifications based on functional characteristics of Augmented Reality (AR) types could consider appropriate problem areas.

Table 2.2 Summary of Augmented Reality (AR) categories and types. (Amanda EDWARDS-STEWART, 2016)

Category	Type	Characteristics
Triggered	1a. Marker-based: Paper	Paper marker activates stimuli.
	1b. Marker-based: Object	Most objects can be made into markers.
	2. Location-based	Overlay of digital information on a map or live camera view. GPS may activate stimuli.
	3. Dynamic Augmentation	Meaningful, interactive augmentation with possible object recognition and/or motion tracking.
	4. Complex Augmentation	Augment dynamic view and pull internet information based on location, markers, or object recognition.
View-Based	5. Indirect Augmentation	Image of the real world augmented intelligently.
	6. Non-specific Digital Augmentation	Augmentation of any camera view, regardless of location.

Augmented Reality (AR) has been applied in many sectors with various proposals. Yuvuz et al. (2021) categorized the application of Augmented Reality (AR) into the following six areas:

(1) In entertainment gaming areas, the game developer can use Augmented Reality (AR) to create game applications based on geographical data; for example, in Pokémon GO, players can find their Pokémon characters, train them, and walk to the closed area to make progress in the game (Kosuke Watanabe, 2017).

(2) For education, students can learn the information about their course in a more fun and understandable way via the 3-D virtual image of the subject in the real world with an Augmented Reality (AR) application.

(3) In marketing and advertising, Many Big companies have begun using Augmented Reality (AR) in advertising campaigns and product promotions. For instance, Coca-

Cola released a new advertisement including QR codes on the boxes to play an animation using Coca-Cola's application.

(4) For tourism, Augmented Reality (AR) is also applied to museums and art galleries to provide a unique visitor experience. Through this technology, visitor attractions can create engaging content overlaid with objects or artworks (Jung et al., 2015; Olsson et al., 2012).

(5) For navigation, Augmented Reality (AR) enables various information, such as pictures and the location of buildings in the navigation field. Most navigation systems can only show the path from a user's location to their destination (Chee Oh Chung, 2016).

(6) For browser medicine is a magic mirror ('Miracle') application, which is an Augmented Reality (AR) system that can be used for undergraduate anatomy education and provides real-time manipulation of 3-D rendering of anatomical imagery (Carolien Kamphuis, 2014). The Augmented Reality (AR) application area summary is presented in Table 2.3.

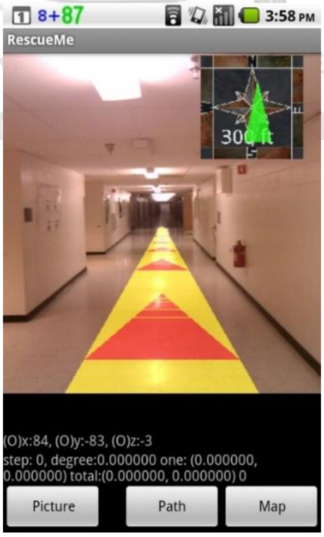
Table 2.3 Summary of the Augmented Reality (AR) application area (modified from Yavuz et al.(2021)

Area	Features, description of potential implementations
Entertainment Gaming	The most promoted area for AR applications
	The area with the highest potential and enthusiasm around it (Aukstakalnis, 2016)
Education	Fun, memorable, and clear ways for learning (augment.com,2020),(Carolien Kamphuis, 2014)
Marketing and Advertising	Enabling brands to reach out to their customers in new ways (G. Kipper, 2012)
Tourism	New interactive ways for virtual tourism for places such as museums and exhibitions (Jung et al., 2015; Olsson et al., 2012)
Navigation	Show the path from a user's current location to their destination (Chee Oh Chung, 2016)
Browser Medicine	Can provide real-time manipulation of 3-D rendering of anatomical imagery (Carolien Kamphuis, 2014)

In recent years, Augmented Reality (AR), an emerging interactive technology (Olsson, 2012), has increased and advanced in the construction industry. This technology has been used as an application that could benefit a project with accelerated working site training and safety, design development, and communication with involved parties from the owner down to the workers and help exceed the owner’s expectations and decrease project costs (Behzadi, 2016). Furthermore, it permits an individual to interact with real-world projects and deal with defects, construction progress, risks, and accidents before they occur (Ahmed, 2018) by exposing a project before it physically exists. As a result, Augmented Reality (AR) has been widely used in various construction projects to protect workers and staff from unpredictable situations.

In the past decade, researchers have made significant progress in the development of Augmented Reality (AR) as a tool for developing a communication system to evacuate in construction projects, including the following:

Ahn and Han (2011) proposed using Rescue Me, a novel system based on indoor mobile AR applications using personalized pedometry and one that recommends the most optimal, uncrowded exit path to users. The results show how RescueMe leverages smartphone sensors, in conjunction with emergency information and daily-based user behavior, to deliver evacuation information in emergency situations.



```
(O)x:84, (O)y:-83, (O)z:-3
step: 0, degree:0.000000 one: (0.000000,
0.000000) total:(0.000000, 0.000000) 0
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Figure 2.11 A screenshot of the mobile front-end component of the RescueMe mobile augmented reality system. (Ahn & Han, 2011)

Feng and Kamat (2012) presented the MARvigator application, which focused on navigation and inspection in the construction project. This presented system used an AR marker as a spatial index to link physical locations with virtual information related to that location, offering a new perspective on utilizing AR markers. The marker recognition module recognizes the user’s location. Then, the AR marker ID is sent to the database, such as MySQL, SQLite, or even a self-defined text file, as a critical value to search for attached information. Simultaneously, the estimated pose of the mobile device relative to the marker is sent to the three-dimensional visualization module. This visualization module takes the estimated pose to render the information sent back from the database on the mobile device's screen for further decision-making by its end-user. The experiments proved MARvigator’s efficiency in helping people find destinations and convenience.

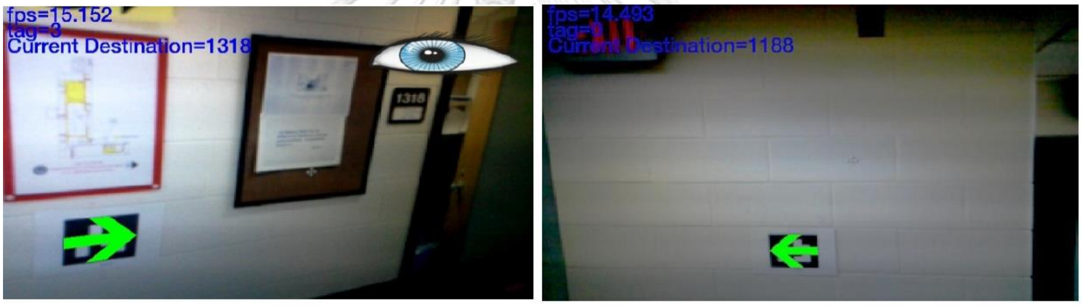


Figure 2.12 Two screenshots showed graphical instructions on how to move to the destination. (Best viewed in color) (Chen Feng, 2012)

Wang et al. (2014) developed a mobile application for instructing occupants from the indoor environment by using Building Information Modeling (BIM) and Augmented Reality (AR). This application can detect the positioning of occupants and visualize their positions in three-dimensional views. If the occupants have installed the application and scanned the physical Quick Response (QR) codes, they will locate themselves and know the nearest evacuation routes.

Cheng et al. (2016) proposed a mobile evacuation/rescue guiding device by applying advanced visualization and tracking technologies. This presented system used Building Information Modeling (BIM), augmented reality (AR), and smoke detectors with Bluetooth wireless sensor network to superimpose the distinct site layout in three-dimensional visualization and immediately grasp the status of the fire and disease in the building. This system can provide data storage for fire agencies to update, query, and share data. Furthermore, apply capabilities of 3D visualization to support fire safety management—the integration of the system framework, as shown in Figure 2.13.

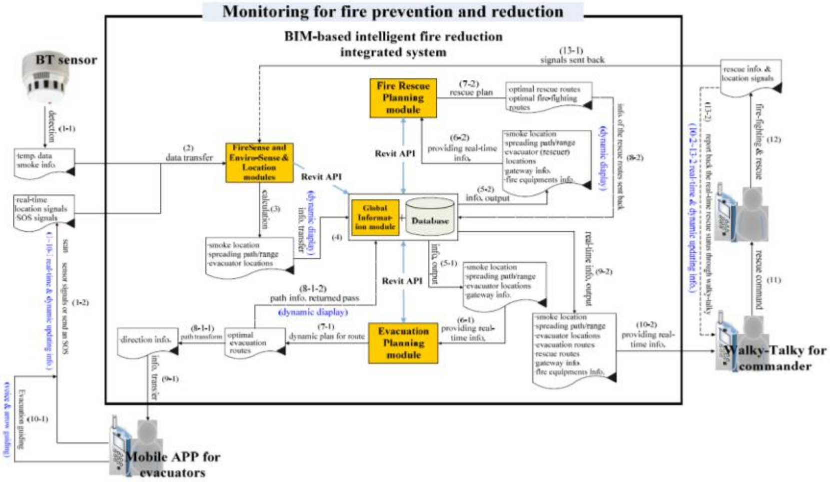


Figure 2.13 Framework of the proposed system (Min-Yuan Cheng, 2016)

Li et al. (2019) proposed a fire reconnaissance robot based on Simultaneous Localization and Mapping (SLAM) technology, thermal imaging technologies, and Augmented Reality (AR). This system can provide a real-time map under rapidly changing fire conditions to guide the firefighters who wear the head-mounted displays (HMDs) to the fire sources or the trapped occupants simultaneously via the images and videos obtained by the robot. In contrast, they can obtain fire-related information without entering hazardous areas. The result showed that the developed fire reconnaissance robot could provide a practically robust platform to improve fire-rescue efficiency and reduce firefighters' fire casualties.

Nam et al. (2019) proposed a system to guide the evacuation route based on augmented reality (AR) and CNN using CCTV image processing in an indoor fire environment. Through a mobile application, people can be able to evacuate even more quickly in situations where there is not much smoke after the fire. The result showed that CNN is generally known to have excellent image detection and recognition accuracy, but it is affected by the quality of the learned data.

Cloud Anchor successfully hosted! Tap to place more stars.

Cloud Anchor successfully hosted! Tap to place more stars.

Figure 2.14 Execution scene of AR-based evacuation route guidance application.

(Nam et al., 2019)

Ajith et al. (2020) proposed the application of indoor navigation systems to guide users to their destinations within a reasonable distance, which put forward an indoor mapping extended to a 3-D feature with Augmented Reality (AR) based on Placenote SDK (Software Development Kit), Unity Game Engine, and XCode IDE are used to build and deploy spatial apps readily on the mobile. This application can assist the person who searches for the destination to be reached with the correct path. (Ajith et al., 2020)

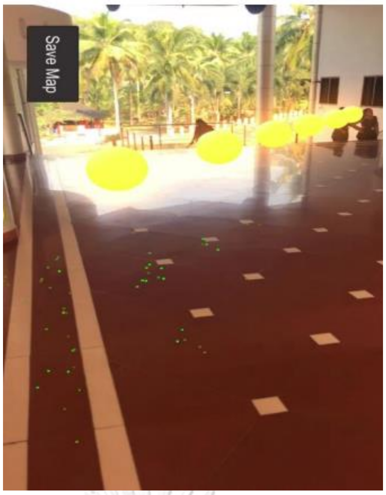
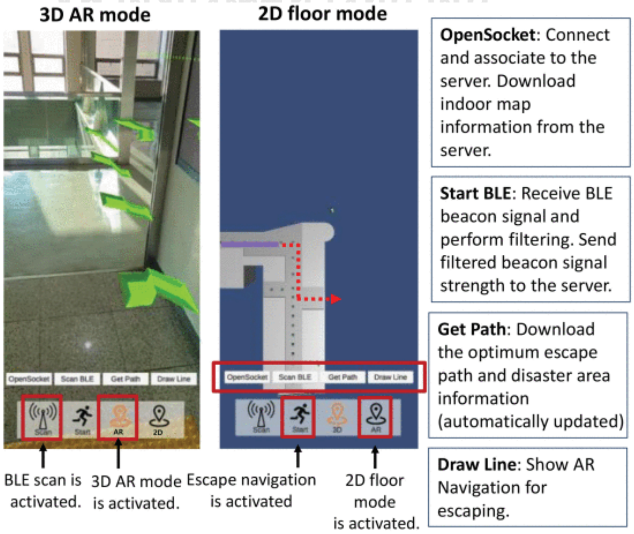


Figure 2.15 Mapped a path by walking from a starting point to a destination point. (Ajith et al., 2020)

Yoo and Choi (2022) proposed a machine-learning-based AR navigation system architecture that defines the required functional modules and their interactions for real-time disaster monitoring, disaster propagation prediction, user localization, individual evacuation route optimization, and AR-based guidance. The results showed that the proposed machine-learning-based system could provide individual users with safe, reliable, and fast emergency evacuation services.



OpenSocket: Connect and associate to the server. Download indoor map information from the server.

Start BLE: Receive BLE beacon signal and perform filtering. Send filtered beacon signal strength to the server.

Get Path: Download the optimum escape path and disaster area information (automatically updated)

Draw Line: Show AR Navigation for escaping.

Figure 2.16 AR-based evacuation path navigation smartphone application (Yoo & Choi, 2022)

Based on the previous research on evacuation routes, factors consideration, and tools to help prevent and reduce the number of injuries and fatalities in emergencies. Therefore, a summary of the topics, study area, and visualization technology has been conducted, as shown in Table 2.4.

Table 2.4 Summary of the previous research related to evacuation route

Authors	**Construction phase**	**Visualization technology**			**Focus of research**
		BIM	**AR**	**Others**	
Shiau, Lu, and Chang (2012)	Post-Construction	✓	-	✓	Fire detector system and evacuation notice
Choi, Choi, and Kim (2014)	Pre - Construction	✓	-	-	Checking for escape stairs installation and exit routes
Wang et al. (2014)	Post-Construction	✓	-	✓	Time to evacuation and safety education and training
Cheng et al. (2016)	Post-Construction	✓	-	✓	Fire prevention equipment information
Kim and Lee (2019)	Pre - Construction	✓	-	-	Path finding
Ma and Wu (2020)	Post-Construction	✓	-	✓	Monitoring of building fire, the fire category, the users' location, and plan optimal action routes
Wehbe and Shahrour (2021)	Post-Construction	✓	-	✓	Fire evacuation fatalities and optimize evacuation routes
Deng et al. (2014)	Post-Construction	✓	-	✓	Emergency evacuation navigation
Tongthong et al. (2023)	Post-Construction	✓	-	✓	Extinguisher installation plan, appropriate locations of fire extinguishers and unsafe areas.

Table 2.4 Summary of the previous research related to evacuation route (continued)

Authors	**Construction phase**	**Visualization technology**			**Focus of research**
		BIM	**AR**	**Others**	
Ahn and Han (2011)	Post-Construction	-	✓	-	The shortest path
Feng and Kamat (2012)	Post-Construction	-	✓	-	Navigation and inspection
Wang et al. (2014)	Post-Construction	✓	-	✓	The shortest path and fire evacuation guidance
Cheng et al. (2016)	Post-Construction	✓	-	✓	Fire prevention equipment information and route optimization information for evacuation and rescue
Li et al. (2019)	Construction	-	✓	✓	Map construction under fire conditions, fire detection, and rescue.
Nam et al. (2019)	Post-Construction	-	✓	✓	Evacuation route
Ajith et al. (2020)	Post-Construction	-	✓	✓	Indoor navigation route
Yoo and Choi (2022)	Post-Construction	-	✓	✓	Navigation and emergency system

2.10 Research gap

Regarding the literature review, diverse evacuation systems have been introduced by previous research. In addition, most developed systems do not focus on an interactive communication system, as real-time communication automatically generates appropriate evacuation routes for a dynamic nature in the construction phases. Moreover, their developed system focuses on the post-construction phases and recommends an evacuation route that only considers the short-distance route and does not consider representing information such as voice and arrow directions for evacuation guidance, virtual green line, exit, distance from the current location to the exit, and the appropriate evacuation route in the construction project. Therefore, a communication system to support evacuation routes from hazardous locations based on real-time information will be developed in this study.

Chapter 3

Methodology

3.1 Introduction

This research consists of six steps of methodology as follows: 1) literature review, 2) construction site observation, 3) system design and development, 4) testing and verification, 5) validation, and 6) research summarization and discussion.

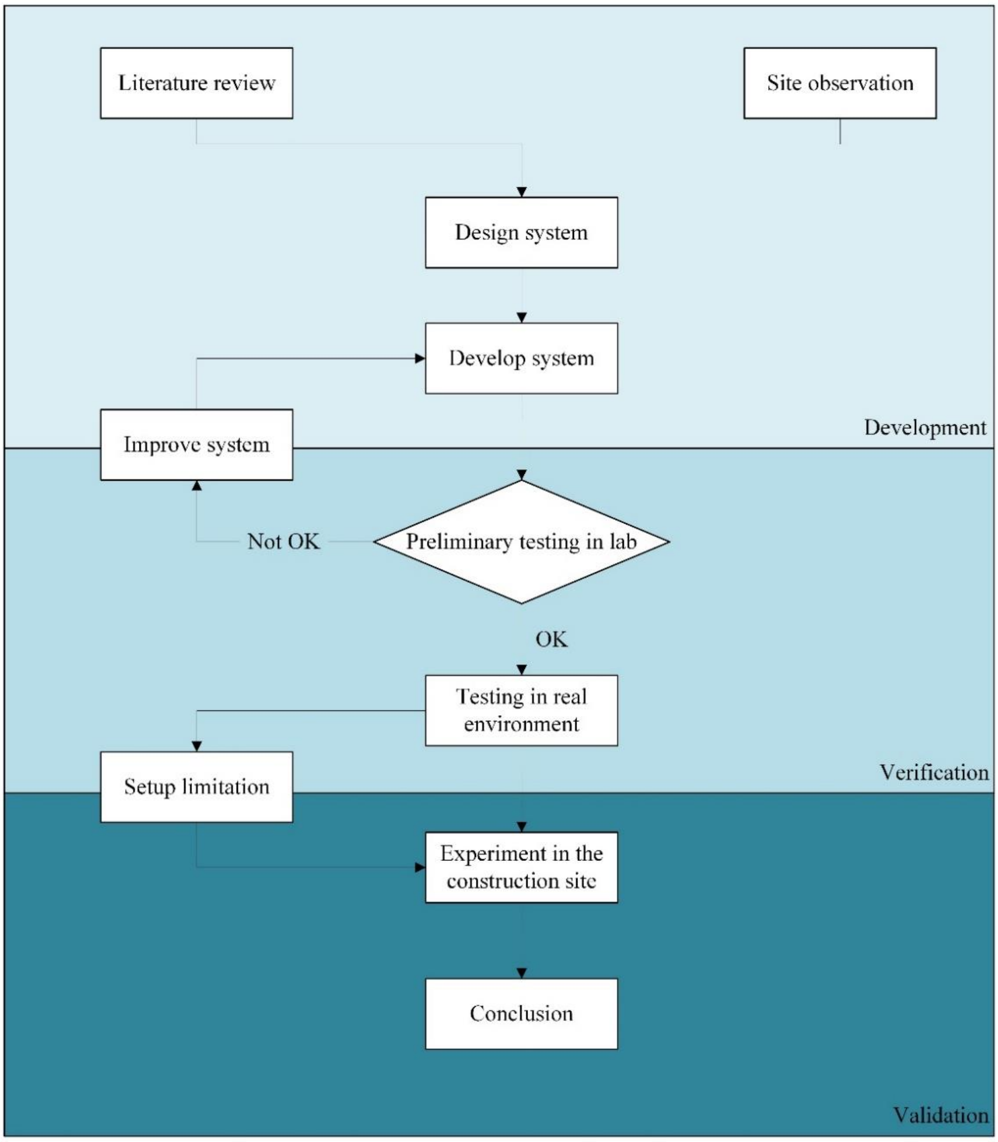


Figure 3.1 Research methodology

3.2 Research methodology

3.2.1 Literature review

Journal articles, textbooks, conference proceedings, thesis dissertations, and other documents related to this research are reviewed to explore approaches that can assist in fire safety management, such as fire emergency procedures. Thus, the literature classification in this research is described as follows: (1) definition of real-time, (2) general emergency procedures of the building, (3) the type of evacuation of the high-rise building, (4) the average speed of the evacuee, (5) regulations relating to the evacuation plan, (6) the current practice guide construction sites regarding fire escape and evacuation training and toolbox talks in construction projects, and (7) the definitions, concepts, advantages, and implementation of visualization technology in construction projects.

3.2.2 Construction site observation

According to fire accident statistics for the construction industry, it has been indicated that the causes of fire accidents lead to injuries or the fatalities of construction workers and staff. One of the factors is the dynamic nature of the construction project, which has an indeterminate number of construction workers and staff, including the uncertainty of the quantity of work daily. In addition, the routes in the construction project have been changing every day, which means the construction workers and staff should be familiar with and have experience with the route in the construction project. However, in the current construction project, the evacuation route is presented in the two-dimensional drawings (2-D drawing), and the route has not been updated following the daily construction work schedule. Furthermore, in a normal situation, material handling is one of the construction activities, which requires familiarity with and experience of construction workers and staff with the route and information of the storage location. Therefore, if construction workers and staff are not familiar with the route, they will have a high risk of losing and not getting updated information on evacuation routes, which leads to work delays, injuries, or fatalities.

The construction site surveys were implemented to investigate fire safety management and evacuation planning and identify the problems and requirements related to fire emergency procedures. The data collection methods were interviews, document reviews, photography, and video recording. Part of the interview used a method to describe data and information from engineers and staff responsible for fire safety management. When a fire occurs on the construction site, engineers and staff were asked to describe the fire safety management and evacuation plans for the fire evacuation route. In addition, documentation related to fire safety standards, acts, rules, and regulations used in fire safety management processes will be reviewed.

Photography and video recording were employed to record the construction environment, construction activities, emergency fire exit locations, and the position of construction workers when they worked in real-site conditions were also implemented and analyzed to examine the potential evacuation improvement.

3.2.3 System Design and Development

The concept of the proposed system concept was chosen from the literature review and construction site survey. The problems of current practices in the fire evacuation planning process are analyzed, while the advantages and limitations of visualization technologies are examined to solve those problems. The suitable technology should contain the ability to provide and integrate appropriate real-time fire evacuation information for the construction workers and staff while perceiving the real construction environment. Furthermore, this research posits that this can be an effective tool for supporting decision-making, enabling users to perceive and understand the information clearly and easily. Moreover, it can increase advancement in the construction industry and be used as an application that could benefit a project with accelerated working site training and communication with involved parties, from the owner down to the construction workers.

According to the literature review, the selected visualization technology in this study is Augmented Reality (AR), which allows users to interact with real and virtual objects by overlaying digital information and 3-D objects on real objects. This technology has been deployed to support decision-making at design stages (Farzad Pour Rahimiana, 2020) and enables users to perceive and understand information clearly and easily. Moreover, it can increase advancement in the construction industry and be used as an application that could benefit a project with accelerated working site training and safety, design development, and communication with involved parties, from the owner down to the construction workers. Therefore, Augmented Reality (AR) was appropriate for testing this research hypothesis.

A prototype system was designed and developed for this research in three parts due to the tasks collected from site observation: BIM authoring, a marker-based location, and application authoring. The situation for the prototype system development is that a fire occurred in the construction project, workplaces obstructed hallways from materials and equipment constantly changing, and the number of users in the passenger lift is limited.

In the first part, BIM authoring A prototype application combining Building Information Modeling (BIM) and Augmented Reality (AR) was implemented to demonstrate the proposed framework. A virtual construction working area is created from an As-Built drawing related to the data and information from the construction project. Firstly, a 3-D model of the building's architecture was created with a Level of Detail (LOD) of 300 using Autodesk Revit 2022 based on as-built drawings. Therefore, construction elements, fire exits, stairs, and temporary facilities such as a passenger lift implemented to assign the location of working areas in the 3-D model are the same as in the real world. A Level of Detail 300 includes columns, beams, and floors in the structural phase, as well as windows, doors, walls, and stairs in the architecture phase, along with their size, shape, location, and geometric data such as length and area (Volk, Stengel, and Schultmann, 2014). The 3-D model was saved in the Industry Foundation Classes (IFC) file format. The model was then exported to the Autodesk Naviswork (NWD) file format and saved in the Autodesk Filmbox (FBX) file format, making it suitable for data exchange between different BIM authoring software applications. Finally, the FBX file format was integrated into the Unity game engine with the assigned textures. This research used the Unity game engine, a cross-platform toolkit developed by Unity Technologies, to create video games and simulations for computers, consoles, and mobile devices. This research used it as the primary platform for creating the application and integrating visualization technologies such as Building Information Modeling (BIM) and Augmented Reality (AR). In addition, this study adopted a previously developed method of linking a digital model to support integrating the information in the 3D model, including 3-D rendering, physics, and collision detection. This method was established using the FBX file format and incorporating programming with C# scripting and other related classes and APIs.

The second part focuses on the developed marker-based location system. Marker-based locations are abundant in buildings, construction sites, and other built environments where engineering operations are conducted, making applying this method very convenient. Markers are distinct patterns that can be either 2D images with visual features that mobile phone cameras can easily recognize and extract (Sun et al., 2009) or natural objects in the real environment. Markers can be either paper-based or physical objects in the real world. The developed marker-based location system uses a marker as a spatial index to link physical location and virtual information. The system operates as follows: Firstly, the camera captures an image containing a marker on the mobile device. This image is then sent to the classifier algorithm, designed to classify data into different categories or classes, and assumes a relatively balanced distribution of classes to generate the code and create the marker ID. The marker code is then sent to the database as a key value to check for attached information. The system sets the location and direction in the virtual environment; if the code is not recognized in the database, the system does not display any data. As the mobile device moves, the system sends updated data related to the location and direction to the real world in real-time. If the mobile device has not moved, the system does not update any data.

Last is application authoring. This research implemented the proposed system, which is a system in the Unity game engine. In building an application, the Authors also export the Unity project as a Gradle project (Unity Technologies, 2022). After that, use Android Studio to build and run the project into an application for release to users. The proposed system provides real-time information, such as the user's current location, which is used to calculate the distance to the exit via a virtual green line. The system also provides voice and arrow directions for evacuation guidance, virtual green line, exit, and the distance from the current location to the exit and recommends the appropriate evacuation route in case of obstacle avoidance and the optimization of the number of users who are construction workers and staff using the passenger lift is limited.

3.2.4 Proposed system verification

During the development step, the proposed system was constantly tested to check for accuracy in the laboratory. The factors that may have affected system accuracy were collected and used to determine the prototype system's limitations. After testing in the laboratory to ensure the reliability of the proposed system, implementation and experiment in the actual construction environment were performed. The system was tested in the actual construction environment, and implementation was observed. The outputs of the proposed system were collected and analyzed.

3.2.5 Validation

The proposed system was implemented and experimented with within the real construction project. A high-rise building construction project was selected to be a sample project. In this step, an experiment was tested by users who worked on the construction project. The scenario was defined in order to investigate their considerations. The output of the proposed system was provided and evaluated real-time access to information for evacuating from the hazard location in the scenario.

3.2.6 Summarize and discuss the results

The results from this research are summarized and discussed in this process. The recommendations and limitations are also presented. Furthermore, the contributions of this research are also discussed.

Chapter 4

Construction Site Survey and Conceptual System Development

4.1 Introduction

This chapter presents the construction site survey and the concept of the proposed system. Firstly, high-rise construction projects are observed to explore the current fire safety management practices as fire emergency procedures. This study mainly focuses on a fire accident in a construction project. The tasks carried out to prevent loss of life and property from fire occurring at the construction project were investigated in terms of processes and implemented tools. Finally, the conceptual proposed system is presented, developed from observed data, and reviewed literature.

4.2 Overview of construction site survey

This research focuses on a new approach system for fire safety management that can effectively handle the dynamic nature of the construction project, which directly influences the fire evacuation route and work schedule that can impact evacuation performance and visualization technologies based on the literature review in the previous chapter. The field observation processes were carried out at high-rise building construction projects.

According to the construction site survey, walk-in construction site surveys were performed to capture an overview of the construction project, such as fire safety management, which includes fire emergency procedures and fire evacuation routes, and the current practice of each construction project. In addition, questionnaires were designed to collect data concerning fire safety management in the construction project. The seventeen staff members who worked on the high-rise building construction project were selected to participate in answering the questionnaires. The designed questionnaires were divided into four parts. The first two parts were used to survey the respondents' demographic and background information regarding the fire accident in the high-rise building construction project. The distribution of the questionnaires and the details of the survey construction projects are listed in Table 4.1, and the demographic profile of the respondents is presented in Table 4.2.

Table 4.1 Details of construction project observation

Project number	Type of building	Height (m.)
1	Residential	56.10
2	Residential	84.00
3	Residential	55.65
4	Residential	148.50
5	Residential	70.20
6	Residential	33.15

In Table 4.1, most construction projects are residential buildings classified as high-rise buildings following the Thailand Building Control Act B.E. 2535 (1992) definition that the height of the building is over 23 meters.

Table 4.2 Demographic profile of the respondents of construction project observation

Variables	**Distribution (n = 17)**
Gender	
Male	76.5%
Female	23.5%
Education	
Bachelor	47.1%
Master	47.1%
Doctoral	5.9%
Position	
Site Engineer	50%
Office Engineer	18.8%
Senior Architecture	6.3%
Project Engineer	6.3%
Senior Engineer	18.8%
Work experience in high-rise building projects (years)	
< 1	6.1%
3 - 5	62.6%
> 6	31.3%

Table 4.2 Demographic profile of the respondents of construction project observation (continued)

Variables	**Distribution (n = 17)**
Type of construction company	
Real estate	41.2%
Consultant	11.8%
Contractor	23.5%
Government agencies and state enterprises	23.5%

According to the respondents' background, 68.7% had work experience in high-rise building construction projects of less than five years, and 31.3% had work experience of more than six years. Also, 41.2% of the type of construction company were real estate, 23.5% were contractors and government and state enterprises, and 11.8% were consultants, respectively.

Moreover, the subjects were asked to provide their opinions in accordance with one stage of fire safety management, which was experience and understanding of fire accidents in the construction project. According to the questionnaire results, most of the respondents had experience with fire accidents in the construction project. The percentage of the respondents that could perform the stage of fire safety management, which includes fire emergency procedures and fire evacuation routes, and the current practice of each construction project. is presented in Figure 4.1 to Figure 4.4.

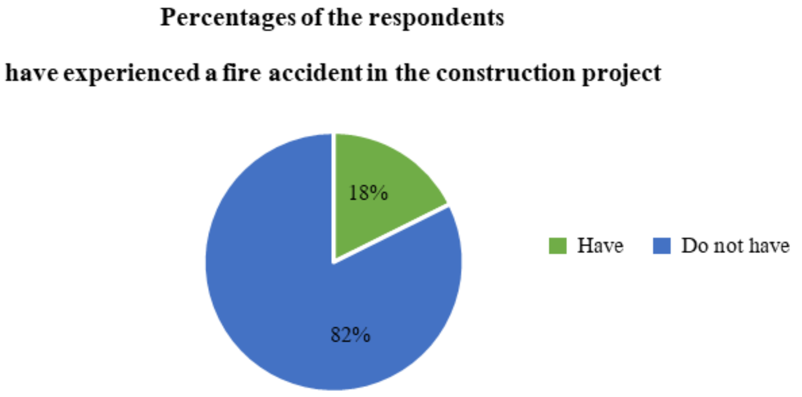


Figure 4.1 Percentages of the respondents have experienced a fire accident in the construction project.

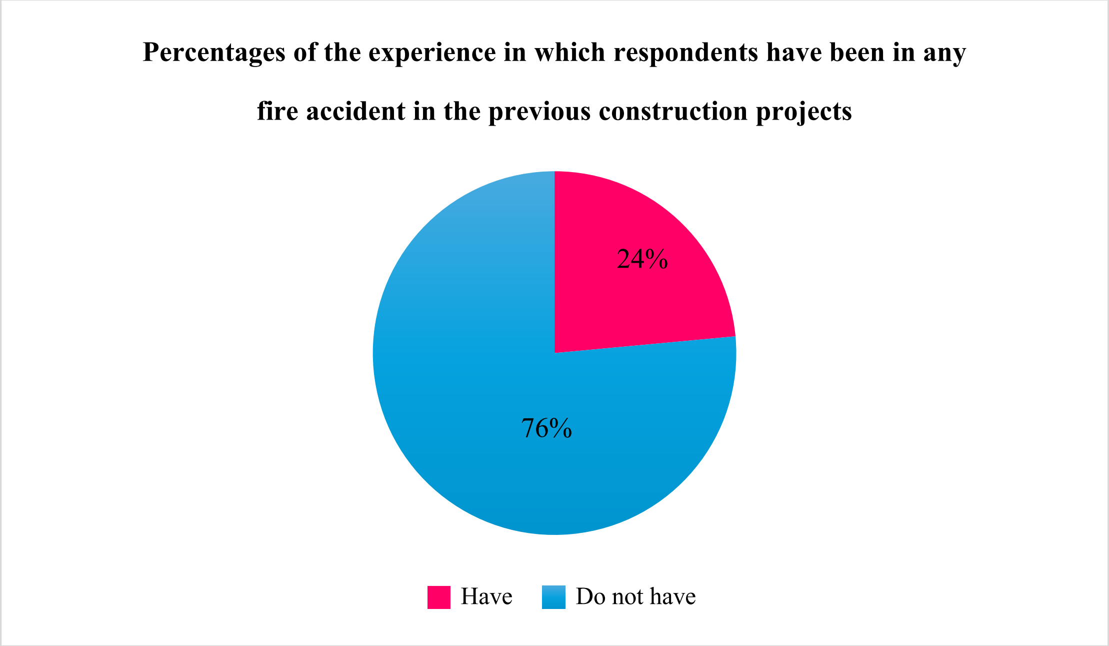


Figure 4.2 Percentages of the experience in which respondents have been in any fire accident in the previous construction projects.

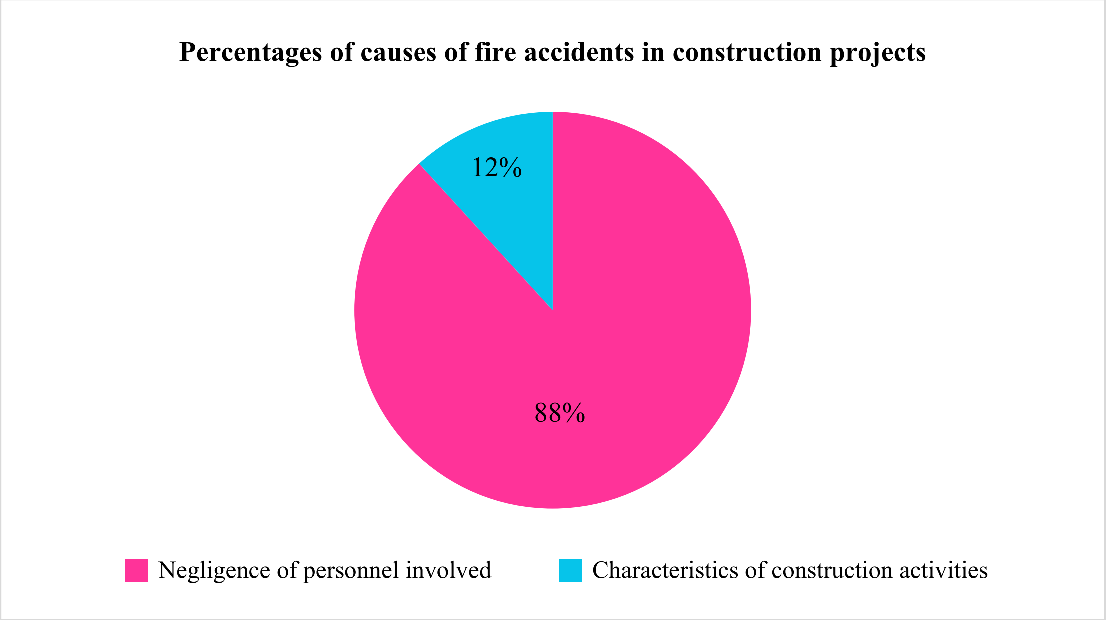


Figure 4.3 Percentages of causes of fire accidents in construction projects.

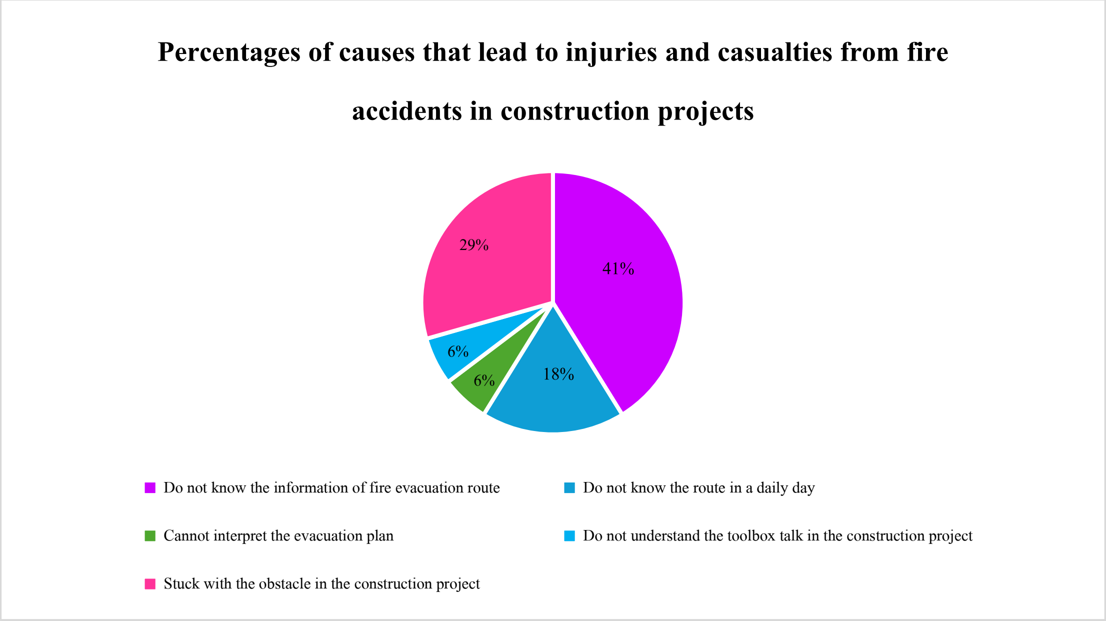


Figure 4.4 Percentages of causes that lead to injuries and casualties from fire accidents in construction projects.

According to the percentages of causes that lead to injuries and casualties from fire accidents in construction projects, 41% did not know the information about fire evacuation routes, 29% were stuck with the obstacle in the construction project, 18% did not know the route in a daily day, and 6% could not interpret the evacuation plan and did not understand the toolbox talk in the construction project, respectively.

Afterward, walk-in construction site surveys were performed to capture an overview of fire safety management as a fire emergency procedure. Photography and video recording were implemented. During the surveys, fire emergency procedures, such as fire evacuation routes in construction drawings and fire exit signs, were found in every sample construction project, as shown in Figure 4.5 to Figure 4.6

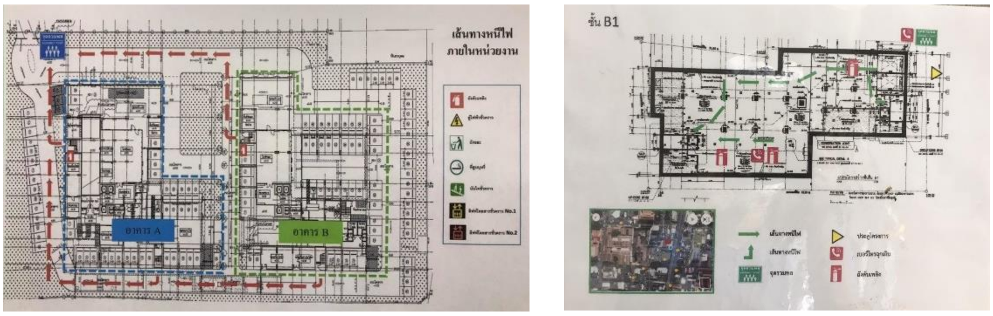
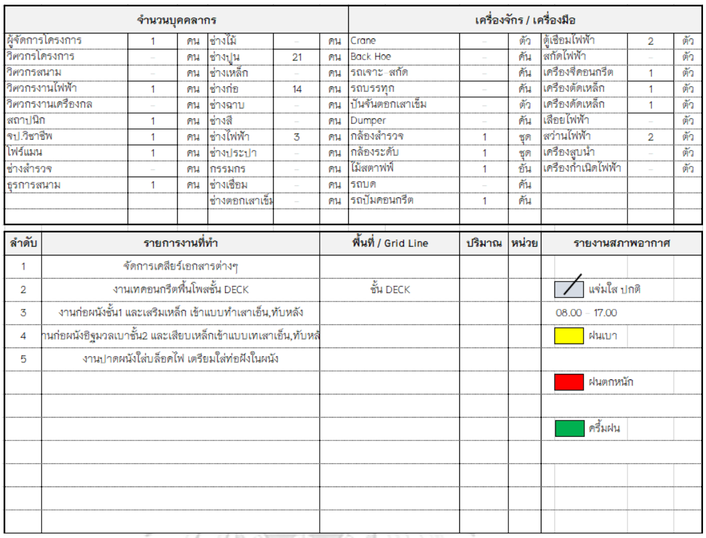


Figure 4.5 Fire evacuation routes in construction project number 1 and project number 3

Figure 4.6 Fire exit signs in construction project number 2 and project number 6

Even though laws and regulations indicate that all exits and access ways must be marked by an approved sign readily visible from any direction of exit access, every sign must be located in such a way that it is readily visible and of the correct size, distinctive color, and design to provide contrast with decorations, interior finish, or other signs. A reliable light source must suitably illuminate every sign. Externally and internally illuminated signs must be visible in normal and emergency lighting. However, most of the construction project was not installed in every position on every floor, and some fire exit signs were unclear and could not be modified according to the construction progress, which could have resulted in construction workers and staff not knowing the appropriate fire evacuation route.

Because the construction characteristics and environment are dynamic, which means the working area, number of construction workers, and route in the construction project will change daily following the construction work schedule. Thus, it is not easy in the event that new construction workers are not familiar with the routes for material handling, including evacuation in construction projects, and may not investigate how to evacuate as fast as possible within the prescribed time, which leads to a high risk of human errors in the decision-making process of selecting the appropriate evacuation route in the construction project.



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วิศวกรโครงการ	-	คน	ช่างปูน	21	คน	Back Hoe	-	คัน	สกัดไฟฟ้า	-	ตัว
วิศวกรสนาม	-	คน	ช่างเหล็ก	-	คน	รถเจาะ-สกัด	-	คัน	เครื่องจี้คอนกรีต	1	ตัว
วิศวกรงานไฟฟ้า	1	คน	ช่างก่อ	14	คน	รถบรรทุก	-	คัน	เครื่องตัดเหล็ก	1	ตัว
วิศวกรงานเครื่องกล	-	คน	ช่างฉาบ	-	คน	ปั้นจั่นตอกเสาเข็ม	-	ตัว	เครื่องตัดเหล็ก	1	ตัว
สถาปนิก	1	คน	ช่างสี	-	คน	Dumper	-	คัน	เลื่อยไฟฟ้า	-	ตัว
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โฟร์แมน	1	คน	ช่างประปา	-	คน	กล้องระดับ	1	ชุด	เครื่องสูบน้ำ	-	ตัว
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			ช่างตอกเสาเข็ม	-	คน	รถปั้มคอนกรีต	1	คัน			

ลำดับ	รายการงานที่ทำ	พื้นที่ / Grid Line	ปริมาณ	หน่วย	รายงานสภาพอากาศ
1	จัดการเคลียร์เอกสารต่างๆ				
2	งานเทคอนกรีตพื้นโพสชั้น DECK	ชั้น DECK			▨ แจ่มใส ปกติ
3	งานก่อผนังชั้น1 และเสริมเหล็ก เข้าแบบทำเสาเอ็น,ทับหลัง				08.00 - 17.00
4	านก่อผนังอิฐมวลเบาชั้น2 และเสียบเหล็กเข้าแบบเทเสาเอ็น,ทับหลั				🟨 ฝนเบา
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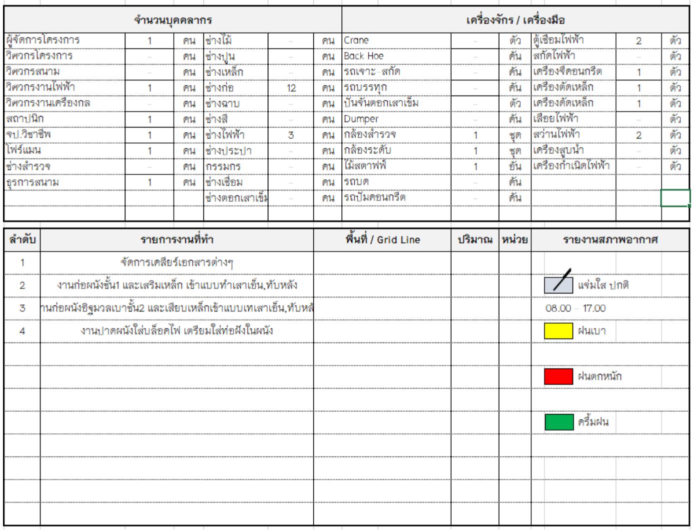
Figure 4.7 Example of construction work schedule on day 1.



จำนวนบุคคลากร						เครื่องจักร / เครื่องมือ					
ผู้จัดการโครงการ	1	คน	ช่างไม้	-	คน	Crane	-	ตัว	ตู้เชื่อมไฟฟ้า	2	ตัว
วิศวกรโครงการ	-	คน	ช่างปูน	-	คน	Back Hoe	-	คัน	สกัดไฟฟ้า	-	ตัว
วิศวกรสนาม	-	คน	ช่างเหล็ก	-	คน	รถเจาะ-สกัด	-	คัน	เครื่องจี้คอนกรีต	1	ตัว
วิศวกรงานไฟฟ้า	1	คน	ช่างก่อ	12	คน	รถบรรทุก	-	คัน	เครื่องตัดเหล็ก	1	ตัว
วิศวกรงานเครื่องกล	-	คน	ช่างฉาบ	-	คน	ปั้นจั่นตอกเสาเข็ม	-	ตัว	เครื่องตัดเหล็ก	1	ตัว
สถาปนิก	1	คน	ช่างสี	-	คน	Dumper	-	คัน	เลื่อยไฟฟ้า	-	ตัว
จป.วิชาชีพ	1	คน	ช่างไฟฟ้า	3	คน	กล้องสำรวจ	1	ชุด	สว่านไฟฟ้า	2	ตัว
โฟร์แมน	1	คน	ช่างประปา	-	คน	กล้องระดับ	1	ชุด	เครื่องสูบน้ำ	-	ตัว
ช่างสำรวจ	-	คน	กรรมกร	-	คน	ไม้สตาฟฟ์	1	อัน	เครื่องกำเนิดไฟฟ้า	-	ตัว
ธุรการสนาม	1	คน	ช่างเชื่อม	-	คน	รถบด	-	คัน			
			ช่างตอกเสาเข็ม	-	คน	รถปั้มคอนกรีต	-	คัน			

ลำดับ	รายการงานที่ทำ	พื้นที่ / Grid Line	ปริมาณ	หน่วย	รายงานสภาพอากาศ
1	จัดการเคลียร์เอกสารต่างๆ				
2	งานก่อผนังชั้น1 และเสริมเหล็ก เข้าแบบทำเสาเอ็น,ทับหลัง				▨ แจ่มใส ปกติ
3	านก่อผนังอิฐมวลเบาชั้น2 และเสียบเหล็กเข้าแบบเทเสาเอ็น,ทับหลั				08.00 - 17.00
4	งานปาดผนังใส่บล็อคไฟ เตรียมใส่ท่อฝังในผนัง				🟨 ฝนเบา
					🟥 ฝนตกหนัก
					🟩 ครึ้มฝน

Figure 4.8 Example of construction work schedule on day 2.

Figure 4.9 Example of the number of workers and construction activities on day 1.

Figure 4.10 Example of the number of workers and construction activities on day 2.

Figure 4.11 Example of construction worker in material handling activity.

According to the data from the construction site surveys indicated that the considerable causes that lead to injuries and casualties from fire accidents in construction projects are as follows:

(1) Did not know the information about fire evacuation routes.
(2) Stuck with the obstacles in the construction project.
(3) Did not know the route on a daily day.
(4) Could not interpret the evacuation plan.
(5) Did not understand the toolbox talk in the construction project.

In addition, the data from walk-in construction site surveys suggested that the current practice of fire emergency procedure as a fire evacuation plan is usually guided in two-dimensional (2-D) views, has poor visibility, and is not updated with the construction work schedule. Meanwhile, the construction project did not install fire exit signs in every position on every floor, and some fire exit signs were unclear and could not be modified. The working area, including the route, would change according to the construction progress. Therefore, a new approach to the communication system can effectively handle the dynamic nature of the construction project, which directly influences the evacuation route and work schedule that can impact evacuation performance. Moreover, the problem of providing the inappropriate evacuation route will be solved by proposing a system that can efficiently reduce potential hazards when an emergency occurs in the construction project by automatically generating appropriate evacuation routes as an effective tool is needed to support decision-making and enable common users, who were construction workers and staff to perceive and understand information clearly and efficiently for evacuation purposes.

4.3 Proposed conceptual system

In order to reduce the number of injuries and fatalities caused by fire accidents in construction projects, an effective tool is needed to support decision-making and enable construction workers and staff to perceive and understand information clearly and efficiently for evacuation purposes. Furthermore, this tool could advance the construction industry and be an application that benefits a project with accelerated on-site training and communication with all parties involved, from the owner down to the construction workers.

Emergency plan in construction projects are insufficient to identify hazardous areas and evacuation routes, as they are displayed in two dimensions (2-D). Thus, construction workers and staff cannot quickly interpret the drawings, understand their position within the construction project, and select appropriate evacuation routes. Moreover, many emergency casualties have been directly linked to delayed evacuation services in facilities where real-time information updates were lacking (Wang et al., 2014). This lack of real-time information can cause users to be unable to access the real-time location of the evacuation route in an emergency. However, construction site surveys found that most evacuation routes in construction drawings were displayed in two dimensions (2-D), as shown in Figure 4.5, and were not installed on every floor of the construction project. Fire exit signs in three sample projects were unclear, which could result in not knowing the appropriate evacuation route. Furthermore, new construction workers do not know and are not familiar with the route of the construction project. In addition, in case of obstruction, the working area and route in the evacuation route are not updated, followed by the progress of construction.

Therefore, to reduce the number of injuries and fatalities in the event of emergencies in construction projects, it is essential to prepare and develop a communication system to assist construction workers and staff, in the dynamic nature of the construction project, to observe evacuation guidance representing information such as voice and arrow directions for evacuation guidance, virtual green line, exit, and distance from the current location to the exit and the material storage to new construction workers, who do not familiar with the route in a material handling activity, including the appropriate evacuation route in case of obstacle avoidance in the construction project.

According to the literature review in Chapter 2, previous research has made significant progress in visualization technologies such as Building Information Modeling (BIM) and Augmented Reality (AR) for managing emergency evacuation in construction projects. These technologies provide simulations of the physical building components, the construction work area environment, the obstacle position, and the fire exit, enabling construction workers and staff to visualize and quickly interpret the integrated information. However, the real and present construction project conditions also significantly influence the evacuation route, as temporary works constantly change workplaces and obstruct hallways with materials and equipment.

This research gains ideas from the mentioned problems to develop a new communication system to support evacuation routes for preventing and reducing the number of injuries in construction projects. The proposed system provides real-time evacuation information by Building Information Modeling (BIM) and Augmented Reality (AR) that integrate with the user's mobile phone. All real-time fire evacuation information on the following topics:

1. The current location
2. The exit
3. The route and location of material storage
4. The shortest evacuation route from the current location to the destination
5. The virtual green line, voice, and arrow direction for evacuation guidance
6. The update on the total number of construction workers and staff in the construction project
7. The obstacle avoidance system, which provides the appropriate evacuation route

4.3.1 Ideas for improvement of a communication system

The idea to improve a communication system came from the evacuation plan that is usually guided in two-dimensional (2-D) views to explain hazardous areas, evacuation routes, and fire exit signs, which are also unclear. This presentation cannot interpret the drawings quickly. It is not easy to understand their exact position within the building, including the characteristics of construction phases continuously changed workplaces. The number of occupants, spaces, and evacuation routes changed from one day to another, which could result in not knowing the appropriate evacuation route for obstruction avoidance.

Material handling is one of the construction activities that requires familiarity with and experience of construction workers and staff with the route and information of the storage location. Thus, if construction workers and staff are unfamiliar with the route, they will have a high risk of losing and not getting updated information on evacuation routes, leading to work delays, injuries, or fatalities. However, in the current construction project, the evacuation route is presented in the two-dimensional drawings (2-D drawing), and the route has not been updated following the daily construction work schedule.

In order to perform this task required a communication system based on real-time information that may improve the decision-making process and provide real-time access to information for evacuating and guidelines to direct construction workers and staff to evacuate as fast as possible from the hazard location—the proposed system aimed to assist construction workers and staff when a fire occurred at the construction project. Evacuation information such as the current location, the exit, the location of material storage, the appropriate evacuation route from the current location to the destination, the virtual green line, voice, and arrow direction for evacuation guidance is produced, stored in the database, which can be retrieved and presented in the real world scene.

4.4 System and expected benefits

With this knowledge, the proposed system could provide real-time access to information such as the current location, exit, distance of the shortest route from the current location to the destination, and virtual green line, voice, and arrow direction for evacuation guidance. Furthermore, the proposed system recommended the appropriate evacuation route to the user in real-time regarding the route to the material storage and obstacle avoidance. Therefore, this proposed system is practical and convenient for decision-making, helping users find destinations quickly and efficiently.

4.5 Conclusion

In this chapter, the current practice guide to evacuation in the construction project, such as evacuation routes and fire exit signs, was explored in the construction site survey. The walk-in method, interviews, photography, and video recording were implemented in this step. The findings of construction site surveys found that most evacuation routes in construction drawings were displayed in two dimensions (2-D) and were not installed on every floor of the construction project, including fire exit signs in three sample projects, which were unclear. Moreover, most construction projects still use only two-dimensional (2-D) of evacuation routes, and the route of the working area, which was the material handling activity, is not updated and is followed by the construction progress. Only one of the sample construction projects utilizes visualization information technology such as Building Information Modeling (BIM) in their projects.

The problems of the current emergency procedure consist of the evacuation route presented in construction drawings displayed in two-dimensional (2-D) and fire exit signs are also unclear. This presentation cannot interpret the drawings quickly. It is not easy to understand their exact position within the construction project, including the characteristics of construction phases continuously changed workplaces. The number of occupants, spaces, and evacuation routes changed from one day to another, which could result in not knowing the appropriate fire evacuation route. For example, new construction workers do not know and are not familiar with the route of the construction project. In addition, the working area and route are not updated and followed by the construction progress in case of obstruction.

Therefore, the communication system could assist occupants in the dynamic nature of the construction project to observe evacuation guidance representing information. Moreover, the communication system could improve the decision-making process and provide evacuation information and guidelines directly to construction workers and staff in the construction project as quickly as possible.

Chapter 5

System Design and Algorithm Development

5.1 Introduction

This chapter presents the design and development of a communication system proposed according to the conceptual idea presented in Chapter 4. The system is designed to support evacuation routes of a dynamic nature in the construction project to develop a communication system using visualization technologies such as Building Information Modeling (BIM) and Augmented Reality (AR). In addition, the Unity game engine is a cross-platform toolkit to create video games and simulations for computers, consoles, and mobile devices. The marker-based location system uses a marker as a spatial index to link physical locations and virtual information. Additionally, the proposed calculation and algorithms are based on C# scripting in combination with other related classes and APIs, which calculate the distance from the current location to the exit with a virtual green line and provide voice and arrow directions for evacuation guidance, including obstacle avoidance, provide the working area and route for material handling update by the work schedule in the construction project. The preparation procedures for developing the prototype system are also described.

5.2 System design

In this section, the proposed system was developed to improve fire safety management and provide information for evacuating and routes of working areas to construction workers and staff in construction projects is presented. The proposed system architecture is configured and shown in Figure 5.1. The hardware components for developing this system consist of a laptop computer and mobile phone. The generated markers' patterns are optimized for image targets and were prepared to track the process according to algorithms based on C# scripting in combination with other related classes and APIs. The proposed system, which is named The Self Care using Technology Evacuation System (SCT Evacuation System), was developed on a laptop computer.

The developed system architecture in this research consists of three elements: 1)BIM authoring, 2) A marker-based location, and 3) Application authoring. Overall, the study demonstrated that the integration of Building Information Modeling (BIM) and Augmented Reality (AR) could be applied and facilitate the automatic update of the digital model and storage of data in a standard file format (Rahimiana et al., 2019), and display of the user's location in the virtual environment and presentation of the virtual fire evacuation route and provide the working area and route for material handling followed by the work schedule, display of the user's location in the virtual environment, obstacle avoidance system, and optimization the number of users, which are construction workers and staff in real-time on a real-world scene. Furthermore, this research posits that this can be an effective tool for supporting decision-making, enabling users to perceive and understand the information clearly and easily. Moreover, it can increase advancement in the construction industry and be used as an application that could benefit a project with accelerated working site training and communication with involved parties, from the owner down to the construction workers.

Figure 5.1 demonstrates the framework of the proposed system. Seamless information exchange was a significant focus of this study; therefore, the Industry Foundation Classes (IFC) file format and the Autodesk Revit and Autodesk Navisworks (NWD) file formats were utilized as standard files. Firstly, the IFC model is exported into an Autodesk Filmbox (FBX) file format and integrated into the Unity game engine to create a virtual model in the virtual environment. This virtual model generates a dataset of fire exits and markers, which display the user's location in the virtual environment. Then, C# is the primary programming language used for scripting to calculate the shortest evacuation route and obstacle avoidance system, provide the working area and route for material handling followed by the work schedule. Finally, the proposed system can visualize and detect markers that trigger the display of the user's location and the shortest and obstacle avoidance system in real-time on a real-world scene.

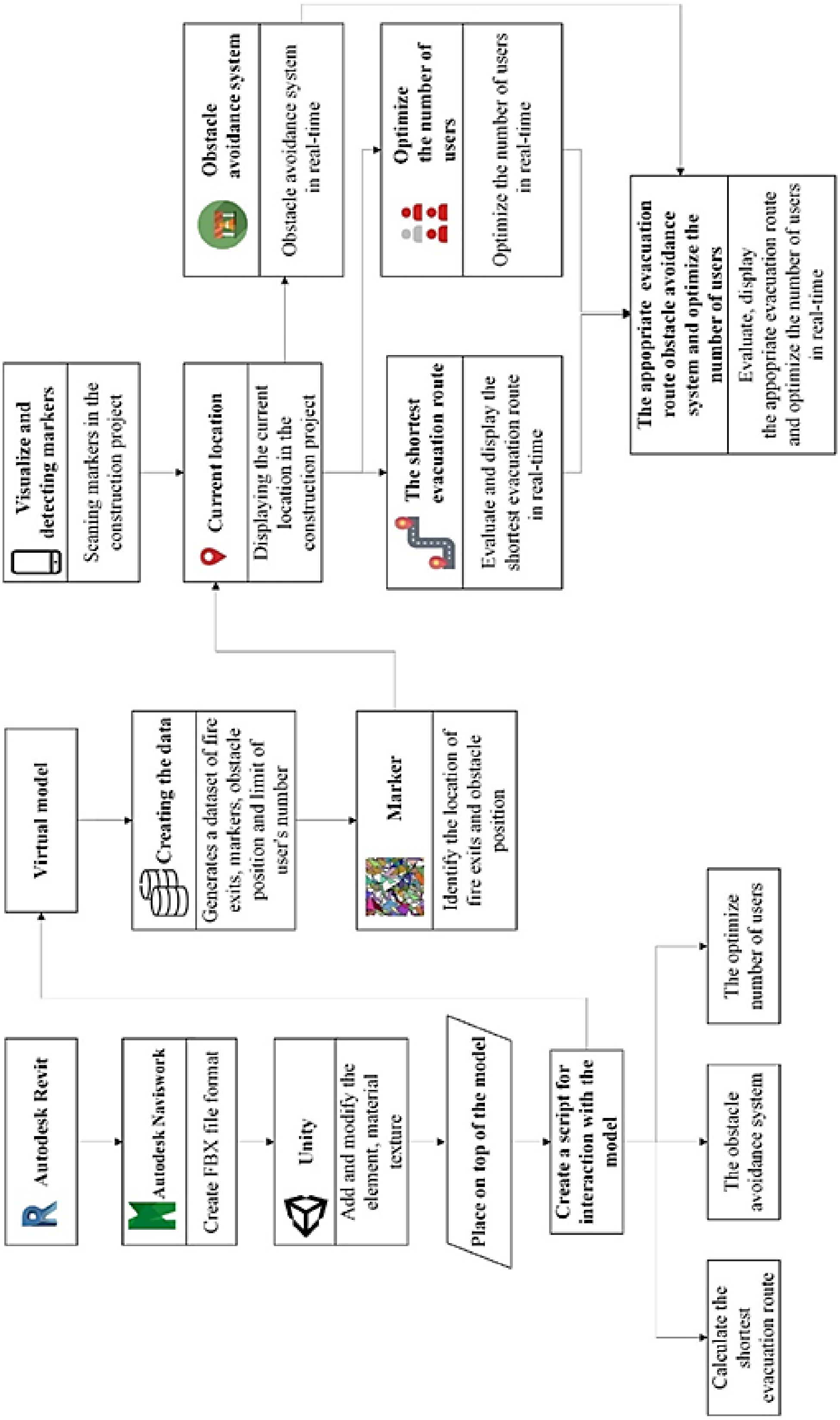


Figure 5.1 The framework of the proposed system
]

5.3 System preparation

5.3.1 Hardware preparation

In this research, the hardware components for developing the proposed system include a laptop computer, mobile phone, and markers. This section describes the functionalities of each hardware component. The mobile phone selected for this study is the Google Pixel 4, chosen for its specifications. The primary features of this mobile phone are its high-resolution camera, lightweight, and easily portable. The primary camera is built around a 1/2.55-inch sensor with a 12.2 MP resolution and 1.4µm pixels, coupled to a 27mm-equivalent f/1.7 lens with optical image stabilization. The mobile phone also includes Accelerometer and Gyrometer sensors to calculate the horizontal azimuth of the mobile device.

5.3.1.1. Lenovo Legion Y520

In the system design and development process, Lenovo Legion Y520 was the primary laptop, which is CPU: Intel i7 processor, Nvidia GeForce GTX 1050 graphics card, 15.6 inches (1920x1080) Full HD IPS, Memory Size: 4 GB DDR4, and Hard Disk Drive: 1 TB 5400 RPM was the machine used to create the application.

Figure 5.2 Lenovo Legion Y520

5.3.1.2. Google Pixel 4

In the system design and development process, Google Pixel 4 was the primary mobile phone, which is Android 10, SoC: Qualcomm Snapdragon 855, CPU: Octa-core (1 × 2.84

GHz Kryo 485 Gold Prime & 3 × 2.42 GHz Kryo 485 Gold & 4 × 1.78 GHz Kryo 485 Silver), Memory: 6 GB LPDDR4X, Storage: 64 GB or 128 GB UFS 2.1, The Pixel 4 using a 5.7-inch (140 mm) 1080p panel.

Figure 5.3 Google Pixel 4

5.3.1.3. Pattern of markers in the proposed system

In this research, the patterns of the generated markers are optimized for use as image targets. Each marker is randomly generated and unique. The material composition of a marker consists of padding surrounded by a thick border and a high-contrast pattern of either a template line, triangles, or quadrilaterals, with the marker size being 20.5 cm., as shown in Figure 5.4, was installed in the construction project and virtual model.

Figure 5.4 Example of the markers.

5.3.2 Software preparation

5.3.2.1. AutoCAD

AutoCAD is a computer-aided design (CAD) software that uses architects, engineers, and construction professionals to produce accurate 2D and 3D drawings. Only the length and width of the construction elements that can be measured along the X and Y axis are also shown. This software's purpose is to describe an object's size and shape and provide information on acceptable variations, materials, and any other information that can assist in a complete understanding of the item. This research focused on As-built drawings of the construction project. The case study in the construction project was focused on the high-rise building project.

Figure 5.5 AutoCAD Software.

Figure 5.6 The two-dimensional (2-D) model created by AutoCAD Software.

5.3.2.2. Autodesk Revit

Autodesk Revit is a Building Information Modeling (BIM) tool widely used in architecture, engineering, and construction. This software is designed to increase productivity and accuracy across the project lifecycle, from conceptual design to analysis and visualization to fabrication and construction. This software is a virtual plan that simulates the structure, such as the building's width, height, and depth, to look as close to reality as possible. The three-dimensional (3-D) model was created by Autodesk Revit 2022 for illustration in a virtual environment, as shown in Figure 5.7.

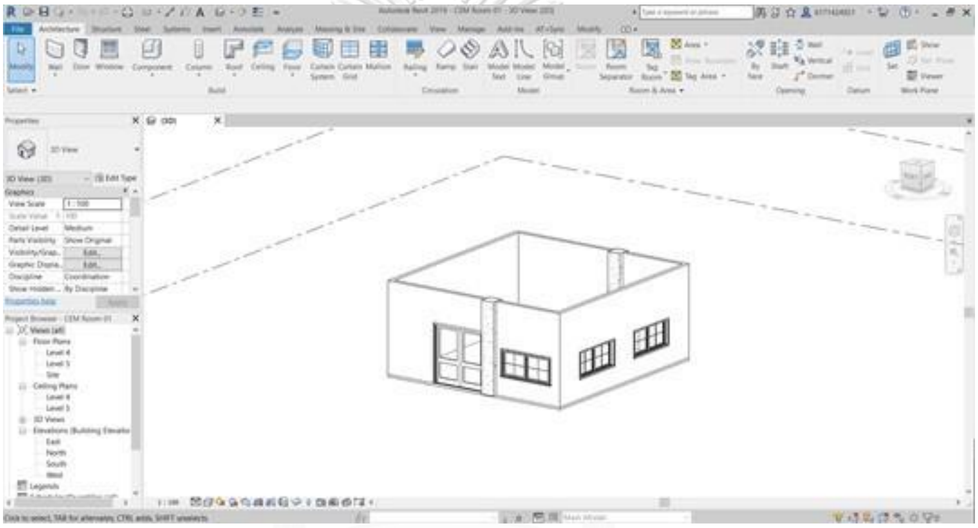


Figure 5.7 The Architecture of the 3D model using Autodesk Revit 2022.

5.3.2.3. Autodesk Naviswork Manage

Autodesk Navisworks Manage is a comprehensive project review solution that supports design intent, analysis, and communication. This software can represent virtual coordinates and analyze and communicate design intent and constructability utilizing multidisciplinary design data such as Building Information Modeling (BIM) and digital prototypes. Meanwhile, this software combines design and construction data into a single model and creates synchronized project views that combine Autodesk Revit and AutoCAD file formats, including geometry, images, and data.

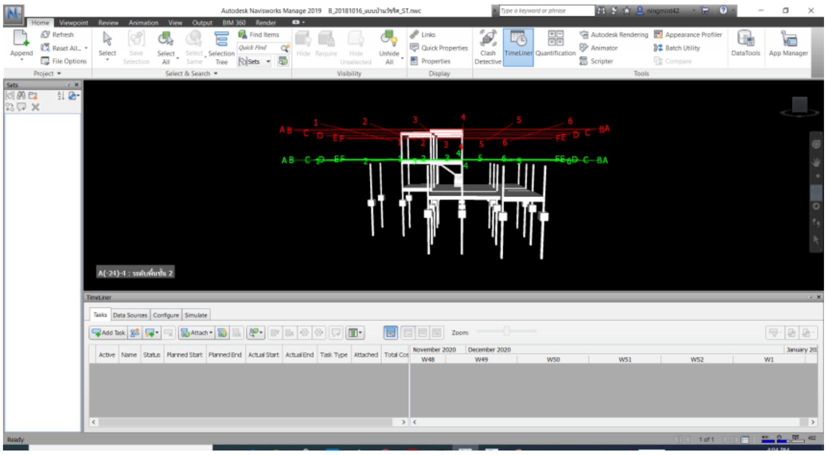


Figure 5.8 The Architecture of the 3D model in Autodesk Naviswork Manage.

5.3.2.4. Unity Game Engine

Unity Game Engine is a cross-platform toolkit developed by Unity Technologies for developing video games and simulations for computers, consoles, and mobile devices. This software supports two-dimensional and three-dimensional graphics, including 3D rendering, physics, and collision detection, and a built-in Visual Studio and C# scripting in combination with a collection of other related classes and APIs. Assets, which refer to elements in this software, can vary from textures and materials to meshes, scripts, and physics-related components. Unity Game Engine software, as shown in Figure 5.9, was applied to develop the Virtual Environment models to enhance the reality of the construction site environment.

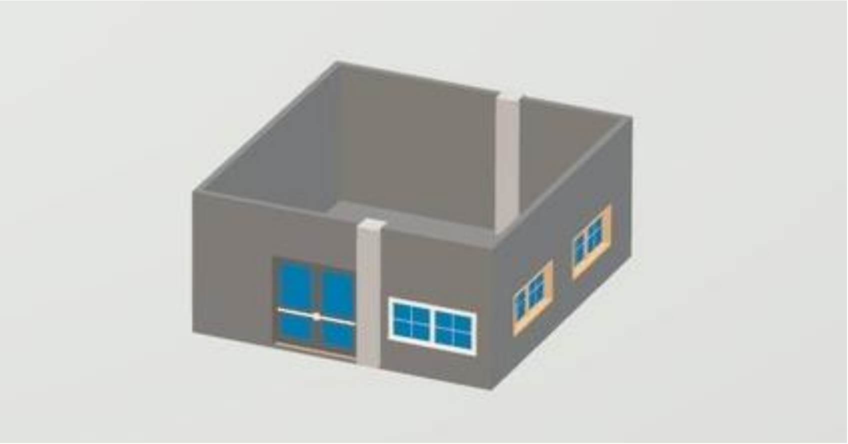


Figure 5.9 The Virtual Environment of the building using the Unity Game Engine.

5.3.3 Vuforia Engine

In this research, Vuforia Engine is the most widely used platform for Augmented Reality (AR) development and supports most mobile phones, tablets, eyewear, and AR glasses. The selection reasons were that this platform is free for non-commercial purposes, widely used in academic areas, and low-cost, enabling developers to easily add advanced computer vision functionality to Android, iOS, and UWP apps for creating AR experiences that realistically interact with objects and the environment (Vuforia, 2023). Vuforia Engine supports 2D and 3D objects, including multiple target configurations. Moreover, this platform recognizes and captures planar images or 3D objects in real-time, allowing developers to place virtual objects through the viewfinder and adjust their position on the camera's background (Liu et al., 2018). {Xinqi Liu, 2018 Vuforia Engine is supported in multiple development environments and is supported on many devices. The API is exposed in C for Android, iOS, and UWP and C# development within the Unity Engine, a primary platform to develop the proposed system. In addition, the Vuforia Engine could detect and track the image by comparing extracted natural features from the camera image against a known target resource database. For developing the proposed system, the image target feature uses a spatial link to display physical location and virtual information.

5.4 BIM authoring

To enhance the interpretation and understanding of construction workers and staff regarding the evacuation route and to select appropriate evacuation routes in the construction project, the optimal approach for achieving this goal is to provide them with as much realistic information as possible. The proposed system can generate and superimpose 2D and 3D computer graphics onto real-world scenes. However, the 3D modeling provides real-time access to information for evacuating, and guidelines to direct construction workers and staff must be prepared and used as input data. This section describes the process for creating the 3D model and supported files.

5.4.1 3D modeling

In this study, there were two case studies consisting of 1) the Department of Civil Engineering Building at Chulalongkorn University is a five-story building used for classrooms, offices, and meeting rooms. The total area is 5,832 square meters, and the height is 26 meters. 2) The construction project for an engine building, which was a construction project for Chulalongkorn University Demonstration Secondary School, as a case study, is a six-story high-rise construction project of 1,032.83 square meters, and the height is 26.10 meters.

Firstly, a 3D model of the building's architecture was created with a Level of Detail (LOD) of 300 using Autodesk Revit 2022 based on as-built drawings. Therefore, the room and exit locations in the 3D model are the same as in the real world. A Level of Detail 300 includes columns, beams, and floors in the structural phase and windows, doors, walls, and stairs in the architecture phase, along with their size, shape, location, and geometric data such as length and area (Volk et al., 2014). The 3D model was saved in the Industry Foundation Classes (IFC) file format. The model was then exported to the Autodesk Naviswork (NWD) file format and saved in the Autodesk Filmbox (FBX) file format, making it suitable for data exchange between different BIM authoring software applications. Finally, the FBX file format was integrated into the Unity game engine with the assigned textures (Rahimiana et al., 2019).

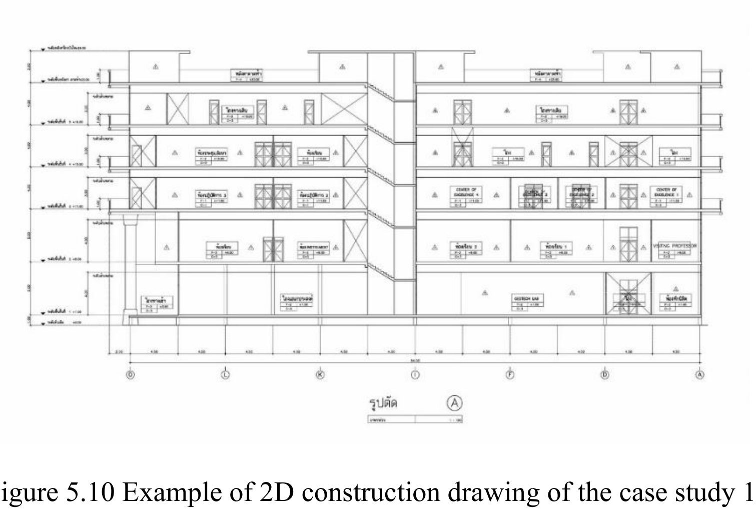


Figure 5.10 Example of 2D construction drawing of the case study 1.

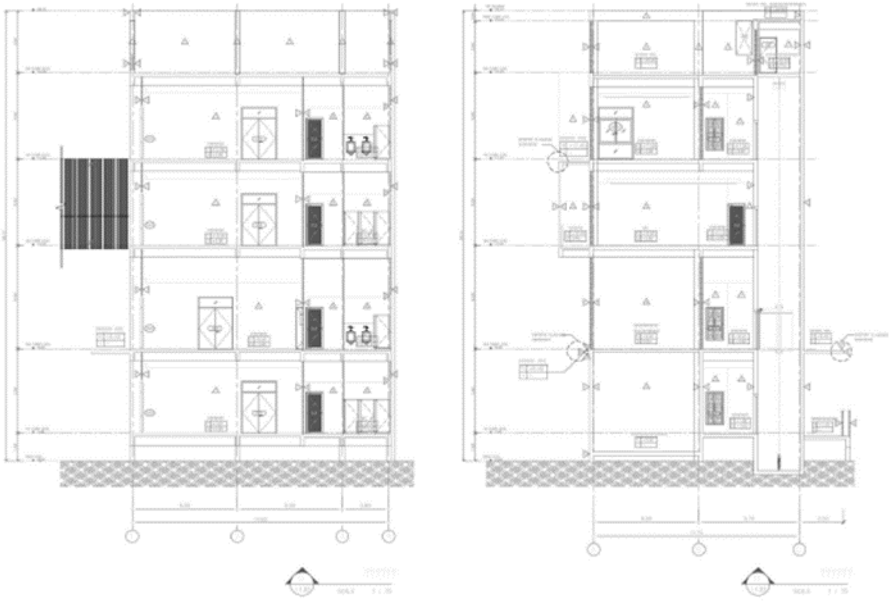


Figure 5.11 Example of 2D construction drawing of the case study 2.

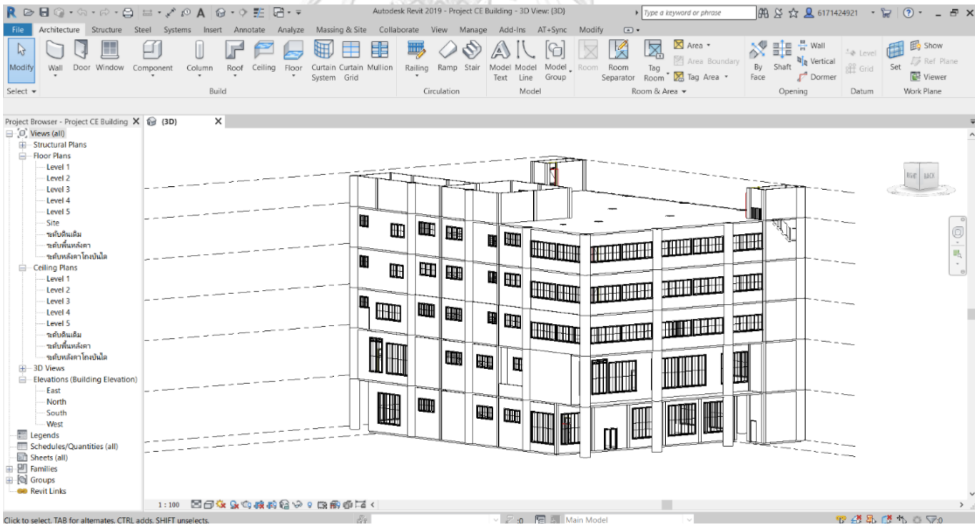


Figure 5.12 Example of the 3D model in case study 1 using Autodesk Revit 2022.

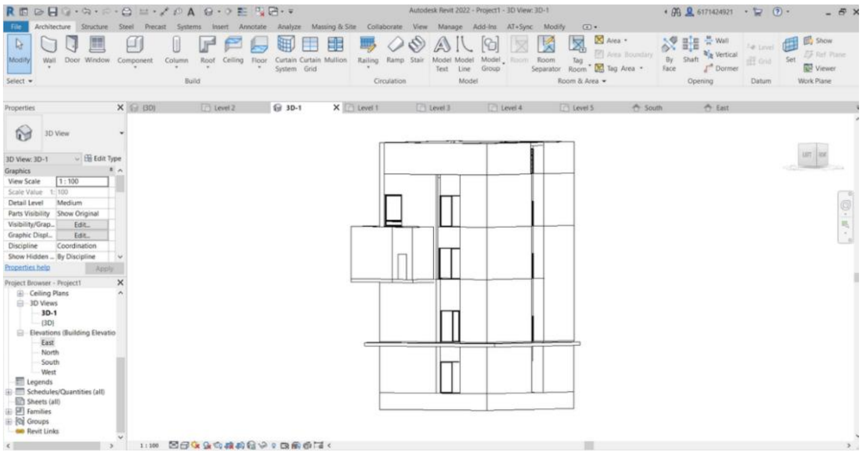


Figure 5.13 Example of the 3D model in case study 2 using Autodesk Revit 2022.

Figure 5.14 Example of the 3D model in case study 1 in Autodesk Filmbox (FBX) file format.

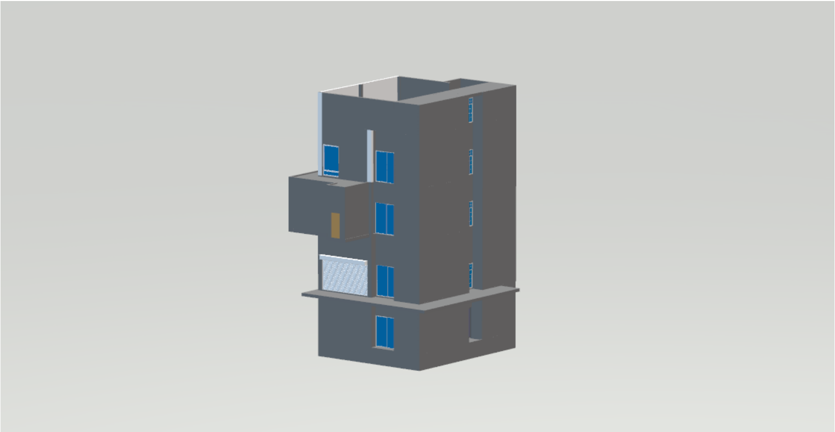


Figure 5.15 Example of the 3D model in case study 2 in Autodesk Filmbox (FBX) file format.

5.4.2 Linking the FBX model and the Unity game engine

The Unity game engine is a cross-platform toolkit developed by Unity Technologies for creating video games and simulations for computers, consoles, and mobile devices. This study used it as the primary platform for creating the application and integrating visualization technologies such as Building Information Modeling (BIM) and Augmented Reality (AR). In addition, this study adopted a previously developed method of linking a digital model to support integrating the information in the 3D model, including 3-D rendering, physics, and collision detection. This method was established using the FBX file format and incorporating programming with C# scripting and other related classes and APIs.

Figure 5.16 Example of the Virtual Environment of case study 1 using the Unity Game Engine.

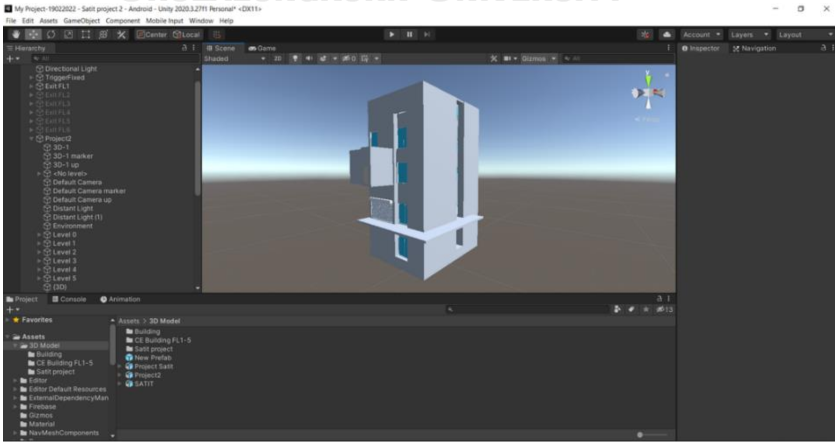


Figure 5.17 Example of the Virtual Environment of case study 2 using the Unity Game Engine.

5.5 A marker-based location

5.5.1 The developed marker-based location system

Marker-based locations are abundant in buildings, construction sites, and other built environments where engineering operations are conducted, making applying this method very convenient. Markers are distinct patterns that can be either 2D images with visual features that mobile phone cameras can easily recognize and extract (Sun et al., 2009) or natural objects in the real environment. In addition, markers can be either paper-based or physical objects in the real world. The developed marker-based location system uses a marker as a spatial index to link physical location and virtual information. The system operates as follows:

Firstly, the camera captures an image containing a marker on the mobile device. This image is then sent to the classifier algorithm, which is a type of algorithm designed to classify data into different categories or classes and assumes a relatively balanced distribution of classes to generate the code and create the marker ID. The marker code is then sent to the database as a key value to check for attached information. Next, the system sets the location and direction in the virtual environment; if the code is not recognized in the database, the system does not display any data. Finally, as the mobile device moves, the system sends updated data related to the location and direction to the real world in real-time. Again, if the mobile device has not moved, the system does not update any data.

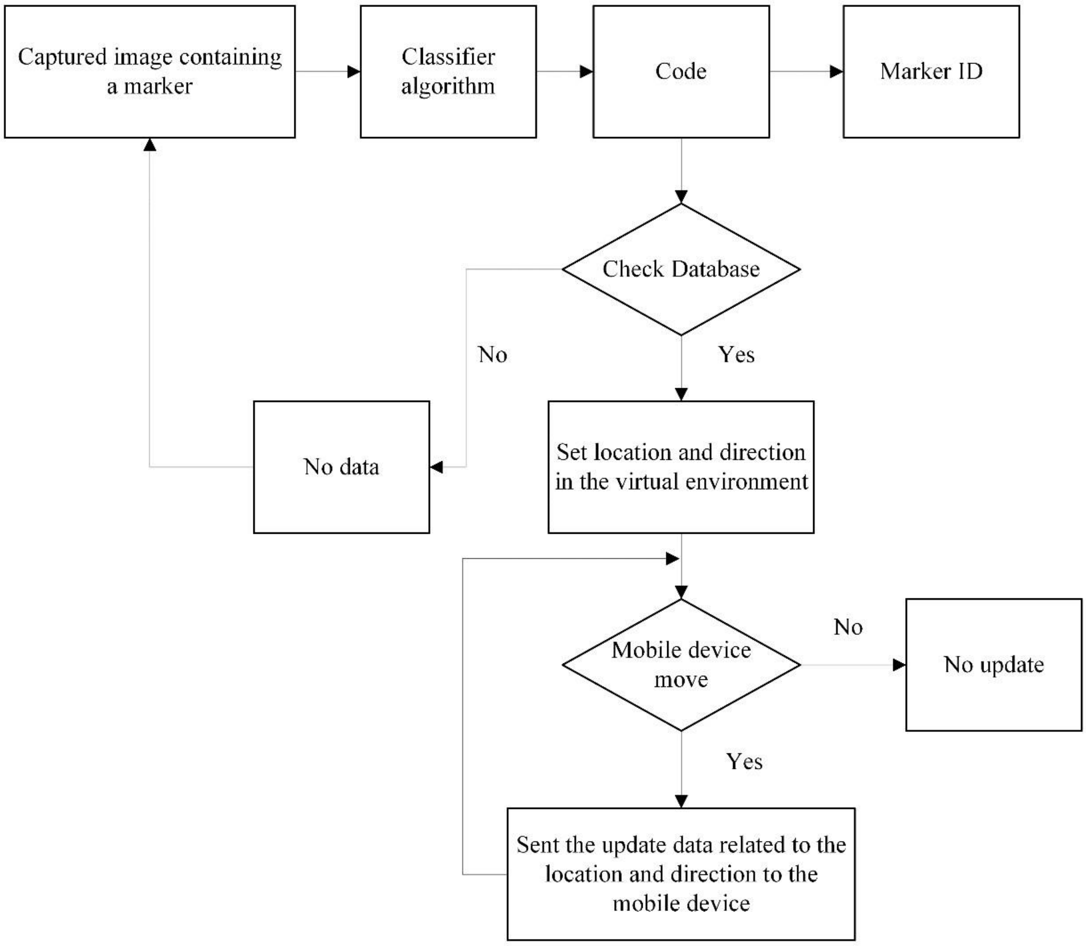


Figure 5.18 Framework of the developed marker-based location system.

5.6 Integration with the Unity game engine

In order to develop the proposed system, the 3D model, which was created from Autodesk Revit 2022 and then imported the 3D model into the Unity game engine to allow the development of virtual environment simulations, this platform proved advantageous. It contributed to creating a high-quality 3D model. Google Pixel 4 was the primary device used for this study, while a laptop with an Intel i7 processor and an Nvidia GEFORCE GTX graphics card was used to create the application.

Google Pixel 4, equipped with voice and arrow direction functions, assists users in evacuation guidance by using the built-in gyroscope and accelerometer sensor to calculate the horizontal azimuth of the mobile device. The mobile device then provides visual and voice direction guidance using a green line and arrow on the screen, constantly pointing toward the recommended optimal evacuation route.

5.7 Integration of Augmented Reality (AR) with the Unity game engine

In order to develop the proposed system that integrates Building Information Modeling (BIM) and Augmented Reality (AR) to provide information to evacuate in the construction project and allow construction workers and staff to perceive and indicate potential hazards, the marker-based location method uses a spatial link to display physical location and virtual information. Additionally, markers are defined in the 3D model in both the virtual and real environments to identify the location of rooms, stairs, and exit locations as nodes in the construction project, as shown in Figures 5.19 and 5.20. Hence, the proposed system utilizes multiple randomly generated and unique marker patterns.

Furthermore, the system relies on seamless connectivity between various sources of real-time location data, an existing BIM model, and a virtual environment. Therefore, it is crucial to establish an effective connection that enables a smooth flow of the construction workers and staff location to the virtual environment in the construction project.

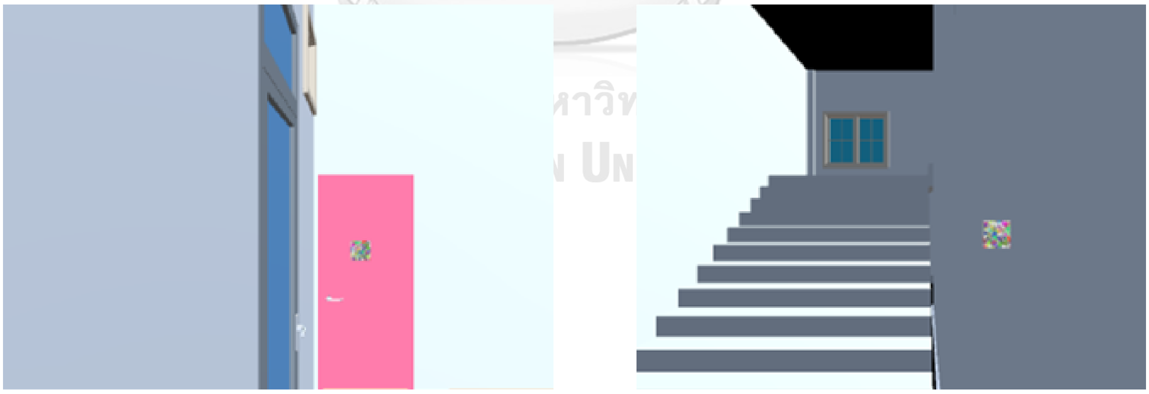


Figure 5.19 Example of the marker's location in the virtual environment.

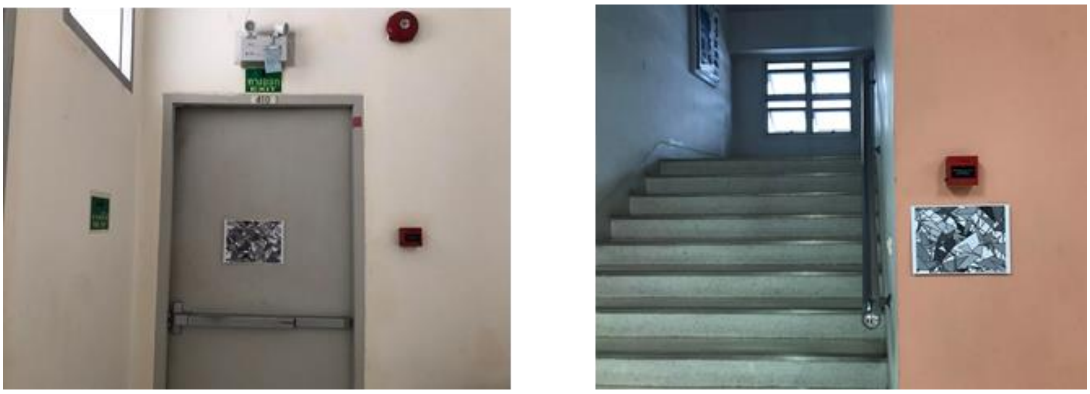


Figure 5.20 Example of the marker's location in the real environment.

5.8 Application authoring

The proposed system provides real-time information, such as the user's current location, which is used to calculate the distance to the exit. The system also provides voice and arrow directions for evacuation guidance, virtual green line, exit, the material storage and distance from the current location to the exit, the identification of users, provides the working area and route for material handling followed by the work schedule, and recommends the appropriate evacuation route in case of obstacle avoidance system in the construction project was also prepared and applied. The two-dimensional (2-D) drawings and the three-dimensional (3-D) model were arranged to support this system. Moreover, the shortest evacuation route calculation, the identification of users, the voice and arrow direction, the obstacle avoidance system, and the working area and route for material handling followed by the work were proposed.

In the proposed system, the starting point is an image containing a marker, which measures the distance to the exit, determines whether the evacuation route adheres to safety rules, and plans the corresponding exits for each location in the construction project. If the user moves away from the exit or does not follow the evacuation guidance, the system will recalculate the distance from the current location and display real-time information to the user on their next interaction.

5.9 Calculation and Algorithms of the proposed system development

5.9.1 The Identification of users algorithm

In order to develop the identification of users at the construction project, the proposed system could identify each user who enters and exits the construction project and update information in real-time using Firebase. In addition, the system could provide information according to the number of users at that time.

An algorithm for identifying users was developed; a flowchart of this algorithm is described in Figure 5.21. In the beginning, users input data such as name and surname. Subsequently, the system would update and collect data: name, surname, and device ID. Then, the system would immediately provide the information according to the number of users.

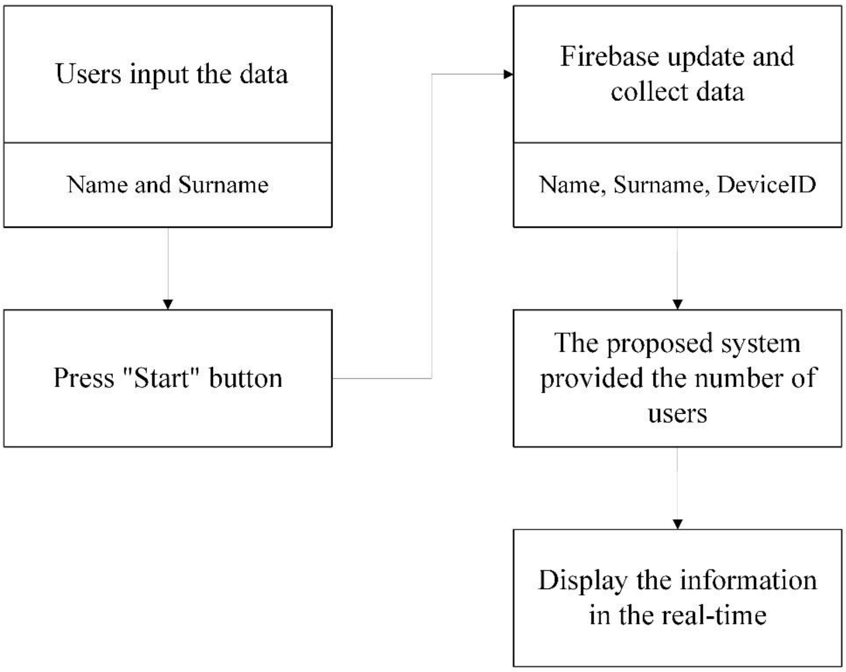
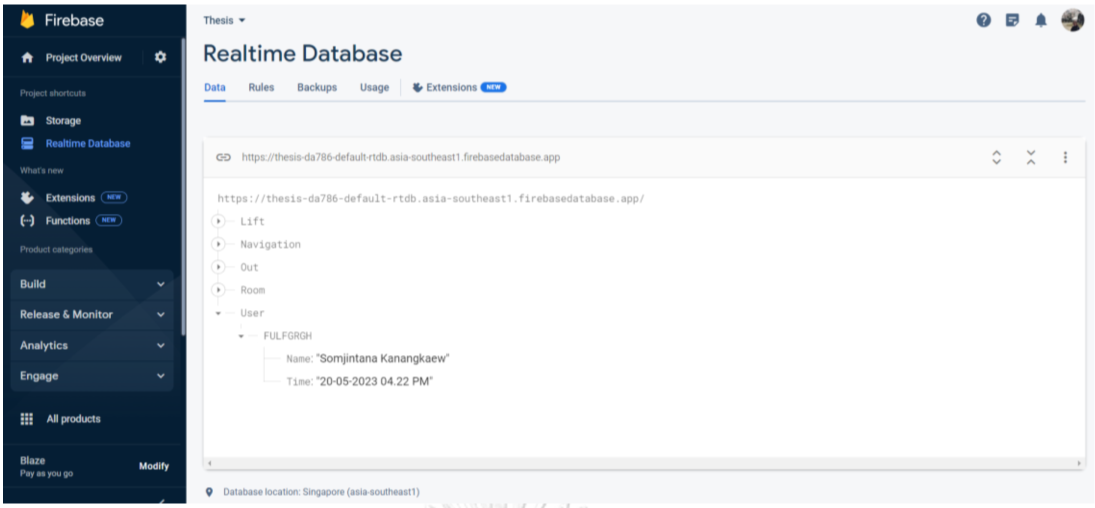


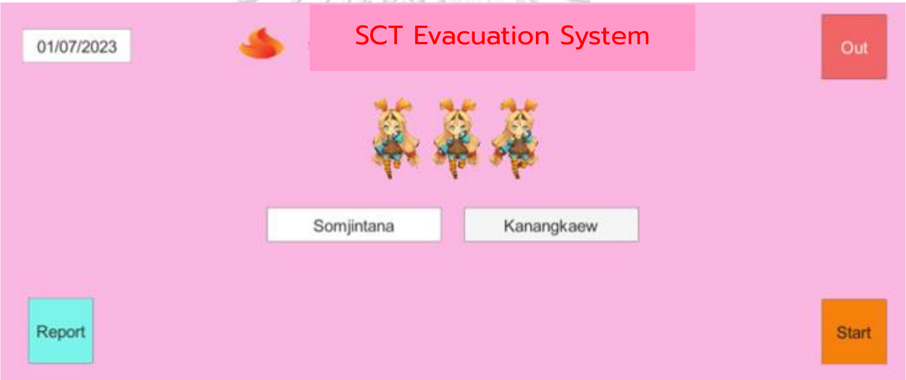
Figure 5.21. Flowchart of the Identification of users algorithm.

Figure 5.22 and Figure 5.23 present examples of Firebase and the output of the identification of the users system.



```
https://thesis-da786-default-rtdb.asia-southeast1.firebasedatabase.app/
  Lift
  Navigation
  Out
  Room
  User
    FULFGRGH
      Name: "Somjintana Kanangkaew"
      Time: "20-05-2023 04.22 PM"
```

Figure 5.22. The example of Firebase to the data of users.



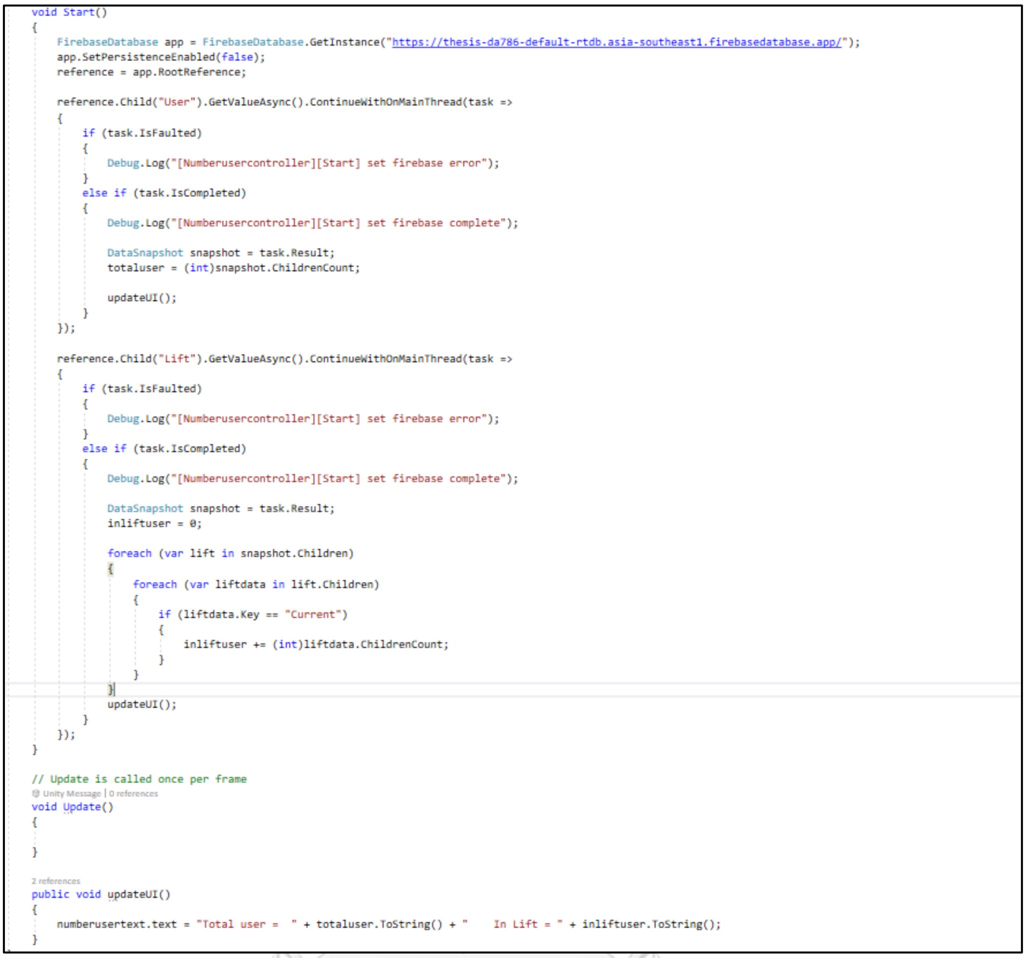
01/07/2023

Somjintana

Kanangkaew

Figure 5.23. The output of the Identification of users system.

The code for the identification of users is presented as follows.



```
void Start()
{
    FirebaseDatabase app = FirebaseDatabase.GetInstance("https://thesis-da786-default-rtdb.asia-southeast1.firebasedatabase.app/");
    app.SetPersistenceEnabled(false);
    reference = app.RootReference;

    reference.Child("User").GetValueAsync().ContinueWithOnMainThread(task =>
    {
        if (task.IsFaulted)
        {
            Debug.Log("[Numberusercontroller][Start] set firebase error");
        }
        else if (task.IsCompleted)
        {
            Debug.Log("[Numberusercontroller][Start] set firebase complete");

            DataSnapshot snapshot = task.Result;
            totaluser = (int)snapshot.ChildrenCount;

            updateUI();
        }
    });

    reference.Child("Lift").GetValueAsync().ContinueWithOnMainThread(task =>
    {
        if (task.IsFaulted)
        {
            Debug.Log("[Numberusercontroller][Start] set firebase error");
        }
        else if (task.IsCompleted)
        {
            Debug.Log("[Numberusercontroller][Start] set firebase complete");

            DataSnapshot snapshot = task.Result;
            inliftuser = 0;

            foreach (var lift in snapshot.Children)
            {
                foreach (var liftdata in lift.Children)
                {
                    if (liftdata.Key == "Current")
                    {
                        inliftuser += (int)liftdata.ChildrenCount;
                    }
                }
            }
            updateUI();
        }
    });
}

// Update is called once per frame
Unity Message | 0 references
void Update()
{

}

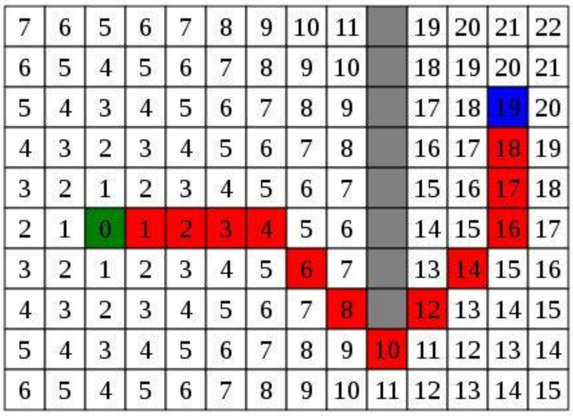
2 references
public void updateUI()
{
    numberusertext.text = "Total user =  " + totaluser.ToString() + "    In Lift = " + inliftuser.ToString();
}
```

Figure 5.24. The code of the identification of users.

5.9.2 The Shortest Evacuation Route

In this proposed system, determining the shortest evacuation route was one of the challenges in reducing the number of injuries and fatalities caused by emergency situation in construction projects. The proposed system for the evacuation system is an integrated framework that stores location data in a 3D model, calculates the shortest evacuation route for each construction worker and staff, and generates a green line to display the virtual evacuation route with voice and arrow directions in the construction project. Building Information Modeling (BIM) serves as an effective visualization tool that assists in allocating evacuation areas in the construction project to each exit based on the latest locations of fires and evacuees. C# is the primary programming language used for scripting in this study. Thus, the shortest evacuation route is calculated using the A* algorithm.

The A* algorithm is a heuristic search algorithm that finds the shortest paths between a starting node and an end node. In addition, it employs a heuristic function to estimate the cost of reaching the goal, which aids in efficiently searching for the optimal path, as shown in Figure 5.25. The advantage of the A* algorithm is that it is simple and relatively fast (Erke et al., 2020). Moreover, the A* algorithm can be computed according to Equation 5.1.



7	6	5	6	7	8	9	10	11		19	20	21	22
6	5	4	5	6	7	8	9	10		18	19	20	21
5	4	3	4	5	6	7	8	9		17	18	19	20
4	3	2	3	4	5	6	7	8		16	17	18	19
3	2	1	2	3	4	5	6	7		15	16	17	18
2	1	0	1	2	3	4	5	6		14	15	16	17
3	2	1	2	3	4	5	6	7		13	14	15	16
4	3	2	3	4	5	6	7	8		12	13	14	15
5	4	3	4	5	6	7	8	9	10	11	12	13	14
6	5	4	5	6	7	8	9	10	11	12	13	14	15

Figure 5.25. Example of finding the shortest paths using the A* algorithm (Mahadevi et al., 2012)

$$f(n) = g(n) + h(n) \tag{5.1}$$

Where $f(n)$ = the cost function from an initial point to the destination

$g(n)$ = the actual cost from an initial point to the node n in state space

$h(n)$ = the estimated cost of the optimal path from node n to the destination.

The system demonstrates the results of the shortest evacuation route to assist construction workers and staff in evacuating from hazardous areas to the destination as quickly as possible. The algorithm for presenting the shortest evacuation route is shown in Figure 5.26. The system starts with a captured image containing a marker, which serves as the starting point. The marker carries its coordinate data in an XYZ axis and is utilized to measure the distance to the exit in the construction project. Next, it calculates the distance between the marker and the exit, verifies if the evacuation route adheres to the rules, and plans the corresponding exits for each position within the construction project. If construction workers and staff move far from the exit or fail to follow the evacuation guidance, the proposed system will recalculate the distance from the current location and provide real-time information to guide them accordingly in subsequent instances.

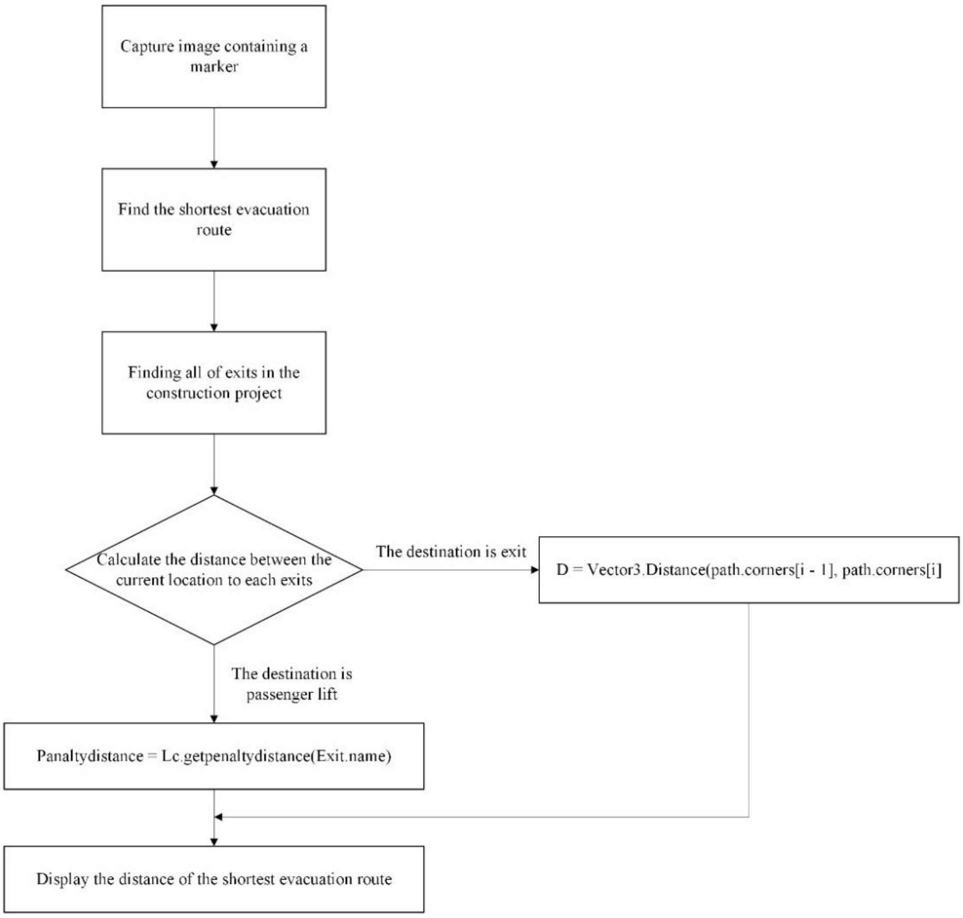


Figure 5.26. Flowchart of the shortest evacuation route.

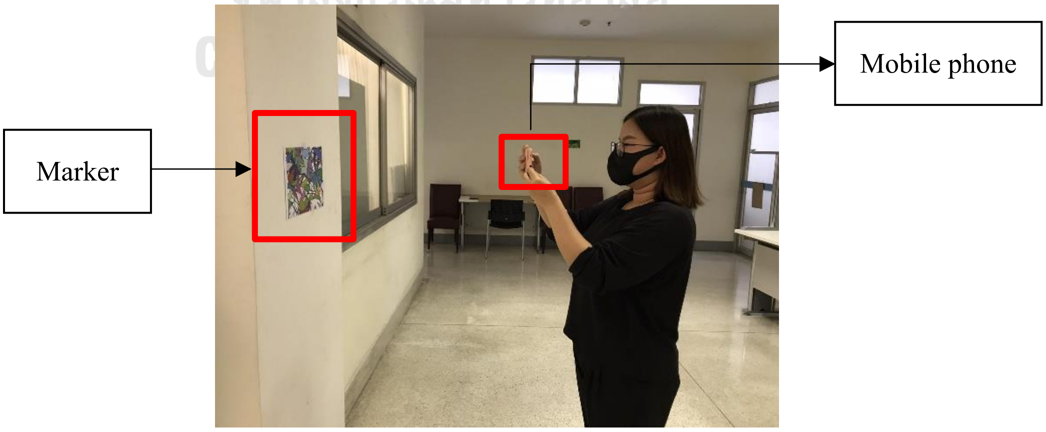
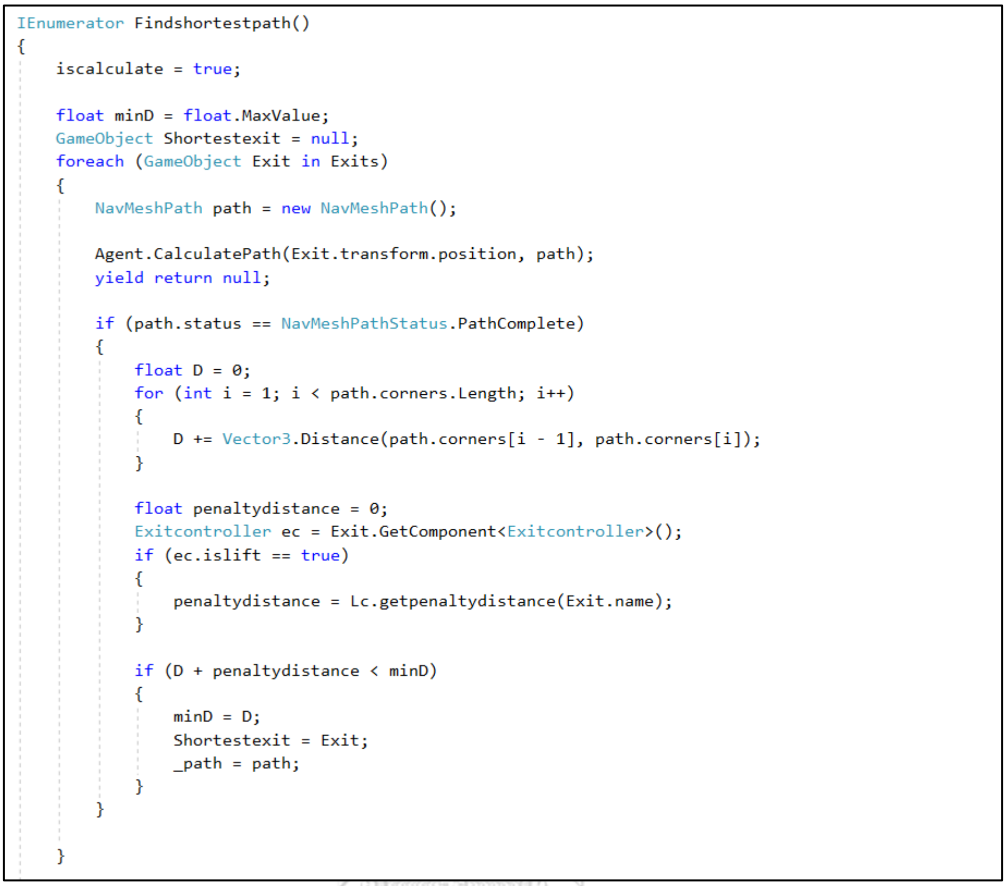


Figure 5.27. Example of a captured image containing a marker process.

The codes for calculation of the shortest evacuation route in the construction project are shown as follows.



```
IEnumerator Findshortestpath()
{
    iscalculate = true;

    float minD = float.MaxValue;
    GameObject Shortestexit = null;
    foreach (GameObject Exit in Exits)
    {
        NavMeshPath path = new NavMeshPath();

        Agent.CalculatePath(Exit.transform.position, path);
        yield return null;

        if (path.status == NavMeshPathStatus.PathComplete)
        {
            float D = 0;
            for (int i = 1; i < path.corners.Length; i++)
            {
                D += Vector3.Distance(path.corners[i - 1], path.corners[i]);
            }

            float penaltydistance = 0;
            Exitcontroller ec = Exit.GetComponent<Exitcontroller>();
            if (ec.islift == true)
            {
                penaltydistance = Lc.getpenaltydistance(Exit.name);
            }

            if (D + penaltydistance < minD)
            {
                minD = D;
                Shortestexit = Exit;
                _path = path;
            }
        }

    }
```

Figure 5.28. The codes for calculation of the shortest evacuation route.

5.9.3 The shortest virtual evacuation route algorithm

In order to create the proposed system for the construction project, the type of algorithm was classified as the shortest virtual fire evacuation route. The algorithm was developed to implement the shortest virtual fire evacuation route on a real-world scene, aiming to support decision-making and enable users to perceive and understand the information clearly and easily.

An algorithm for the shortest virtual evacuation route, as shown in Figure 5.29. The process begins with a captured image with a marker, which serves as the starting point. Next, the proposed system detected the markers and calculated the shortest evacuation route from the current location to the exit. Subsequently, the system renders the shortest virtual evacuation route as a virtual green line, which is displayed in the real-world scene to provide evacuation guidance.

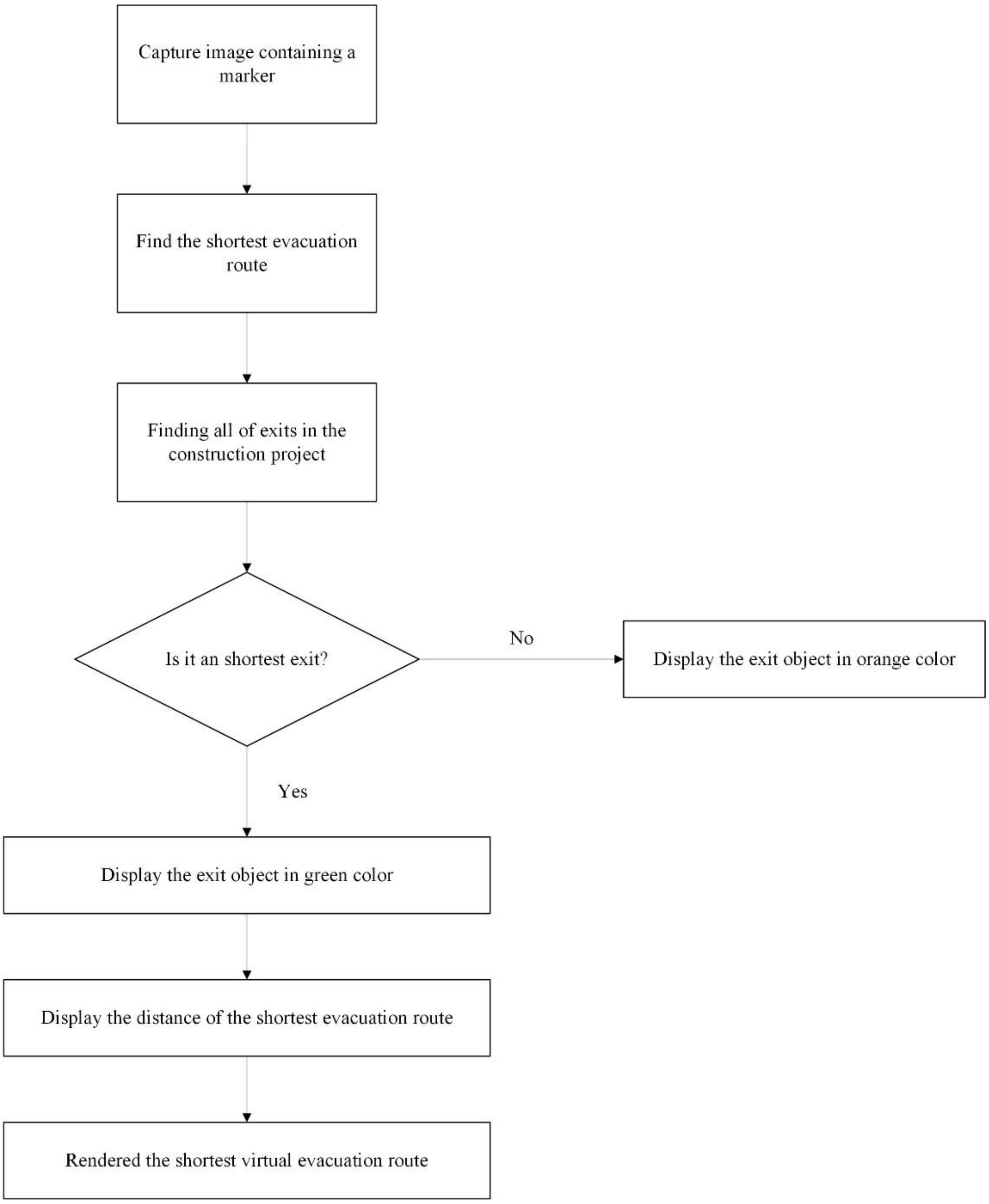


Figure 5.29. Flowchart of the shortest virtual evacuation route.

Figure 5.30 presents the output of the proposed system with the shortest virtual evacuation route.

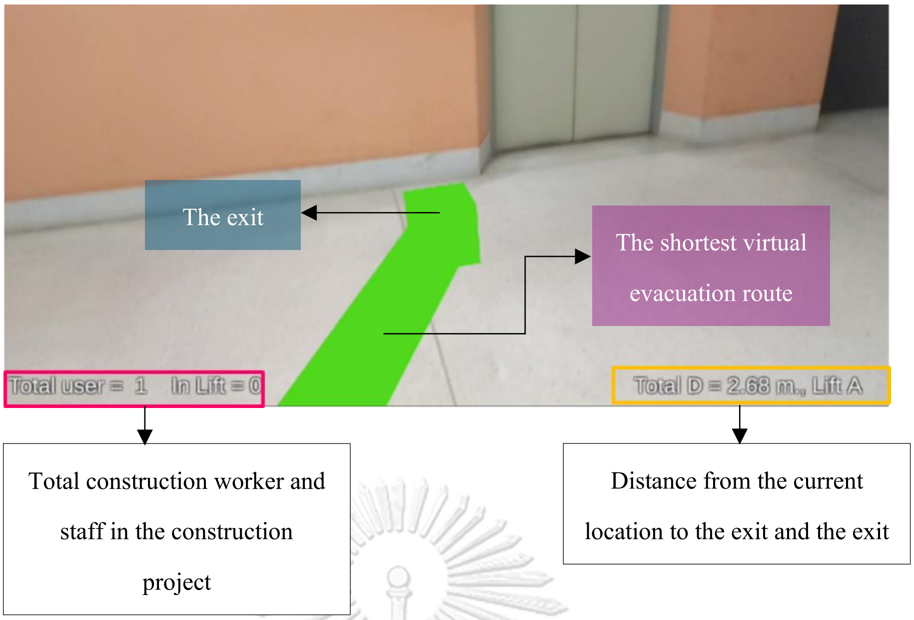
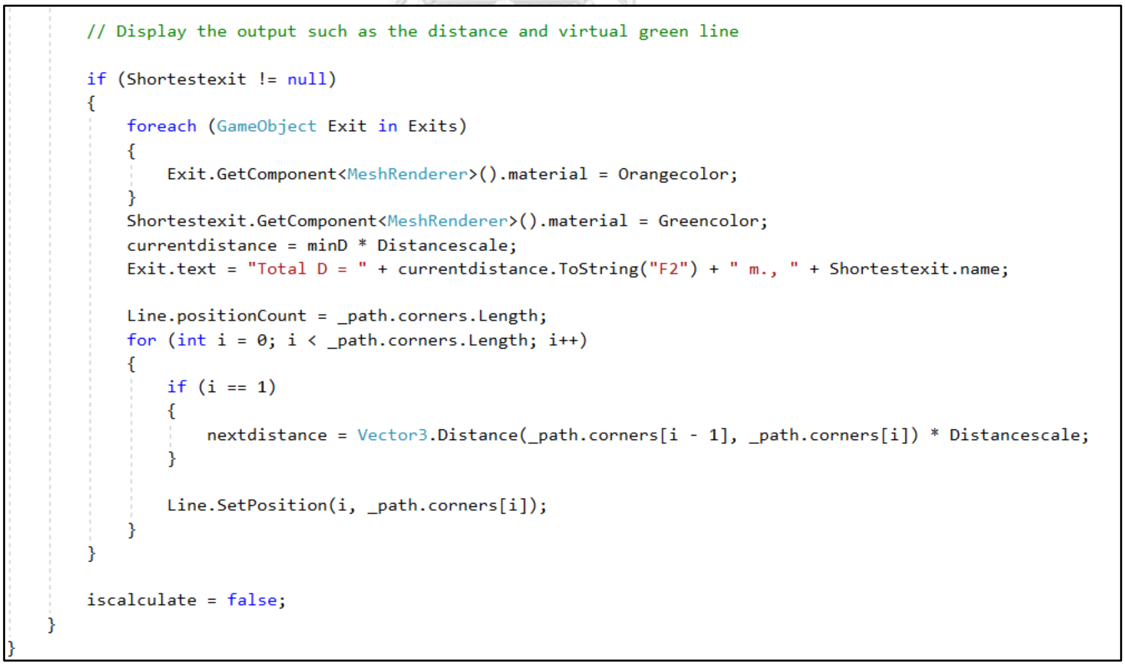


Figure 5.30. The output of the proposed system with the shortest virtual evacuation route.

The codes for rendering the shortest virtual evacuation route as a virtual green line are presented as follows.



```
        // Display the output such as the distance and virtual green line

        if (Shortestexit != null)
        {
            foreach (GameObject Exit in Exits)
            {
                Exit.GetComponent<MeshRenderer>().material = Orangecolor;
            }
            Shortestexit.GetComponent<MeshRenderer>().material = Greencolor;
            currentdistance = minD * Distancescale;
            Exit.text = "Total D = " + currentdistance.ToString("F2") + " m., " + Shortestexit.name;

            Line.positionCount = _path.corners.Length;
            for (int i = 0; i < _path.corners.Length; i++)
            {
                if (i == 1)
                {
                    nextdistance = Vector3.Distance(_path.corners[i - 1], _path.corners[i]) * Distancescale;
                }

                Line.SetPosition(i, _path.corners[i]);
            }
        }

        iscalculate = false;
    }
}
```

Figure 5.31. The codes for the shortest virtual evacuation route.

5.9.4 The voice and arrow direction algorithm

The voice and arrow direction algorithms in this study were classified into two types based on the construction project scenario. The first algorithm was developed to be applied to scenarios where an emergency situation occurred during the construction project or when there was low visibility due to haze, which obstructed vision. Therefore, having a voice to indicate the direction is one solution for assisting the construction workers and staff in such scenarios. The second algorithm was developed for implementation in a scenario where the construction project is in a dark situation, which may be caused by external factors such as smoke from a fire. Consequently, the visibility of the intersection within the construction project is unclear. Therefore, having an arrow as a picture could be used to notify them when they are close to the intersection, which could help them avoid injury.

5.9.4.1. The voice direction algorithm

In order to create the voice direction system in the construction project, the proposed system must be able to indicate the direction, such as “turn right,” “turn left,” and “go straight” to the construction workers and staff when there is low visibility due to haze, which obstructs vision.

An algorithm for voice direction was developed, and a flowchart of this algorithm is described in Figure 5.32. The process begins with a captured image containing a marker, which serves as the starting point. Next, the proposed system detects the markers and calculates the shortest fire evacuation route from the current location to the exit. When the proposed system calculates and displays the shortest evacuation route, the voice direction algorithm simultaneously checks for the same route. If an intersection is encountered along the way, the proposed system will provide a notice 3 seconds before reaching that area, ensuring that individuals are aware and prepared before reaching the intersection. Finally, the proposed system displays the output through the voice direction on their mobile phones.

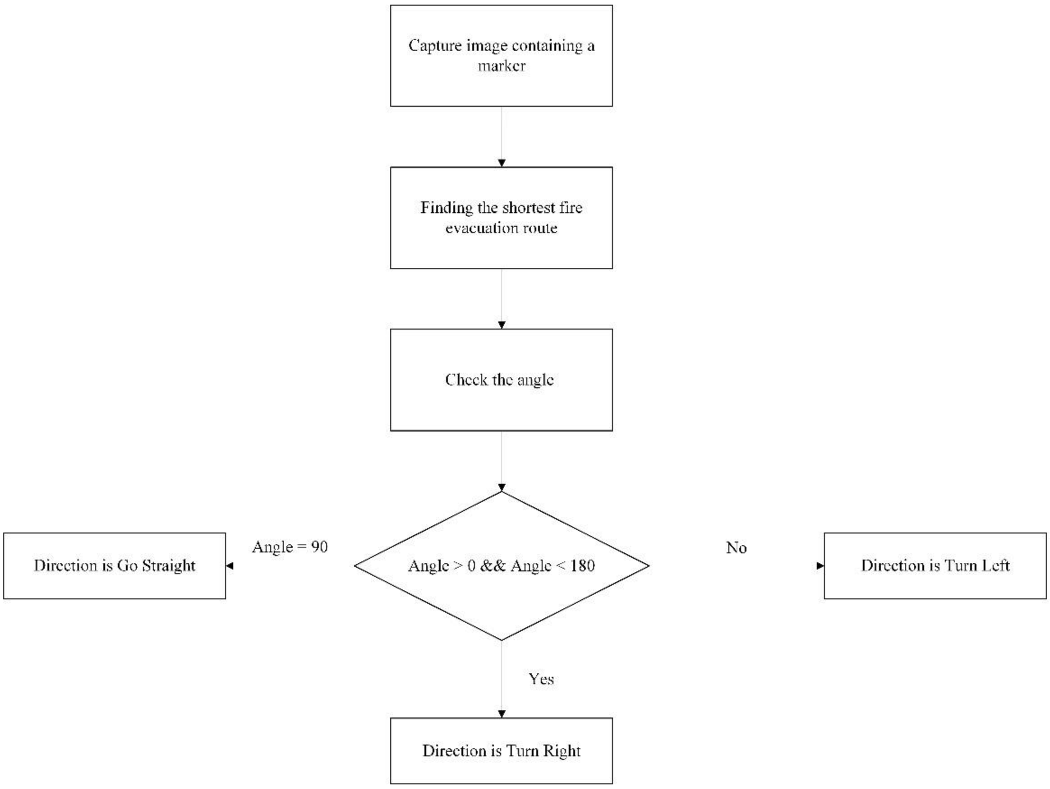
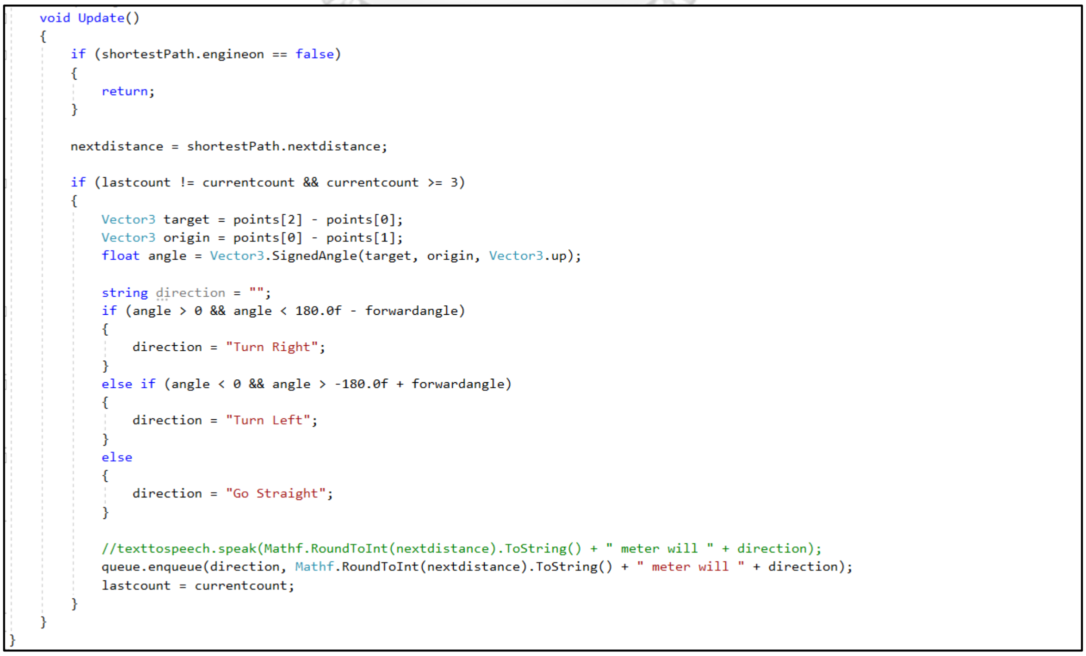


Figure 5.32. Flowchart of the voice direction algorithm.

The code for voice direction is presented as follows.



```
    void Update()
    {
        if (shortestPath.engineon == false)
        {
            return;
        }

        nextdistance = shortestPath.nextdistance;

        if (lastcount != currentcount && currentcount >= 3)
        {
            Vector3 target = points[2] - points[0];
            Vector3 origin = points[0] - points[1];
            float angle = Vector3.SignedAngle(target, origin, Vector3.up);

            string direction = "";
            if (angle > 0 && angle < 180.0f - forwardangle)
            {
                direction = "Turn Right";
            }
            else if (angle < 0 && angle > -180.0f + forwardangle)
            {
                direction = "Turn Left";
            }
            else
            {
                direction = "Go Straight";
            }

            //texttospeech.speak(Mathf.RoundToInt(nextdistance).ToString() + " meter will " + direction);
            queue.enqueue(direction, Mathf.RoundToInt(nextdistance).ToString() + " meter will " + direction);
            lastcount = currentcount;
        }
    }
}
```

Figure 5.33. The code for voice direction algorithm.

5.9.4.2. The arrow direction algorithm

The second algorithm was developed for implementation in a scenario where the construction project is in a dark situation, possibly caused by external factors like smoke from a fire. As a result, the visibility of intersections within the construction project is unclear. Therefore, using arrow directions as pictures, such as "turn left" and "turn right," could be used to notify individuals when they are close to an intersection. The proposed system will display the output as arrow directions on the screen, which can help protect construction workers and staff from injuries.

An algorithm for voice direction was developed, and a flowchart of this algorithm is described in Figure 5.34. The process begins with a captured image containing a marker, which serves as the starting point. Next, the proposed system detects the markers and calculates the shortest evacuation route from the current location to the exit. Once the proposed system calculates and displays the shortest evacuation route, the arrow direction algorithm concurrently checks for the same route. If an intersection is encountered along the way, the proposed system will provide a notice 3 seconds before reaching that area, ensuring that individuals are aware and prepared before reaching the intersection. Finally, the proposed system displays the output through arrow direction images on their mobile phones, as shown in Figure 5.35.

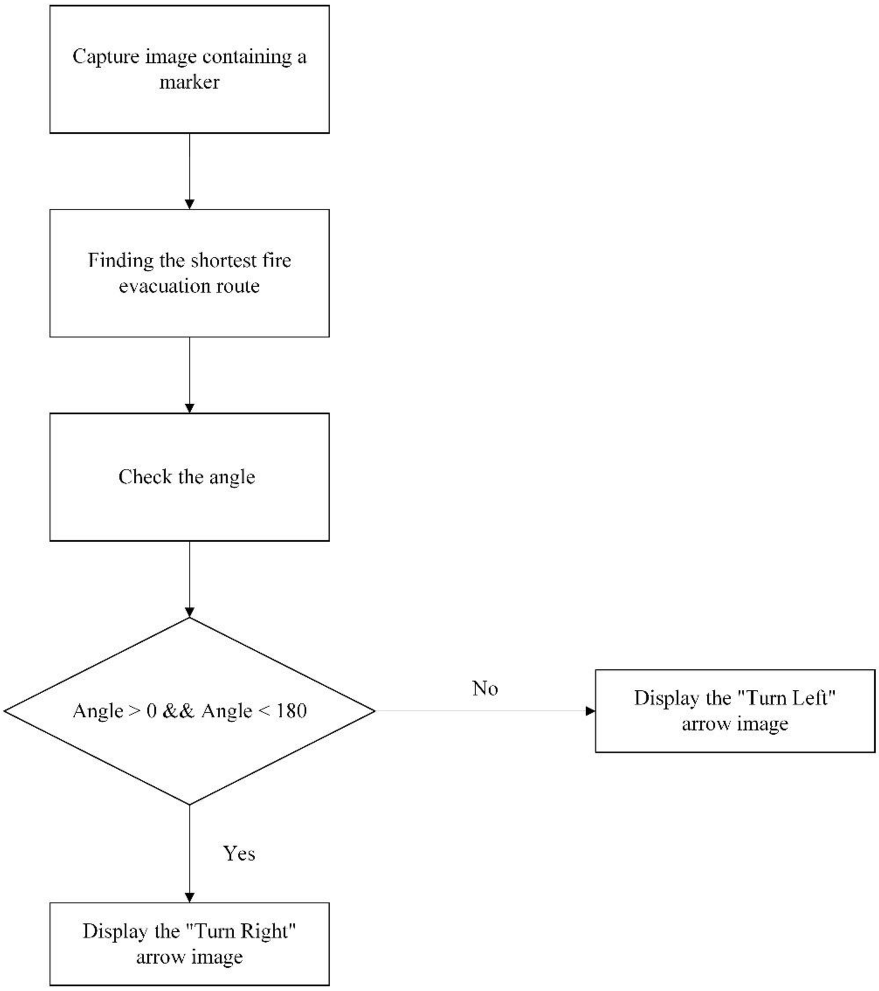


Figure 5.34. Flowchart of the arrow direction algorithm.

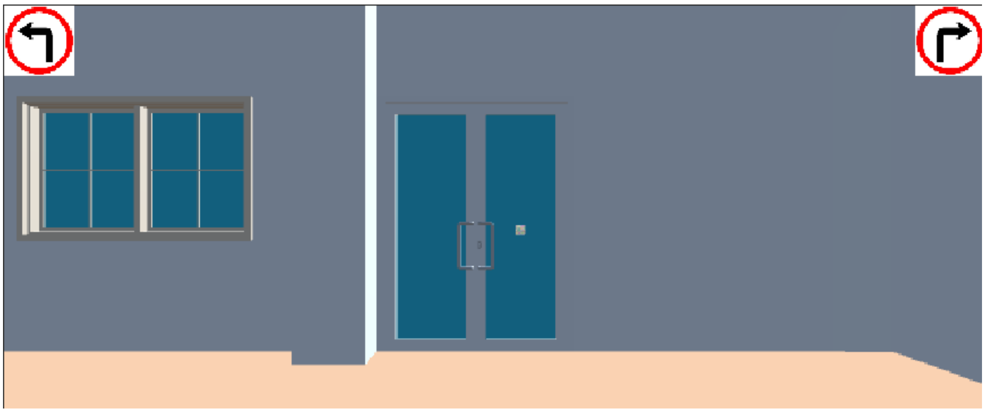
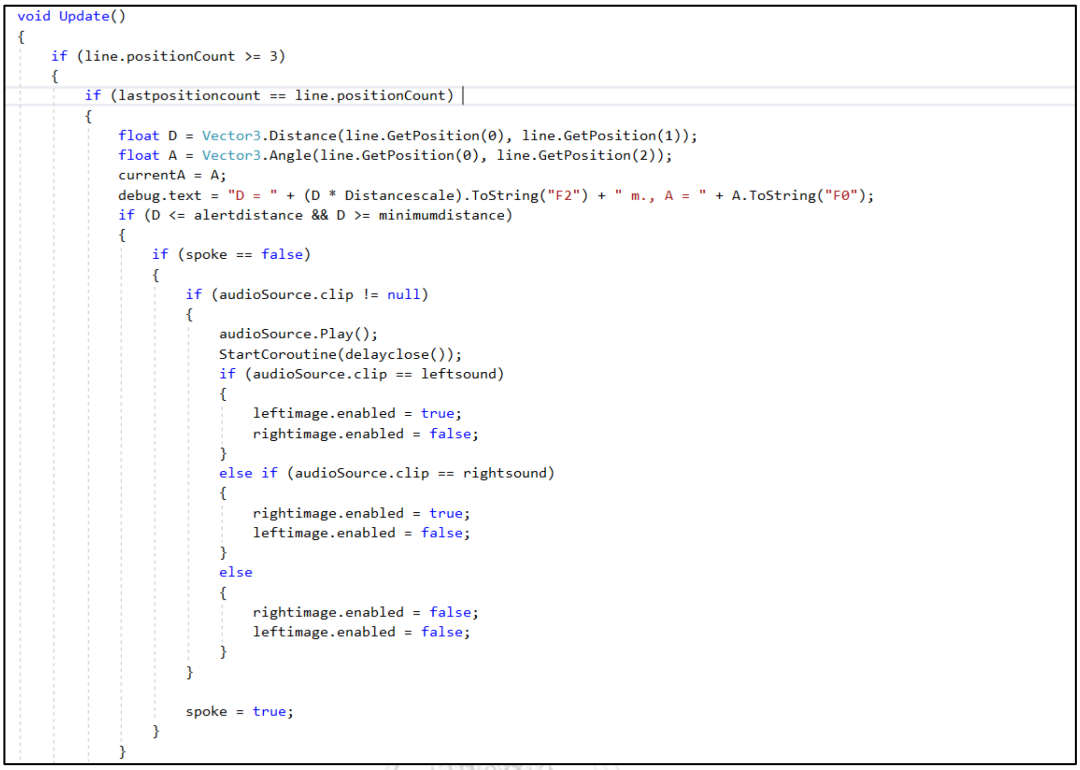


Figure 5.35. The output of the proposed system with the arrow direction image.

The code for the arrow direction is presented as follows.



```
void Update()
{
    if (line.positionCount >= 3)
    {
        if (lastpositioncount == line.positionCount) |
        {
            float D = Vector3.Distance(line.GetPosition(0), line.GetPosition(1));
            float A = Vector3.Angle(line.GetPosition(0), line.GetPosition(2));
            currentA = A;
            debug.text = "D = " + (D * Distancescale).ToString("F2") + " m., A = " + A.ToString("F0");
            if (D <= alertdistance && D >= minimumdistance)
            {
                if (spoke == false)
                {
                    if (audioSource.clip != null)
                    {
                        audioSource.Play();
                        StartCoroutine(delayclose());
                        if (audioSource.clip == leftsound)
                        {
                            leftimage.enabled = true;
                            rightimage.enabled = false;
                        }
                        else if (audioSource.clip == rightsound)
                        {
                            rightimage.enabled = true;
                            leftimage.enabled = false;
                        }
                        else
                        {
                            rightimage.enabled = false;
                            leftimage.enabled = false;
                        }
                    }

                    spoke = true;
                }
            }
```

Figure 5.36. The code for the arrow direction algorithm.

5.9.5 The real-time obstacle avoidance algorithm

The real-time obstacle avoidance algorithm in this study was classified into two types based on the construction site environment. The first algorithm was developed for applications to synchronize data on real-time spreadsheets. The second algorithm was developed to create, edit, and collaborate on real-time Google Spreadsheets, a web-based spreadsheet program developed by Google. It utilized internet access to identify and update the position of materials and temporary works in the construction project. C# is the primary programming language used for scripting in this study. Therefore, this algorithm can be applied to identify and update the position of materials and temporary works, which may pose obstacles for construction workers and staff. The real-time obstacle avoidance algorithm will be thoroughly described in the next section.

5.9.5.1. The real-time obstacle avoidance algorithm to synchronize data on the Google spreadsheets

To create the real-time obstacle avoidance algorithm and synchronize data on Google Spreadsheets, the concept of this algorithm is based on the understanding that the construction project environment is constantly evolving. As a result, evacuation routes within the construction project also change. Therefore, the proposed development system introduces an online update capability to keep the evacuation routes up-to-date and display information in accordance with the changing construction project environment.

An algorithm was developed to synchronize data on Google spreadsheets, and the flowchart of this algorithm is described in Figure 5.37. The process begins with input data, specifically, the XYZ coordinates of the obstacles observed daily during the construction project. The authors then establish the obstacles' positions in the virtual model, obtain the XYZ coordinates for each position based on the evolving construction project environment, and input the data into Google spreadsheets to update the changing construction project environment, such as the obstacle position, work activities, work process, etc.

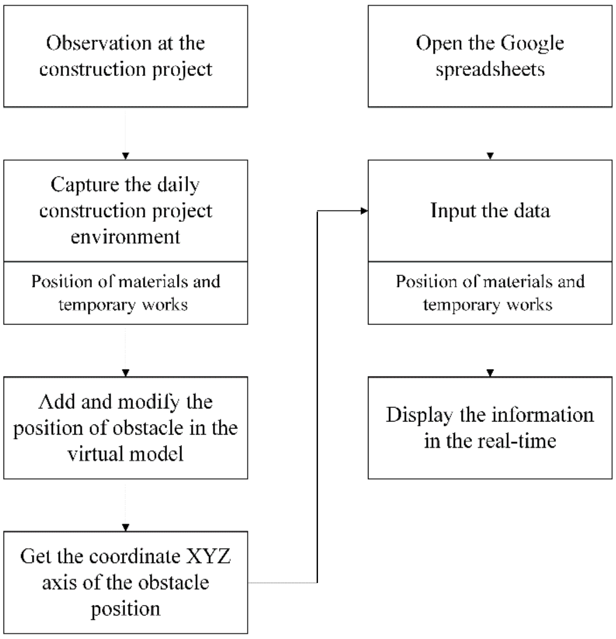
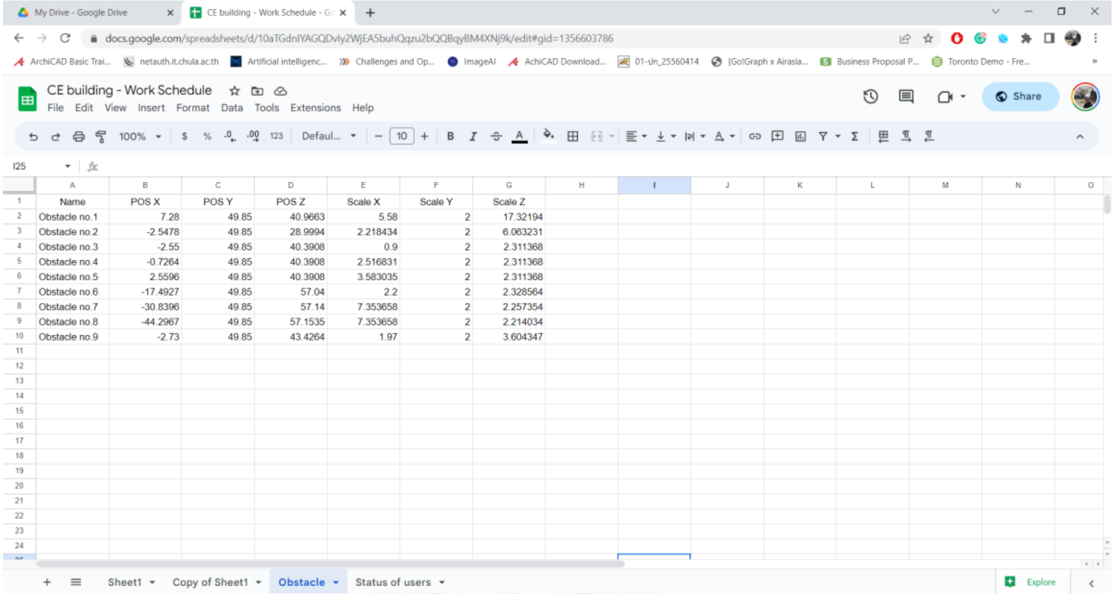


Figure 5.37. Flowchart of the algorithm to synchronize data on Google spreadsheets.



Name	POS X	POS Y	POS Z	Scale X	Scale Y	Scale Z
Obstacle no.1	7.28	49.85	40.9663	5.58	2	17.32194
Obstacle no.2	-2.5478	49.85	28.9994	2.218434	2	6.063231
Obstacle no.3	-2.55	49.85	40.3908	0.9	2	2.311368
Obstacle no.4	-0.7264	49.85	40.3908	2.516831	2	2.311368
Obstacle no.5	2.5596	49.85	40.3908	3.583035	2	2.311368
Obstacle no.6	-17.4927	49.85	57.04	2.2	2	2.328564
Obstacle no.7	-30.8396	49.85	57.14	7.353658	2	2.257354
Obstacle no.8	-44.2967	49.85	57.1535	7.353658	2	2.214034
Obstacle no.9	-2.73	49.85	43.4264	1.97	2	3.604347

Figure 5.38. Example of the Google spreadsheet.

The code for synchronizing data on the Google spreadsheets is presented as follows.

```
public class Plancontroller : MonoBehaviour
{
    public string googlesheeturl;
    public Googlesheetdata data;
    public Appdata appdata;
    public Directioncontroller dc;


    // Start is called before the first frame update
    void Start()
    {
        GameObject appdatago = GameObject.Find("Appdata");
        if (appdatago != null)
        {
            appdata = appdatago.GetComponent<Appdata>();

            StartCoroutine(getgooglesheet());
        }
    }

    IEnumerator getgooglesheet()
    {
        UnityWebRequest request = UnityWebRequest.Get(googlesheeturl);
        yield return request.SendWebRequest();

        data = JsonConvert.DeserializeObject<Googlesheetdata>(request.downloadHandler.text);

        setmodelfromplan();
    }
```

Figure 5.39. The code for synchronizing data on the Google spreadsheets algorithm.

5.9.5.2. The real-time obstacle avoidance algorithm

Construction site environments involve many temporary works and constantly changing workplaces. As a result, the number of occupants, spaces, and evacuation routes can vary daily (Marzouk and Daour, 2018). Additionally, obstructed hallways from materials and equipment can make it challenging to identify evacuation routes. Therefore, it is essential to design an evacuation route application that can avoid obstacles in real-time.

The proposed architecture for the real-time obstacle avoidance system is an integrated framework that stores location data in the 3-D model and avoids obstacles in the building. Building Information Modeling (BIM) is an effective visualization tool that helps allocate evacuation areas in the building, and Google Spreadsheet is a web-based spreadsheet program developed by Google. It allows users to create, edit, and collaborate on spreadsheets in real-time, which use internet access to identify and update the position of materials and temporary works in the 3-D model, as shown in Figure 5.42. C# is the primary programming language used for scripting in this study.

The real-time obstacle avoidance system using the A* algorithm effectively plans collision-free paths in complex environments. It is widely used in robotics and autonomous systems for navigation and the range of information provided by Google Sheets. The system must sense the environment and detect obstacles to plan a collision-free path. The detected obstacles are then marked in the graph as nodes or edges that cannot be traversed. The A* algorithm is then applied to find the shortest path from the starting node to the goal while avoiding obstacles.

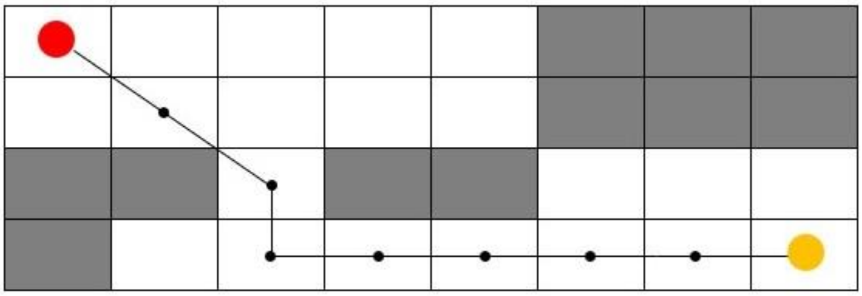


Figure 5.40. The concept of obstacle avoidance system using A* algorithm.

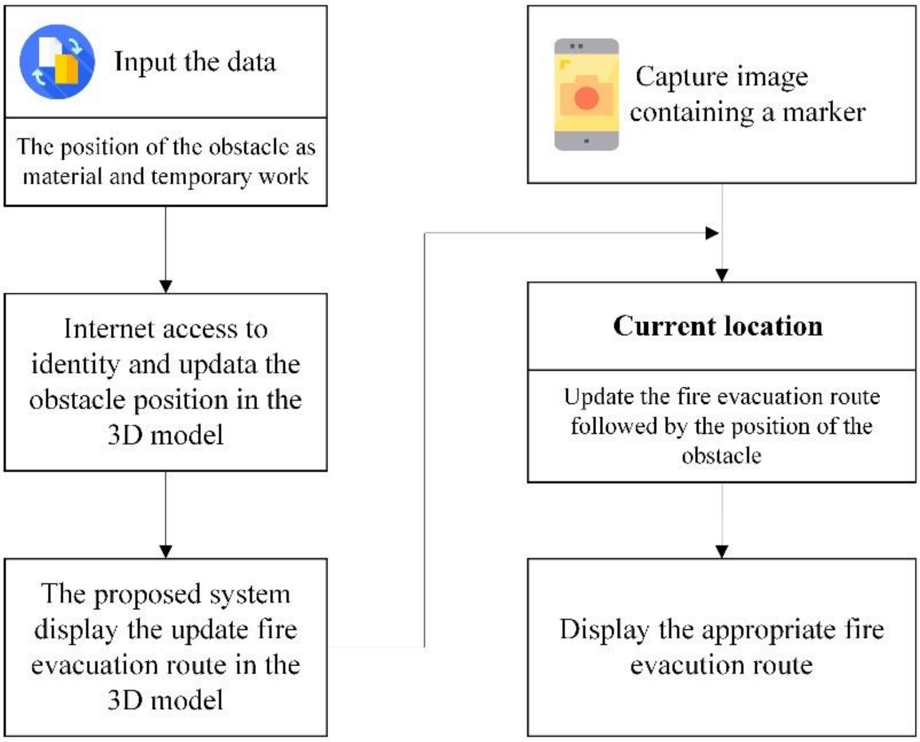


Figure 5.41. The framework of the real-time obstacle avoidance system.

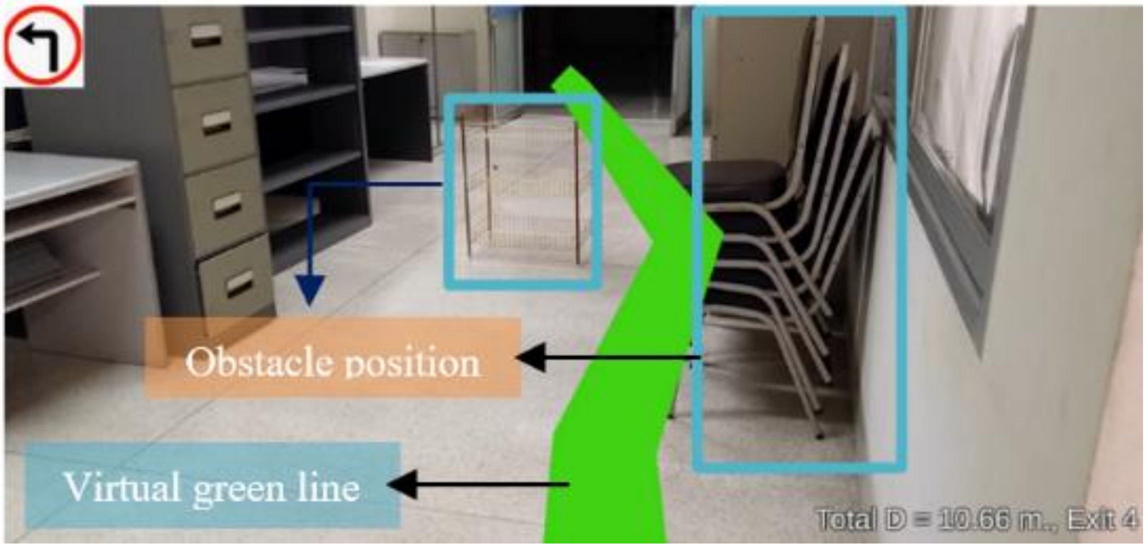
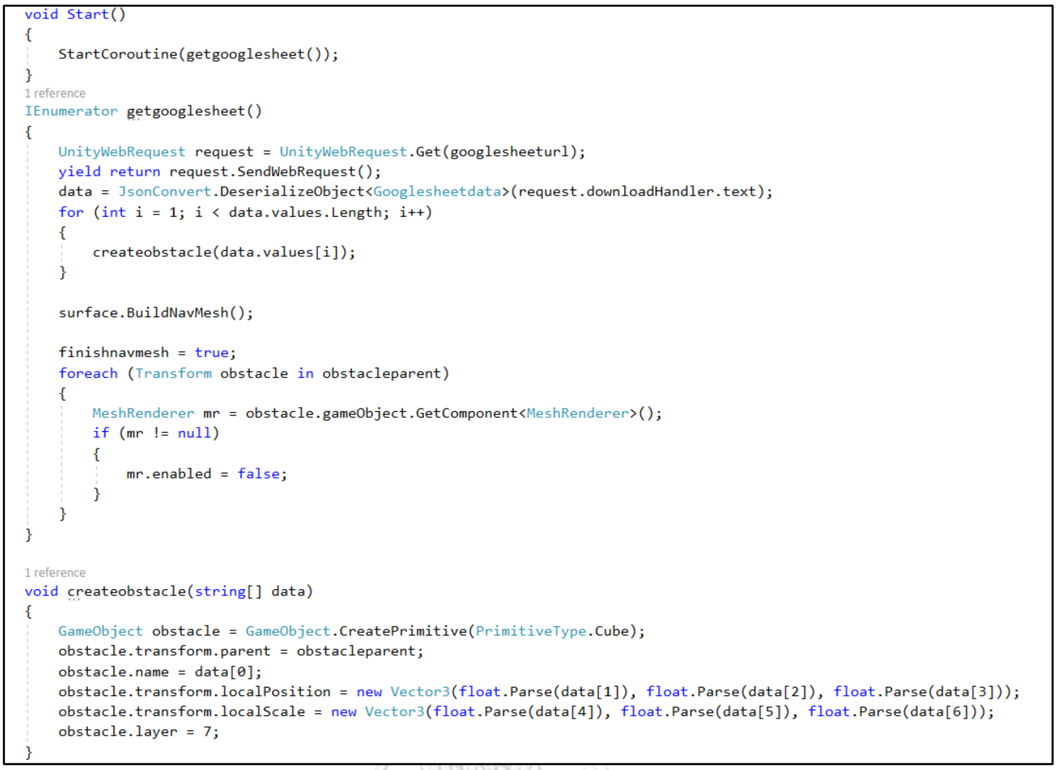


Figure 5.42. The output of the real-time obstacle avoidance system.

The code for the real-time obstacle avoidance system is presented as follows.



```
void Start()
{
    StartCoroutine(getgooglesheet());
}
1 reference
IEnumerator getgooglesheet()
{
    UnityWebRequest request = UnityWebRequest.Get(googlesheeturl);
    yield return request.SendWebRequest();
    data = JsonConvert.DeserializeObject<Googlesheetdata>(request.downloadHandler.text);
    for (int i = 1; i < data.values.Length; i++)
    {
        createobstacle(data.values[i]);
    }

    surface.BuildNavMesh();

    finishnavmesh = true;
    foreach (Transform obstacle in obstacleparent)
    {
        MeshRenderer mr = obstacle.gameObject.GetComponent<MeshRenderer>();
        if (mr != null)
        {
            mr.enabled = false;
        }
    }
}

1 reference
void createobstacle(string[] data)
{
    GameObject obstacle = GameObject.CreatePrimitive(PrimitiveType.Cube);
    obstacle.transform.parent = obstacleparent;
    obstacle.name = data[0];
    obstacle.transform.localPosition = new Vector3(float.Parse(data[1]), float.Parse(data[2]), float.Parse(data[3]));
    obstacle.transform.localScale = new Vector3(float.Parse(data[4]), float.Parse(data[5]), float.Parse(data[6]));
    obstacle.layer = 7;
}
```

Figure 5.43. The code for the real-time obstacle avoidance system.

5.9.6 The material handling route algorithm

The material handling route algorithm in this study was classified into two types based on the construction project's dynamic nature and work schedule. The first algorithm was developed for applications to synchronize the work schedule data on real-time spreadsheets. The second algorithm was developed to create, edit, and collaborate on real-time Google Spreadsheets, a web-based spreadsheet program developed by Google. It utilized internet access to identify and update the position of working areas and material storage in the construction project. C# is the primary programming language used for scripting in this study. Therefore, this algorithm can be applied to identify and update the working areas and the route to the material storage directly to the construction workers and staff. The material handling route algorithm will be thoroughly described in the next section.

5.9.6.1. The real-time material handling route algorithm to synchronize work schedule data on the Google spreadsheets

To create the material handling route algorithm and synchronize data on Google Spreadsheets, the concept of this algorithm is based on the work schedule, which is the daily finish date of each construction activity. As a result, routes of the material handling and working area within the construction project also change. Therefore, the proposed development system introduces an online update capability to keep the material handling and working area routes up-to-date and display information following the changing construction project environment.

An algorithm was developed to synchronize the work schedule data on Google spreadsheets, and the flowchart of this algorithm is described in Figure 5.44. The process begins with input data, the floor level, work details, and finish date observed daily during the construction project. The authors then establish the details as the name of each element in the construction activity, which is the working area in the virtual model, and input the data into Google spreadsheets to update the changing construction project environment, such as the working area following the work schedule.

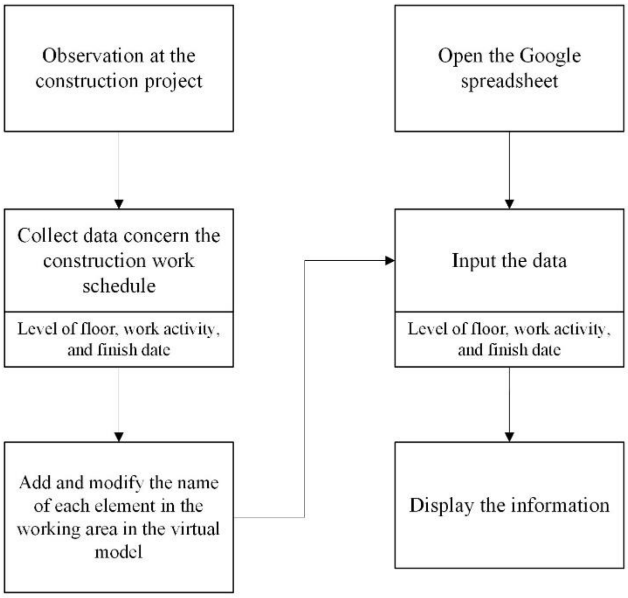
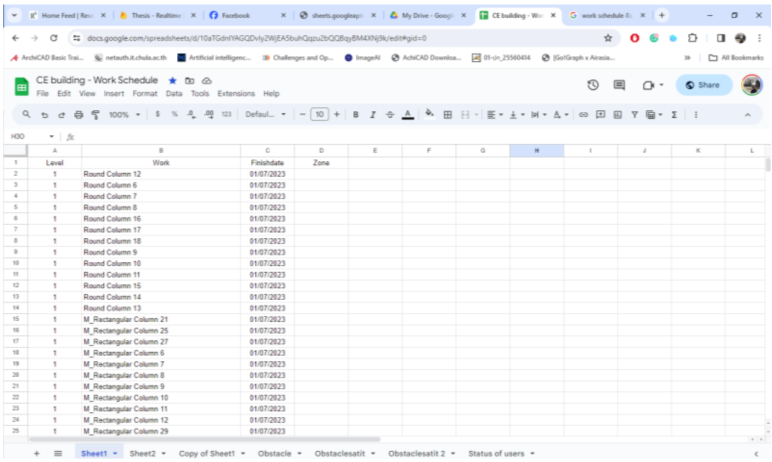


Figure 5.44. Flowchart of the algorithm to synchronize work schedule data on Google spreadsheets.

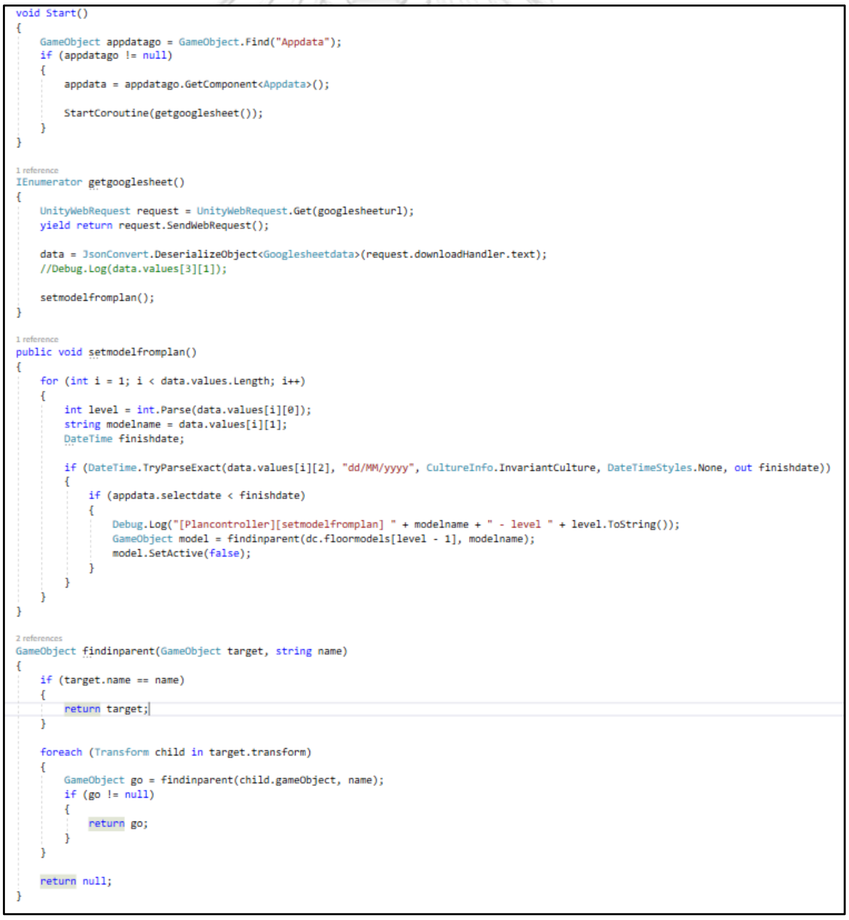


CE building - Work Schedule

	A	B	C	D
1	Level	Work	Finishdate	Zone
2	1	Round Column 12	01/07/2023	
3	1	Round Column 6	01/07/2023	
4	1	Round Column 7	01/07/2023	
5	1	Round Column 8	01/07/2023	
6	1	Round Column 16	01/07/2023	
7	1	Round Column 17	01/07/2023	
8	1	Round Column 18	01/07/2023	
9	1	Round Column 9	01/07/2023	
10	1	Round Column 10	01/07/2023	
11	1	Round Column 11	01/07/2023	
12	1	Round Column 15	01/07/2023	
13	1	Round Column 14	01/07/2023	
14	1	Round Column 13	01/07/2023	
15	1	M_Rectangular Column 21	01/07/2023	
16	1	M_Rectangular Column 25	01/07/2023	
17	1	M_Rectangular Column 27	01/07/2023	
18	1	M_Rectangular Column 6	01/07/2023	
19	1	M_Rectangular Column 7	01/07/2023	
20	1	M_Rectangular Column 8	01/07/2023	
21	1	M_Rectangular Column 9	01/07/2023	
22	1	M_Rectangular Column 10	01/07/2023	
23	1	M_Rectangular Column 11	01/07/2023	
24	1	M_Rectangular Column 12	01/07/2023	
25	1	M_Rectangular Column 29	01/07/2023	

Figure 5.45. Example of the work schedule on the Google spreadsheet.

The code for synchronizing the work schedule data on the Google spreadsheets is presented as follows.



```
void Start()
{
    GameObject appdatago = GameObject.Find("Appdata");
    if (appdatago != null)
    {
        appdata = appdatago.GetComponent<Appdata>();

        StartCoroutine(getgooglesheet());
    }
}

1 reference
IEnumerator getgooglesheet()
{
    UnityWebRequest request = UnityWebRequest.Get(googlesheeturl);
    yield return request.SendWebRequest();

    data = JsonConvert.DeserializeObject<Googlesheetdata>(request.downloadHandler.text);
    //Debug.Log(data.values[3][1]);

    setmodelfromplan();
}

1 reference
public void setmodelfromplan()
{
    for (int i = 1; i < data.values.Length; i++)
    {
        int level = int.Parse(data.values[i][0]);
        string modelname = data.values[i][1];
        DateTime finishdate;

        if (DateTime.TryParseExact(data.values[i][2], "dd/MM/yyyy", CultureInfo.InvariantCulture, DateTimeStyles.None, out finishdate))
        {
            if (appdata.selectdate < finishdate)
            {
                Debug.Log("[Plancontroller][setmodelfromplan] " + modelname + " - level " + level.ToString());
                GameObject model = findinparent(dc.floormodels[level - 1], modelname);
                model.SetActive(false);
            }
        }
    }
}

2 references
GameObject findinparent(GameObject target, string name)
{
    if (target.name == name)
    {
        return target;
    }

    foreach (Transform child in target.transform)
    {
        GameObject go = findinparent(child.gameObject, name);
        if (go != null)
        {
            return go;
        }
    }

    return null;
}
```

Figure 5.46. The code for synchronizing work schedules on the Google spreadsheet algorithm.

5.9.6.2. The route of material handling algorithm

Construction site environments involve many temporary works and constantly changing workplaces; as a result, the number of occupants, spaces, and evacuation routes can vary daily. Material handling is one of the construction activities that requires familiarity with and experience of construction workers and staff with the route and information of the storage location. Thus, if construction workers and staff are unfamiliar with the route, they will risk losing and not getting updated information on evacuation routes, leading to work delays, injuries, or fatalities. Therefore, it is essential to design an evacuation route application that can avoid obstacles in real-time.

The proposed architecture for the route of material handling is an integrated framework that stores location data in the 3-D model and the working area in the building. Building Information Modeling (BIM) is an effective visualization tool that helps allocate evacuation areas in the building, and Google Spreadsheet is a web-based spreadsheet program developed by Google. It allows users to create, edit, and collaborate on spreadsheets in real-time, which use internet access to identify and update the details of each work, followed by the work schedule in the 3-D model. C# is the primary programming language used for scripting in this study.

The route of material handling using the A* algorithm is an effective approach for planning collision-free paths in complex environments. It is widely used in robotics and autonomous systems for navigation and the range of information provided by Google Sheets. The system must sense the environment and detect the construction element, which is construction activities daily, to plan a collision-free path. The detected construction elements are then marked in the graph as nodes or edges that cannot be traversed. The A* algorithm is then applied to find the shortest path from the starting node to the goal while avoiding the route of the unworking area.

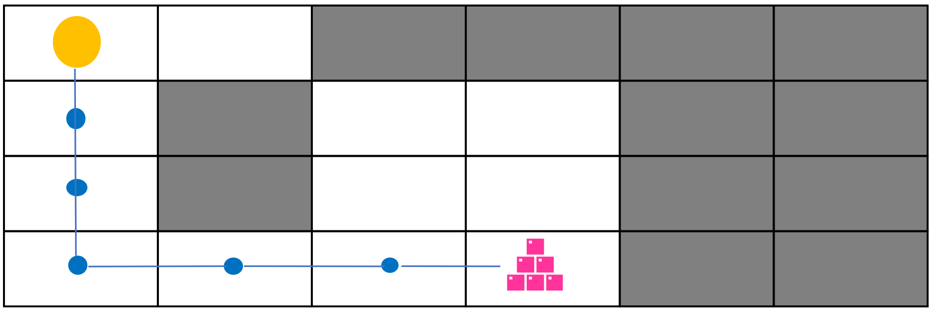


Figure 5.47. The concept of route of material handling using A* algorithm.

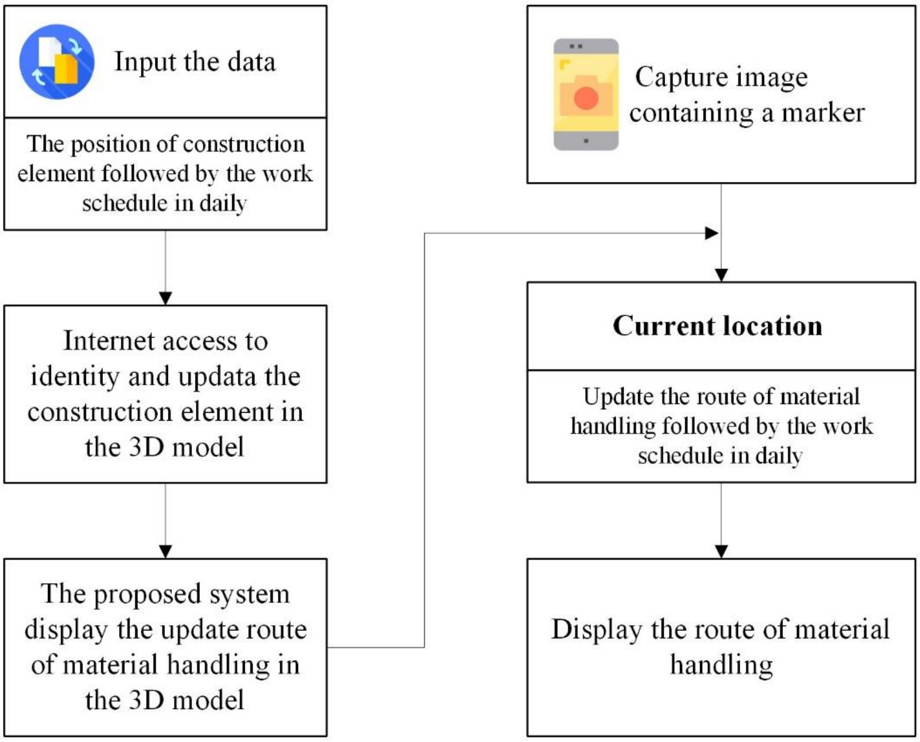
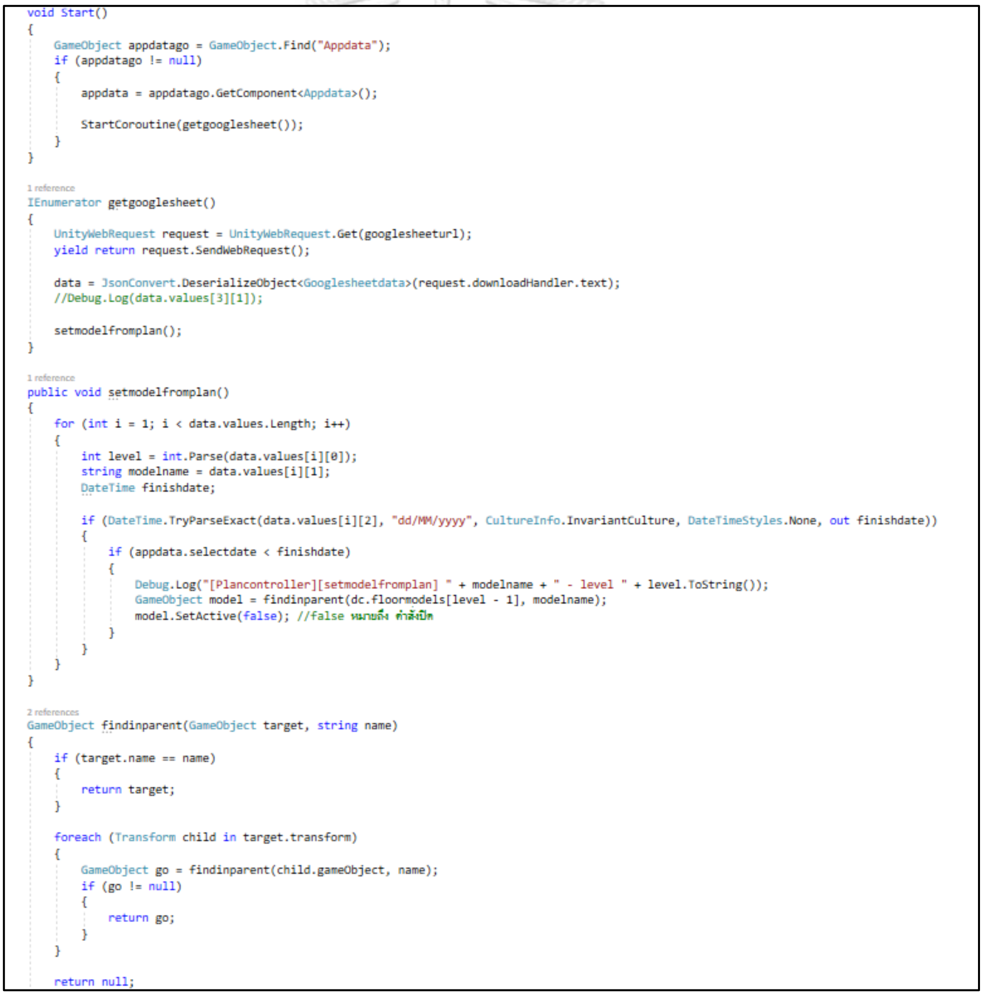


Figure 5.48. The framework of the route of material handling.

Figure 5.49. The output of route of material handling algorithm.

The code for the route of material handling is presented as follows.



```
void Start()
{
    GameObject appdatago = GameObject.Find("Appdata");
    if (appdatago != null)
    {
        appdata = appdatago.GetComponent<Appdata>();

        StartCoroutine(getgooglesheet());
    }
}

1 reference
IEnumerator getgooglesheet()
{
    UnityWebRequest request = UnityWebRequest.Get(googlesheeturl);
    yield return request.SendWebRequest();

    data = JsonConvert.DeserializeObject<Googlesheetdata>(request.downloadHandler.text);
    //Debug.Log(data.values[3][1]);

    setmodelfromplan();
}

1 reference
public void setmodelfromplan()
{
    for (int i = 1; i < data.values.Length; i++)
    {
        int level = int.Parse(data.values[i][0]);
        string modelname = data.values[i][1];
        DateTime finishdate;

        if (DateTime.TryParseExact(data.values[i][2], "dd/MM/yyyy", CultureInfo.InvariantCulture, DateTimeStyles.None, out finishdate))
        {
            if (appdata.selectdate < finishdate)
            {
                Debug.Log("[Plancontroller][setmodelfromplan] " + modelname + " - level " + level.ToString());
                GameObject model = findinparent(dc.floormodels[level - 1], modelname);
                model.SetActive(false); //false หมายถึง คำสั่งปิด
            }
        }
    }
}

2 references
GameObject findinparent(GameObject target, string name)
{
    if (target.name == name)
    {
        return target;
    }

    foreach (Transform child in target.transform)
    {
        GameObject go = findinparent(child.gameObject, name);
        if (go != null)
        {
            return go;
        }
    }

    return null;
```

Figure 5.50. The code for providing the route of material handling followed the work schedule.

5.10 Conclusion

In this chapter, an innovative system was designed to support evacuation routes in a dynamic nature in the construction project. The proposed system was developed to improve decision-making and provide information for evacuating and guidelines for the material handling route to construction workers and staff from hazardous locations in construction projects. In order to develop a communication system, visualization technologies such as Building Information Modeling (BIM) and Augmented Reality (AR). The Unity game engine, the marker-based location system, and Firebase, a free, real-time database widely used in academic research, were implemented.

In addition, the proposed calculation and algorithms are based on C# scripting in combination with other related classes and APIs, which calculate the distance from the current location to the exit with a virtual green line and provide voice and arrow directions for evacuation guidance, the route for material handling, including obstacle avoidance in the construction project were also prepared and applied. The two-dimensional (2-D) drawings and the three-dimensional (3-D) model were arranged to support this system. Moreover, the shortest evacuation route calculation, the identification of users, the voice and arrow direction, the real-time obstacle avoidance, and the material handling route algorithm were proposed.

Furthermore, there were six main algorithms of the proposed system, which consisted of

1) The identification of users algorithm for each user who enters and exits the construction project and provides information according to the number of users.

2) The shortest evacuation system for presenting the shortest fire evacuation route.

3) The shortest virtual evacuation route algorithm to implement the shortest virtual evacuation route on a real-world scene, aiming to support decision-making and enable users to perceive and understand the information clearly and easily.

4) The voice algorithm is applied to scenarios where a emergency situation occurred during the construction project or when there was low visibility due to haze, which obstructed vision, and arrow direction algorithms for implementation in a scenario where the construction project is in a dark situation, which may be caused by external factors such as smoke from a fire.

5) A real-time obstacle avoidance algorithm is applied to identify and update the position of materials and temporary works, which may pose obstacles for construction workers and staff to avoid obstacles.

6) The material handling route algorithm is applied to present the working area and update the route for material handling, followed by the construction work schedule

Chapter 6

Prototype System Development

6.1 Introduction

This chapter presents the development of a prototype system based on the conceptual system design outlined in the previous chapter. The prototype system consists of four main modules to improve fire emergency procedures and provide information on evacuating, including guidelines for the material handling route to construction workers and staff from hazardous locations in construction projects. Each module has distinct content for preparation, input, process, and output. These modules generate diverse results to serve as vital visualized information for the proposed system, enhancing decision-making and delivering real-time information for evacuating and guidelines for the material handling route in the construction project. The following section describes the development of each module. Furthermore, the output results and experiments of the prototype system are presented in the last section.

6.2 Development of the prototype system

The Self Care using Technology Evacuation System (SCT Evacuation System), as shown in Figure 6.1, was developed as a marker-based Augmented Reality (AR) application and integrated visualization technologies, such as Building Information Modeling (BIM), in cooperation with the specific coding as denoted in the previous chapter. To provide real-time information for guidance to construction workers and staff to evacuate from the hazardous location, guidelines for the material handling route for construction workers and staff who are not familiar with the route in the construction project, which update with the construction work schedule, which was both graphic and non-graphic, was prepared and input into the proposed system. Then, each module performed its function, and the visualized results were presented. The output of each module was displayed by using the application.

The prototype system provides the construction workers and staff input with the current working day, their names, and surnames to identify each user who enters and exits the construction project for the initial setup, as shown in Figure 6.2, which allows the system to display the information of construction workers and staff, as shown in Figure 6.3. Due to the tasks collected from site observation, the prototype system was designed and developed for this research in three parts: BIM authoring, a marker-based location, and application authoring. The situation for the prototype system is that in the emergency in the construction project, workplaces obstructed hallways from materials and equipment constantly changing, and the number of users in the passenger lift is limited.

As mentioned above, the prototype system aims to improve fire emergency procedure and provide information for evacuating and guidelines for the material handling route for construction workers and staff unfamiliar with the route in the construction project. The user interface for the prototype system is shown in Figure 6.4.

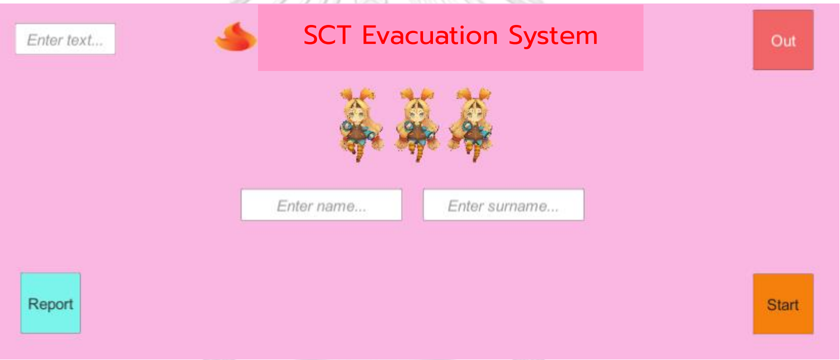
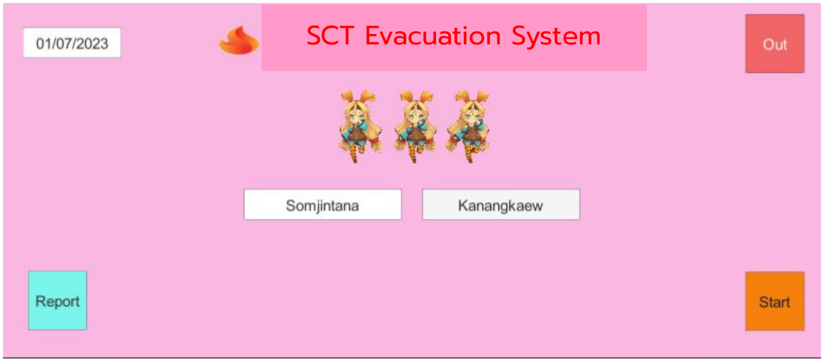


Figure 6.1 The Self Care using Technology Evacuation System
(SCT Evacuation System)



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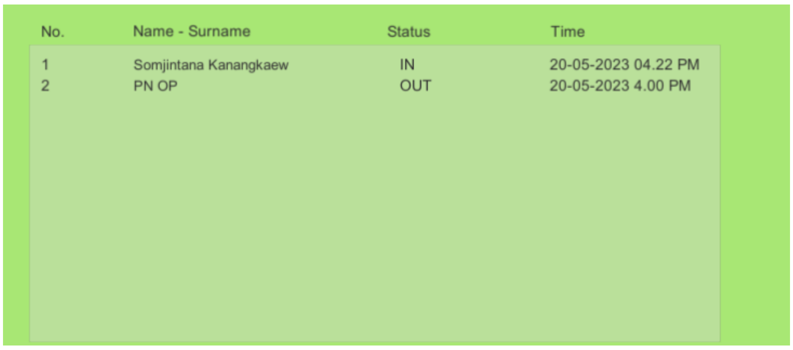
Kanangkaew

Figure 6.2 Initial setup to identify the users.



No.	Name - Surname	Status	Time
1	Somjintana Kanangkaew	IN	20-05-2023 04.22 PM
2	PN OP	OUT	20-05-2023 4.00 PM

Figure 6.3 The system output displayed the information of users.

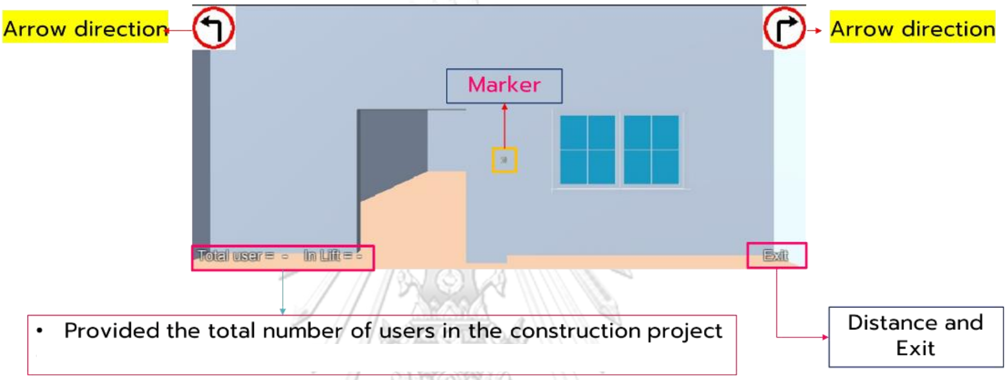


Figure 6.4 The user interface for the prototype system.

The first element was BIM authoring to design and enhance the interpretation and understanding of construction workers and staff regarding the evacuation route and to select appropriate evacuation routes in the construction project. Additionally, it aims to generate and display the user's location in the virtual environment and superimpose 2D and 3D computer graphics onto real-world scenes. Secondly, a marker-based location was developed as a spatial index to link physical location and virtual information. Lastly, application authoring provides real-time information, such as the user's current location, which calculates the distance to the exit via a virtual green line. The system also provides voice and arrow directions for evacuation and guidance on the material handling route via the virtual green line, exit, and the distance from the current location to the exit. It recommends the appropriate evacuation route in case of obstacle avoidance for construction workers and staff. The calculation and algorithm that were formerly mentioned were applied in the development process.

In the next section, the development of the three elements is thought to be described. The user interfaces of the prototype system are also demonstrated.

6.2.1 BIM authoring

A prototype system development combining Building Information Modeling (BIM) and Augmented Reality (AR) was implemented as the first demonstration of the proposed system. This element was developed to generate and display the user's location in the virtual environment and superimpose 2D and 3D computer graphics onto real-world scenes. The following four sub-elements consist of a 3D architectural model of the building generated using Autodesk Revit 2022, exported to the Autodesk Naviswork (NWD) file format and saved in the Autodesk Filmbox (FBX) file format, and linked to the FBX model and the Unity game engine.

This prototype system selected the Department of Civil Engineering Building at Chulalongkorn University as a prototype case study, a five-story building used for classrooms, offices, and meeting rooms. The total area is 5,832 square meters, and the height is 26 meters. These are classified as high-rise buildings following the definition of the Thailand Building Control Act B.E. 2535 (1992). The height of the building is over 23 meters.

<u>6.2.1.1. 3D architectural model of the building generated using Autodesk Revit 2022</u>

This sub-element was created with a Level of Detail (LOD) of 300 using Autodesk Revit 2022 based on as-built drawings. Therefore, the room and exit locations in the 3D model are the same as in the real world. A Level of Detail 300 includes columns, beams, and floors in the structural phase and windows, doors, walls, and stairs in the architecture phase, along with their size, shape, location, and geometric data such as length and area (Volk et al., 2014). The 3D model was saved in the Industry Foundation Classes (IFC) file format.

<u>6.2.1.2. Exported to the Autodesk Naviswork (NWD) file format and saved in the Autodesk Filmbox (FBX) file format</u>

This sub-element was developed and exported from the Industry Foundation Classes (IFC) file format to the Autodesk Naviswork (NWD) file format, then saved NWD file format to the Autodesk Filmbox (FBX) file format, which enables seamless data exchange. Finally, the FBX file format and associated textures were integrated into the Unity game engine (Rahimiana et al., 2019).

6.2.1.3. Linking the FBX model and the Unity game engine

The Unity game engine is a cross-platform toolkit developed by Unity Technologies for creating video games and simulations for computers, consoles, and mobile devices. This study used it as the primary platform for creating the application and integrating visualization technologies such as Building Information Modeling (BIM) and Augmented Reality (AR). In addition, this study adopted a previously developed method of linking a digital model to support integrating the information in the 3D model, including 3-D rendering, physics, and collision detection. This method was established using the FBX file format and incorporating programming with C# scripting in combination with other related classes and APIs.

6.2.2 A marker-based location

The developed marker-based location system utilizes a marker as a spatial index to connect physical locations with virtual information. The system functions as follows: Firstly, the camera captures an image with a marker on the mobile device. The image is then forwarded to the classifier algorithm, which is designed to classify data into different categories or classes and assumes a relatively balanced distribution of classes to create the marker ID by generating the code. Then, the marker code is sent to the database as a key value to look for associated information. Next, the system sets the location and direction in the virtual environment. However, the system does not display any data if the code is not recognized in the database. As the mobile device moves, the system transmits updated data concerning the location and direction to the real world in real-time. The system does not update any data if the mobile device has not moved.

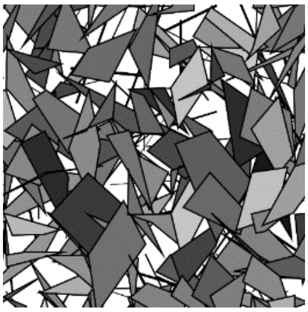


Figure 6.5 Example of the markers used in the prototype system.

6.2.3 Application authoring

The proposed system provides real-time information, such as the user's current location, which is used to calculate the distance to the exit. The system also provides voice and arrow directions for evacuation and guidance on the material handling route via the virtual green line, exit, and distance from the current location to the exit, the identification of users, recommends the appropriate evacuation route in case of obstacle avoidance in the construction project was also prepared and applied. The two-dimensional (2-D) drawings and the three-dimensional (3-D) model were arranged to support this system. Moreover, the shortest evacuation route calculation, the identification of users, the voice and arrow direction, the real-time obstacle avoidance system, and the material handling route were proposed.

The following four steps are employed in the application's performance: preparation, input, process, and output, as shown in Figure 6.6. In the first step, thirty-six markers were installed on the 4th floor as nodes, such as room and exit locations in the building as a case study, shown as orange boxes in Figure 6.7, were prepared and printed out as described. For testing in the Department of Civil Engineering building, the marker size was 20.5 cm. The distance of each node is 4.00 meters. The markers are numbered clockwise, starting from 401 at the first marker in the upper right.

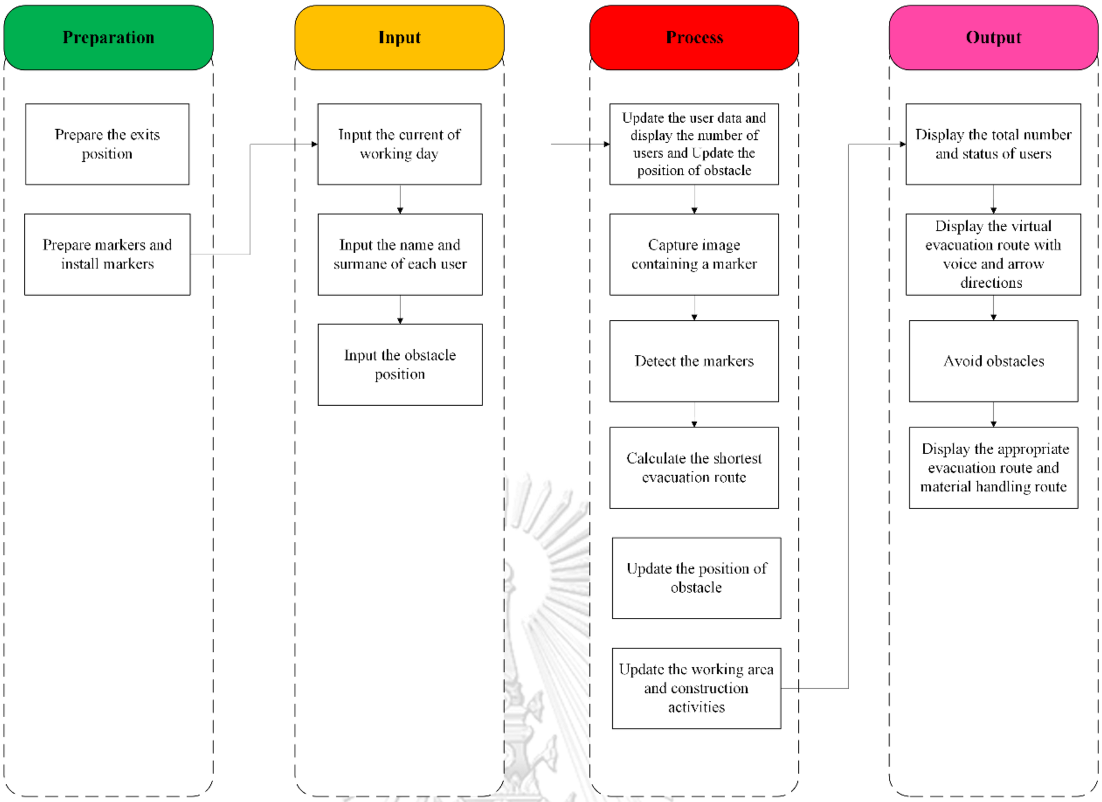


Figure 6.6 Flowchart of application of the prototype system.

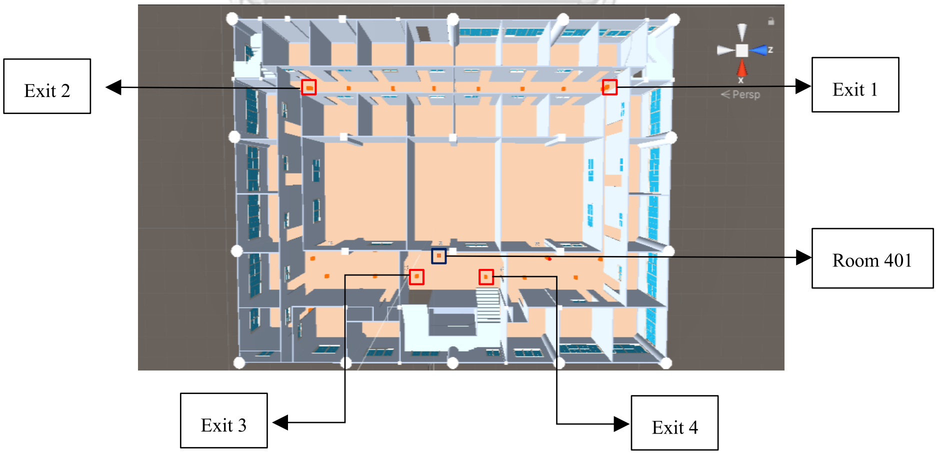


Figure 6.7 Markers preparation and installation in case study 1.

Then, the system requires the user to input data, including the current working day, their names, and surnames, to identify the working day of each user who enters and exits the construction project for the initial setup, as shown in Figure 6.8. After inputting the required data, the system was processed according to the identification of the users algorithm and the material handling route algorithm, beginning with a captured image containing a marker, which serves as the starting point. The marker carries its coordinate data in an XYZ axis, and it is utilized to measure the distance to the exit and provide the working area in the construction project. Next, it calculated the distance from the current location to the exit and route for material handling with a virtual green line. It provided voice and arrow directions for evacuation and route for material handling guidance. If the user moves away from the exit or does not follow the route guidance, the system will recalculate the distance from the current location and display real-time information to the user on their next interaction.

Moreover, this application applies the obstacle avoidance algorithm for detected obstacles that are then marked in the graph as nodes or edges that cannot be traversed. The result of obstacle avoidance would be identifying and detecting obstacles from a Google Sheet in real-time, which uses internet access to identify and update the position of obstacles. When an obstacle appears in a building, the proposed system could avoid obstacles and immediately recommend an appropriate evacuation route to the user, as shown in Figure 6.9.

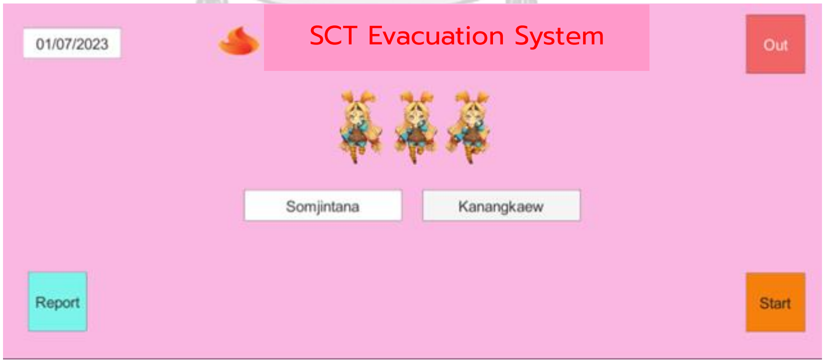


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Figure 6.8 Example of inputting the data into the system.

(a) (b)

Figure 6.9 Example results of the obstacle avoidance system.

6.3 Testing the prototype system

The developed prototype applications in the proposed system were tested to check for the outputs, and then the system's verification and validation were done and described in the next chapter. The testing for the outputs of each function was done in both the virtual and the real environment. Factors like internet signal, 3D model size, and lighting were specified differently. Therefore, the testing setup is explained in this section.

6.3.1 Virtual environment testing

Before this proposed system was implemented in the real environment, it was tested in the virtual environment to check the preliminary outputs. Moreover, some outputs of the prototype application could be verified for accuracy in the virtual environment. Many markers were created, prepared, and installed in the model in the virtual environment. The patterns of the generated markers are optimized for use as image targets. Each marker is randomly generated and unique. The material composition of a marker consists of colored padding surrounded by a thick colored border and a high-contrast pattern of either a template line, triangles, or quadrilaterals, with the marker size being 20.5 cm.

Markers are also defined in the 3D model in the virtual and real environments to identify the location of rooms and exits in case study 1. Meanwhile, The system works based on seamless connectivity between various sources of real-time location data, an existing BIM model, and a virtual environment. Therefore, an effective connection must be established to allow a seamless flow of the user's location to the virtual environment in the building.

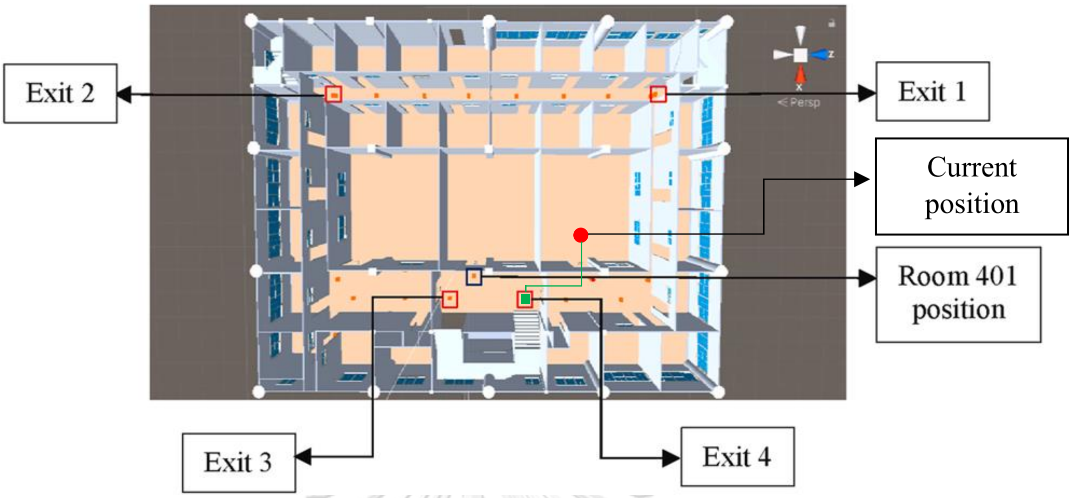


Figure 6.10 Example of output from the virtual environment testing.

The limitation of the prototype system consists of lighting, which affects the tracking markers process, and the internet signal is weak and there is no internet signal; as a result, the proposed system could not display the information in real-time. In addition, one limitation is that the proposed system can only provide real-time information if the user captures an image containing a marker on the mobile device. This means that if the user is not near a marker location, they will not receive real-time information from the system.

The testing results were presented as an example of output windows demonstrated in the previous section. All prototype applications could satisfactorily perform and generate the output results in response to the application development purposes.

6.3.2 Real environment testing

After testing the system in the virtual environment, a real environment was also required to investigate the implementation of the system at the real construction site. The proposed system should provide the output as real-time access to information with the user's augmented views via mobile phones. The prototype system provides real-time information, such as the user's current location, which is used to calculate the distance to the exit via a virtual green line. The system also provides voice and arrow directions for evacuation and route for material handling guidance, virtual green line, exit, and distance from the current location to the exit and recommends the appropriate evacuation route in case of obstacle avoidance.

The proposed system requires the user to input the data, such as the current date, name, and surname, as shown in Figure 6.11 and Figure 6.12. After inputting the required data, the system was updated and displayed the number of users in real-time.

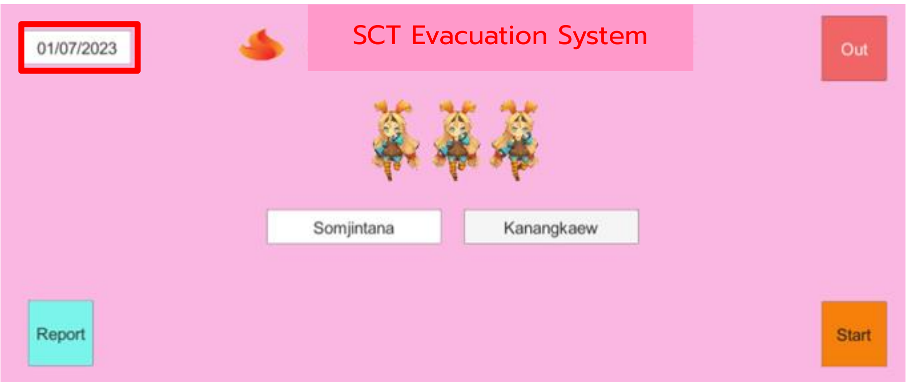
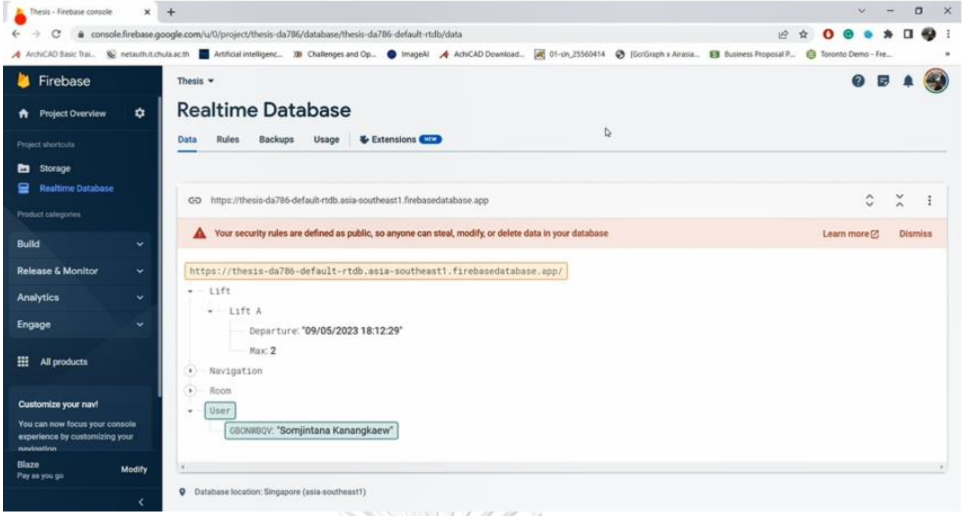


Figure 6.11 The user inputs the current date in the proposed system.

Figure 6.12 The user inputs the data as name and surname in the proposed system.



https://thesis-da786-default-rtdb.asia-southeast1.firebasedatabase.app

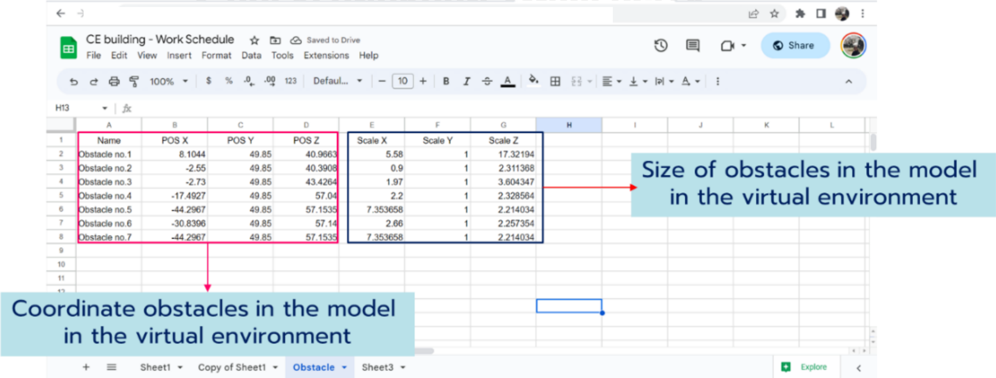
Your security rules are defined as public, so anyone can steal, modify, or delete data in your database

```
https://thesis-da786-default-rtdb.asia-southeast1.firebasedatabase.app/
- Lift
    - Lift A
        Departure: "09/05/2023 18:12:29"
        Max: 2
+ Navigation
+ Room
- User
    GBONWBQV: "Somjintana Kanangkaew"
```

Database location: Singapore (asia-southeast1)

Figure 6.13 Firebase updated the data of users in real-time.

Then, the next process was to input data; there are two processes, specifically, the XYZ coordinates of the obstacles and construction activities as work elements followed by the construction work schedule observed daily during the construction project. The users then establish the obstacles' positions and the working area in the virtual model, obtain the XYZ coordinates and sizing for each position based on the evolving construction project environment, and input the data into Google spreadsheets to update the changing construction project environment, such as the obstacle position and work activities followed by the construction work schedules.

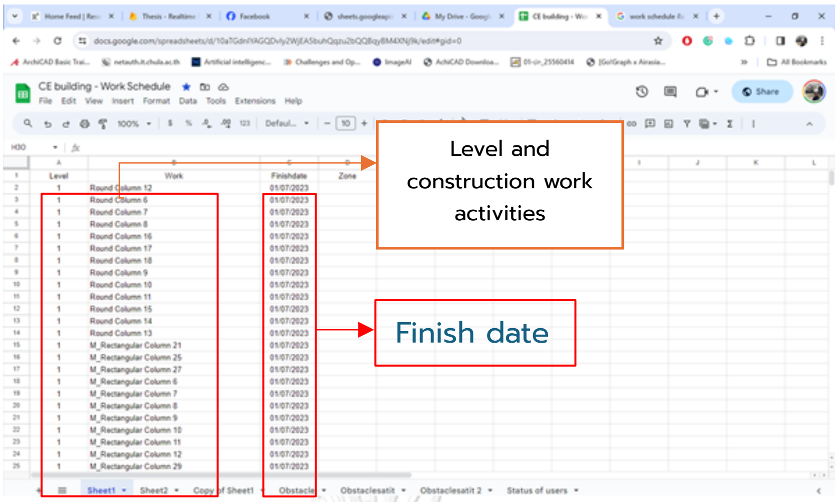


Name	POS X	POS Y	POS Z	Scale X	Scale Y	Scale Z
Obstacle no.1	8.1044	49.85	40.9663	5.58	1	17.32194
Obstacle no.2	-2.55	49.85	40.3908	0.9	1	2.311368
Obstacle no.3	-2.73	49.85	43.4264	1.97	1	3.604347
Obstacle no.4	-17.4927	49.85	57.04	2.2	1	2.328564
Obstacle no.5	-44.2967	49.85	57.1535	7.353658	1	2.214034
Obstacle no.6	-30.8396	49.85	57.14	2.66	1	2.257354
Obstacle no.7	-44.2967	49.85	57.1535	7.353658	1	2.214034

Size of obstacles in the model in the virtual environment

Coordinate obstacles in the model in the virtual environment

Figure 6.14 Example of coordinate and sizing of the obstacle.



Level	Work	Finishdate	Zone
1	Round Column 12	01/07/2023	
1	Round Column 6	01/07/2023	
1	Round Column 7	01/07/2023	
1	Round Column 8	01/07/2023	
1	Round Column 16	01/07/2023	
1	Round Column 17	01/07/2023	
1	Round Column 18	01/07/2023	
1	Round Column 9	01/07/2023	
1	Round Column 10	01/07/2023	
1	Round Column 11	01/07/2023	
1	Round Column 15	01/07/2023	
1	Round Column 14	01/07/2023	
1	Round Column 13	01/07/2023	
1	M_Rectangular Column 21	01/07/2023	
1	M_Rectangular Column 25	01/07/2023	
1	M_Rectangular Column 27	01/07/2023	
1	M_Rectangular Column 6	01/07/2023	
1	M_Rectangular Column 7	01/07/2023	
1	M_Rectangular Column 8	01/07/2023	
1	M_Rectangular Column 9	01/07/2023	
1	M_Rectangular Column 10	01/07/2023	
1	M_Rectangular Column 11	01/07/2023	
1	M_Rectangular Column 12	01/07/2023	
1	M_Rectangular Column 29	01/07/2023	

Figure 6.15 Example of construction activities and finish date of each activity.

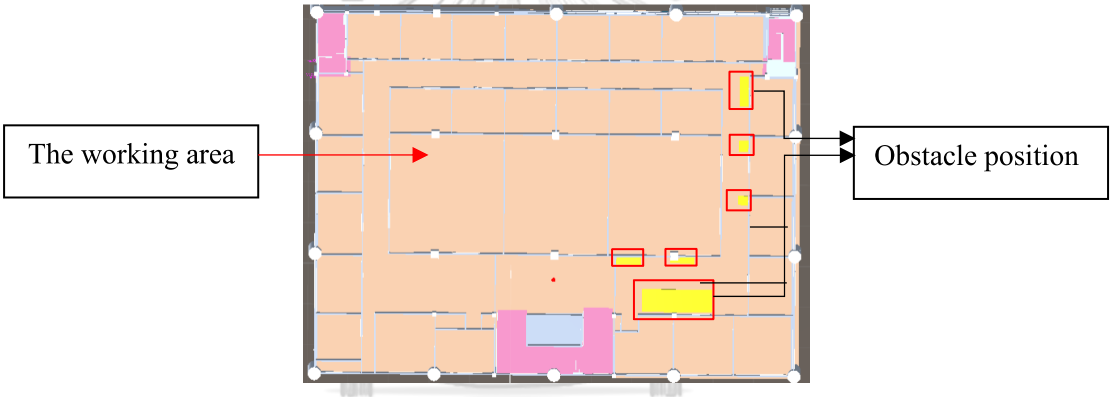


Figure 6.16 Example of the working area and coordinating the obstacle position in the virtual environment.

In case of obstacle avoidance, the proposed system will avoid the obstacle and recommend the appropriate evacuation route to the user in real-time. For this testing designed, three case studies for data collection in the case of obstacle avoidance systems as follows:

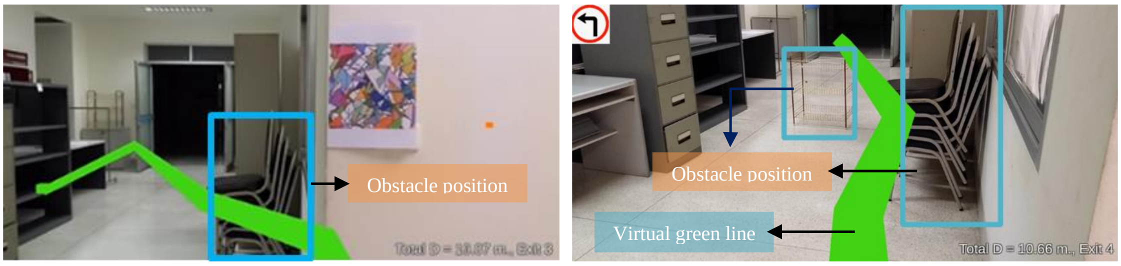
1. Case 1: The real environment in normal condition
2. Case 2: Adding one obstacle location
3. Case 3: Adding two obstacle locations

(a) (b) (c)

Figure 6.17 Three case studies of obstacle positions in the real environment.

Then, the following process was an image containing a marker, which is used to measure the distance to the exit, determine whether the evacuation route adheres to safety rules, and plan the corresponding exits for each room in the building. The proposed system could detect markers to identify and update the position of obstacles from a Google Sheet in real-time, using internet access to identify and update the position of obstacles. When an obstacle appears in a building, the proposed system could avoid obstacles and immediately recommend an appropriate evacuation route to the user and provide real-time access to information such as the current location, exit, distance of the shortest route from the current location to the destination, and virtual green line, voice, and arrow direction for evacuation guidance to the user in real-time. On the other hand, if the user moves away from the exit or does not follow the evacuation guidance, the system will recalculate the distance from the current location and display real-time information to the user on their next interaction.

Figure 6.18 An image containing a marker in the real environment.



(a) (b)

Figure 6.19 Example of the output cases 1 and 2 in the real environment.

Figure 6.20 Example of the output case 3 in the real environment.

The preliminary testing in the real environment showed that the proposed system was in the case of an obstacle avoidance system. The proposed system then detected markers that triggered the display of the user's location and the shortest obstacle avoidance system in real-time on a real-world scene. Finally, the system calculated the shortest evacuation route based on distance and recommended the appropriate evacuation route regarding obstacle avoidance, which are exits 3 and 4 in cases 1 and 2, respectively. In addition, in case 3, it was impossible to walk through due to obstructions.

6.4 Conclusion

This chapter demonstrated the development of The Self Care using Technology Evacuation System (SCT Evacuation System), which could provide information for evacuating and guidelines for the route for material handling to construction workers and staff in construction projects. Three parts include BIM authoring, a marker-based location, and application authoring. The prototype system was developed as a marker-based Augmented Reality (AR) application and integrated visualization technologies, such as Building Information Modeling (BIM), in cooperation with the specific coding denoted in the previous chapter. However, each module has distinct content for preparation, input, process, and output. These modules generate diverse results to serve as vital visualized information for the proposed system, which integrates a fire safety management and route for material handling application for construction workers and staff, enhancing decision-making and delivering real-time information for evacuating and providing the route material handling in the construction project.

The proposed system provides information, such as the user's current location, which is used to calculate the distance to the exit. The system also provides voice and arrow directions for evacuation and material handling route guidance, virtual green line, exit, and distance from the current location to the exit, the identification of users, recommends the appropriate evacuation route in case of obstacle avoidance in the construction project was also prepared and applied

Chapter 7

System Verification and Validation

7.1 Introduction

In this chapter, The Self Care using Technology Evacuation System (SCT Evacuation System), developed to provide information to evacuate and guidelines for the route for material handling to construction workers and staff containing hazardous locations in construction projects, was tested to prove that it could accurately and effectively perform. Even though the proposed system could provide the expected output during the development process, it had to be tested to verify accuracy and validate the potential of the system during the construction project. The verification process was done in both the virtual and real environments. Finally, the users, who are construction workers and staff, validated this system. The details are described as follows.

7.2 System Verification

Many functions were developed in the proposed system, such as providing the shortest fire evacuation route from the current location to the exit and presenting a virtual green line to evacuate the users to the exit. In order to verify the accuracy of this system, the mentioned functions are tested in this section. As described in the previous chapter, a weak internet signal is one factor that affects the performance of the proposed system. In this experiment, a personal hotspot was used to solve this problem. The functions were tested to verify the accuracy in both virtual and real environments.

7.2.1 Verifying the accuracy of the proposed system

In this research, the experiment of distance measurement was constantly tested to verify the accuracy of the proposed system using markers with patterns defined in the 3D model in the virtual and real environments based on the application's built-in calibration system. The shortest evacuation route, as the distance from the current location to the exit, was considered as the possible route that could occur. In the experiment, the distance of the evacuation route was manually measured, and used the MATALL Laser distance meter, an advanced instrument used for indoor measurement, as shown in Figure 7.1. The application measured the distance of the fire evacuation route and calculated the shortest one through the proposed system.

Figure 7.1 The MATALL Laser distance meter.

In the virtual environment testing, two case studies were studied. The distances of markers were fixed at 4.00 meters in case study 1 and 3.00 meters in case study 2, respectively. The height of the install markers from the floor level in two case studies was 1.20 meters.

In case study 1, thirty-four markers are installed on the 4th floor as nodes, such as room and exit locations, as orange boxes, as shown in Figure 7.2. The distance of each node is 4.00 meters. The markers are numbered clockwise, starting from 401 at the first marker in the upper right.

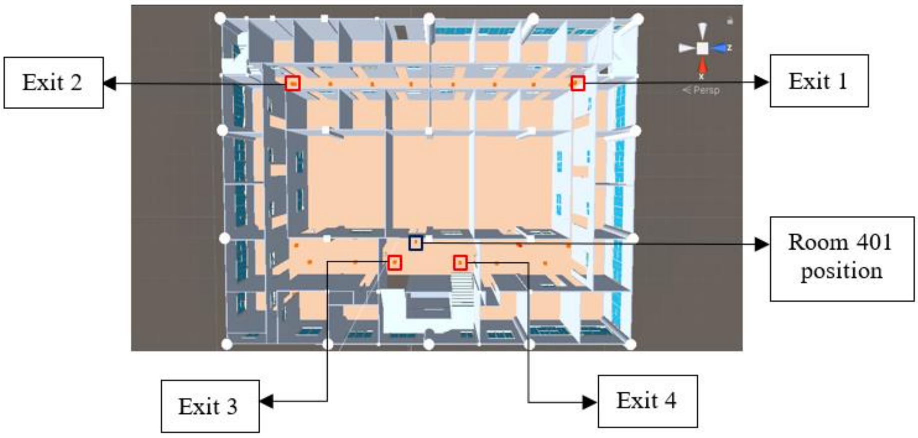
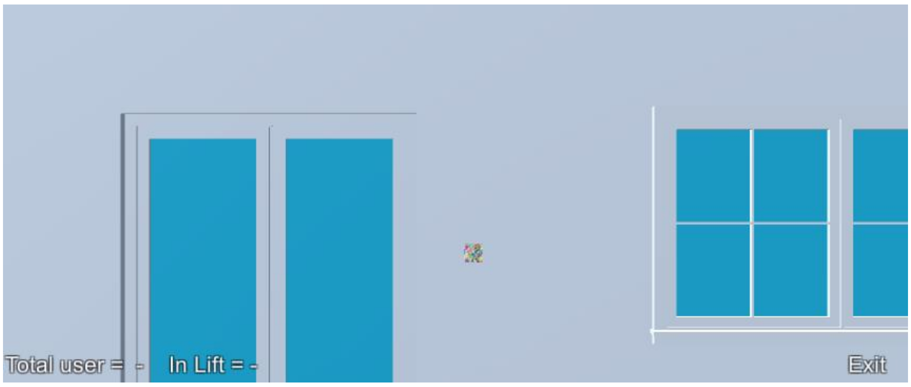


Figure 7.2 Markers installed on the 4th floor of case study 1.



(a)

(b)

Figure 7.3 Example of the marker's location in the virtual environment in case study 1.

In case study 2, fifty-three markers are installed on the 1st, 2nd, and 3rd floor as nodes, such as room, corner, and exit locations, as blue boxes, as shown in Figure 7.4 to Figure 7.7, respectively. The distance of each node is 3.00 meters. The markers are numbered clockwise, starting from 101 at the first marker in the upper right.

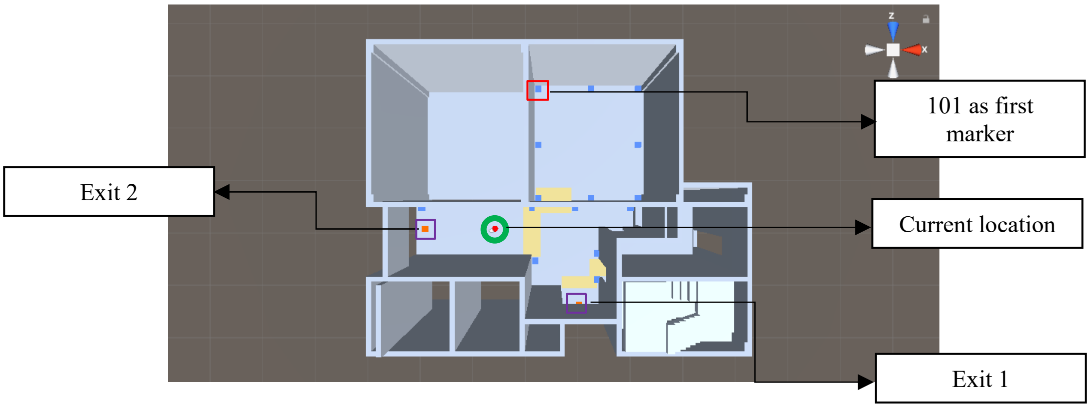


Figure 7.4 Markers preparation and installation on the 1st floor of case study 2.

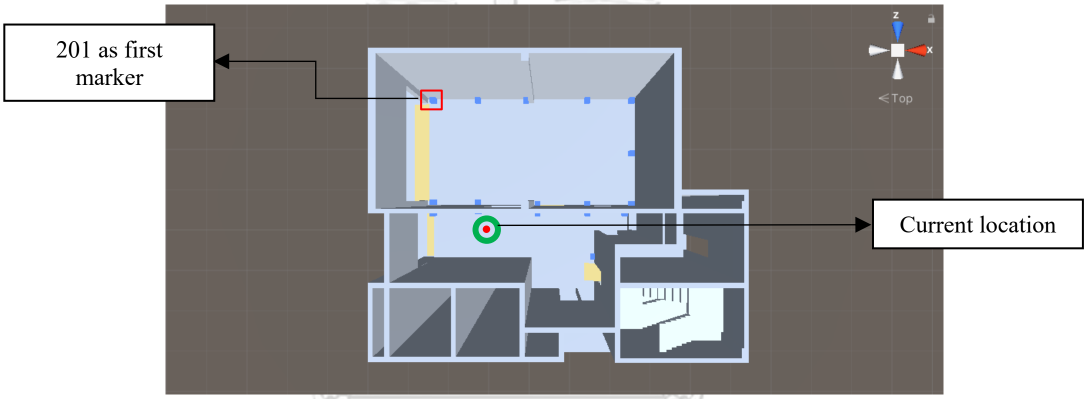


Figure 7.5 Markers preparation and installation on the 2nd floor of case study 2.

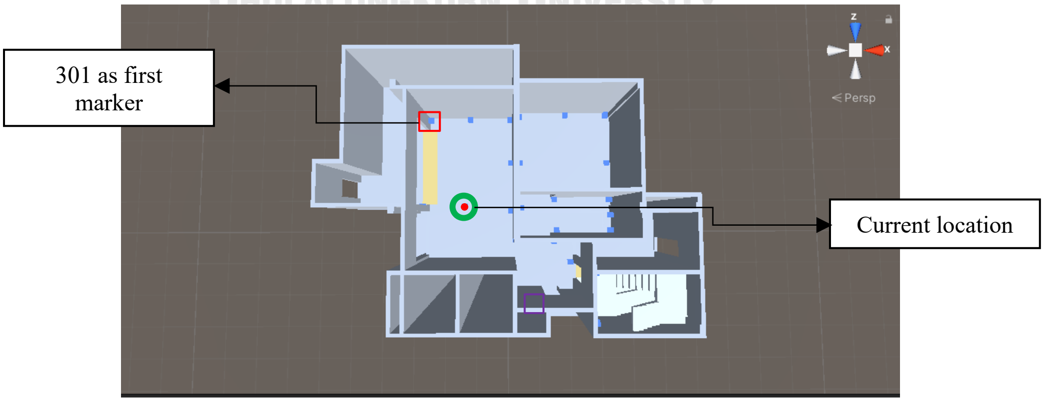
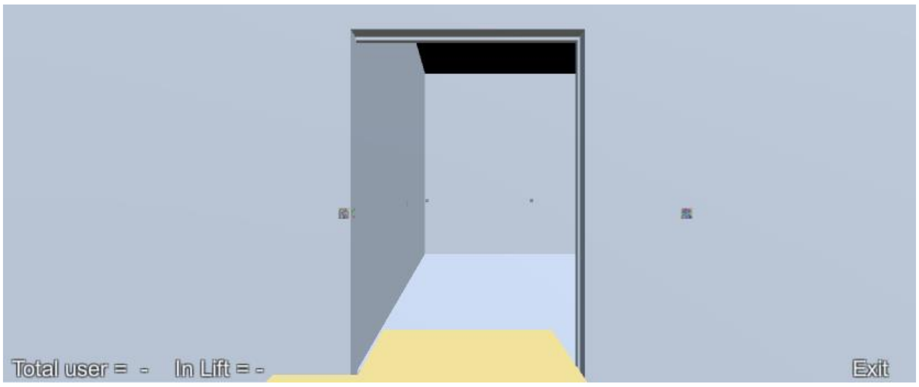
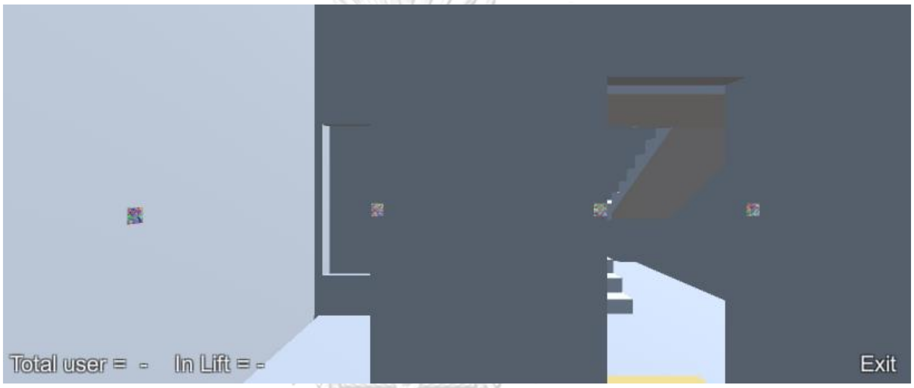


Figure 7.6 Markers preparation and installation on the 3rd floor of case study 2.



(a)



(b)

Figure 7.7 Example of the marker's location in the virtual environment in case study 2.

In the proposed system, measurements were taken from the current marker position, and the system calculated the distance from the user's current location to the exit. The unit of measurement is meters. Then, the system starts with a captured image containing a marker, which serves as the starting point. The marker carries its coordinate data in an XYZ axis and is utilized to measure the distance to the exit in the construction project. Next, it calculates the distance between the marker and the exit. The system also provides real-time information such as the text of distance and exit, voice and direction signs, and a virtual green line on the output screen. Furthermore, if construction workers and staff move far from the exit or fail to follow the evacuation guidance, the proposed system will recalculate the distance from the current location and provide real-time information to guide them accordingly in subsequent instances.

In the real environment testing, thirty-four markers were installed on the 4th floor of case study 1 as nodes, such as room and exit locations, as shown in Figure 7.8. The distance of each node is 4.00 meters. The markers are numbered clockwise, starting from 401 at the first marker in the upper right. In addition, in case study 2, fifty-two markers are installed on the 1st, 2nd, and 3rd floor as nodes, such as room, corner, and exit locations, as shown in Figure 7.9. The distance of each node is 3.00 meters. The markers are numbered clockwise, starting from 101 at the first marker in the upper right.

(a) (b)

Figure 7.8 Example of the marker's location in the real environment in case study 1.

(a) (b)

Figure 7.9 Example of the marker's location in the real environment in case study 2.

This experiment was conducted using the MATALL Laser distance meter, which is an advanced measurement tool used for indoor measurement to measure the distance from the current marker position to the exit. Then, the Matall Laser Distance meter measurements were taken from the current marker position to the exit. The distance was measured three times, and the average distance from the current location to the exit was calculated using the exit data from the proposed system. The unit of measurement is meters.

(a) (b)

Figure 7.10 Measure the distance using the Matall Laser Distance meter in case study 1.

(a) (b)

Figure 7.11 Measure the distance using the Matall Laser Distance meter in case study 2.

From the testing in both virtual and real environments, the distance results were analyzed using the percentage difference, which is the difference between two values divided by the average of the two values shown as a percentage, using Equation 7.1.

$$\text{Percentage Difference} = [V1-V2]/[(V1+V2)/2]\text{x}100 \qquad (7.1)$$

Where

V1 = the distance from MATALL Laser distance meter

V2 = the distance from the proposed system

Then, the average of the percentage difference ($\bar{x}$) can be determined as presented in Equation 7.2 as follows.

$$\bar{x} = \sum \frac{x}{N} \qquad (7.2)$$

Where

x = the percentage difference

N = the number of the measurement

7.2.1.1. Comparison of the difference in the distance between the proposed system and the MATALL Laser distance meter in the case study 1

The distance between the proposed system and the MATALL Laser distance meter was compared using the Percentage Difference in Equation 7.1 and the average of the Percentage Difference ($\bar{X}$) in Equation 7.2. The comparison results are presented in Table 7.1. The average distance of percentage difference was 2.2%, and the graphs from Figure 7.6 to Figure 7.7 were created from comparing the distance between the proposed system and the MATALL Laser distance meter and summarized the percentage difference of all markers, respectively.

Table 7.1 Average The Distance, Exit, and Percentage Difference from the current location to the exit in the case study 1

Marker No.	**Distance (m.)**		**Exit**	**Distance Difference (m.)**	**Percentage Difference**
	Proposed System	The MATALL Laser distance meter			
401	4.17	4.177	4	0.01	0.2%
402	6.28	6.38	4	0.10	1.6%
403	6.58	6.62	4	0.04	0.6%
404	9.73	9.91	4	0.18	1.8%
405	11.39	11.94	4	0.55	4.7%
406	12.27	12.39	4	0.12	1.0%
407	12.97	13.4	4	0.43	3.3%
408	8.58	8.66	1	0.08	0.9%
409	4.00	4.13	1	0.13	3.2%
411	1.33	1.38	1	0.05	3.7%
412	3.48	3.65	1	0.17	4.8%
413	3.48	3.55	1	0.07	2.0%
414	7.52	7.73	1	0.21	2.8%
415	7.52	7.73	1	0.21	2.8%
416	11.56	11.66	1	0.10	0.9%
417	11.56	11.66	1	0.10	0.9%
419	6.34	6.45	3	0.11	1.7%
420	11.82	12.03	3	0.21	1.8%
421	15.00	15.35	3	0.35	2.3%
422	13.39	13.65	3	0.26	1.9%
423	11.56	11.98	3	0.42	3.6%
424	12.35	12.84	3	0.49	3.9%
425	8.59	8.69	2	0.10	1.2%
426	4.20	4.34	2	0.14	3.3%
428	1.24	1.28	2	0.04	3.2%
429	3.42	3.54	2	0.12	3.4%
430	3.42	3.54	2	0.12	4.6%
431	7.41	7.58	2	0.17	2.3%
432	7.41	7.58	2	0.17	2.3%
433	11.48	11.51	2	0.03	0.3%
434	11.48	11.51	2	0.03	0.3%

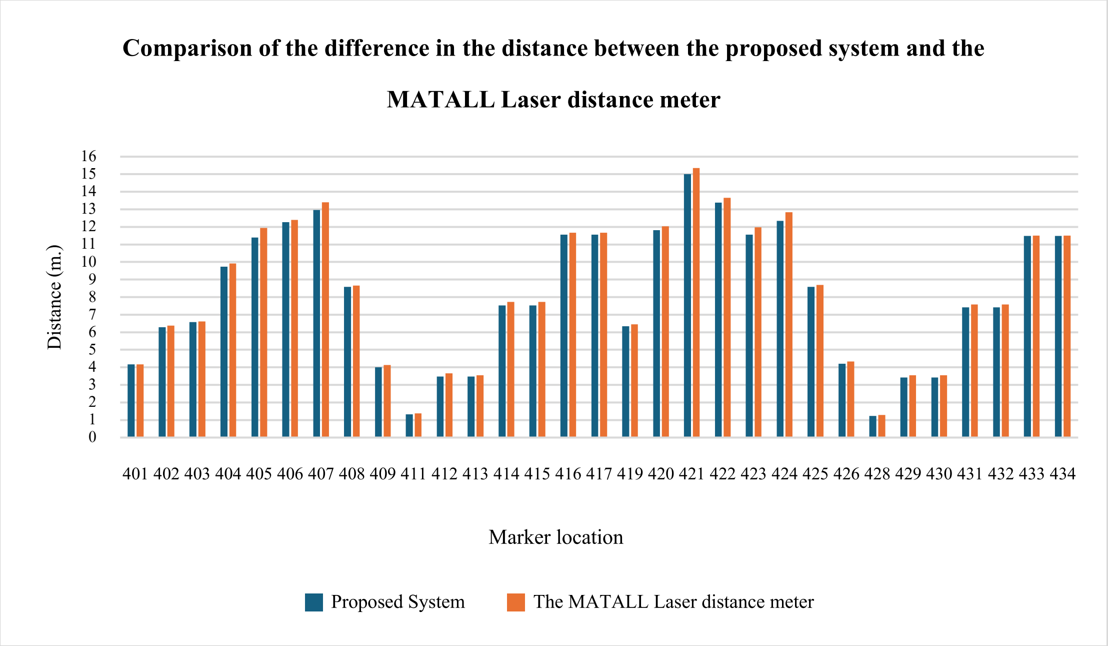


Figure 7.12 The comparison of the distance between the proposed system and the MATALL Laser distance meter.

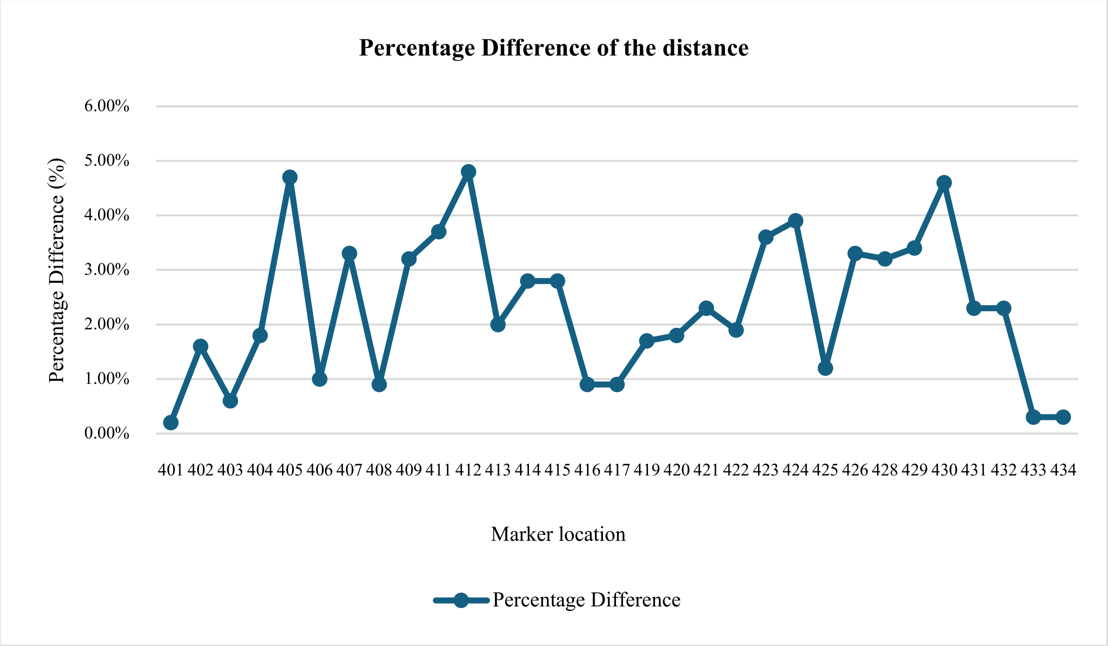


Figure 7.13 Summarizes the percentage difference of distance between the proposed system and the MATALL Laser distance meter.

From both virtual and real environment testing, Table 7.1 and Figure 7.12 to Figure 7.13 presented the average and summarized the percentage difference of all markers measured by the proposed system and MATALL Laser distance meter. The results show that the Percentage Difference between all markers, the distance, the exit, and the average Percentage Difference from the current location to the exit measured by the proposed system are lower than those measured by the MATALL Laser distance meter, which was less than 2.2%. Therefore, this proposed system effectively provides real-time access to information such as the current location, exit, distance of the shortest route from the current location to the destination, and virtual green line, voice, and arrow direction for evacuation guidance. It is convenient for decision-making and helps users find destinations quickly and efficiently.

7.2.1.2. Comparison of the difference in the distance between the proposed system and the MATALL Laser distance meter in the case study 2

The distance between the proposed system and the MATALL Laser distance meter was compared using the Percentage Difference in Equation 7.1 and the average of the Percentage Difference ($\bar{X}$) in Equation 7.2. The comparison results are presented in Table 7.2 to Table 7.4. The average distance of percentage difference was 8%, 7%, and 15%, respectively, and the graphs from Figure 7.14 to Figure 7.15 were created from the comparison of the difference in the distance between the proposed system and the MATALL Laser distance meter and summarized the percentage difference of all markers, respectively.

Table 7.2 Average The Distance, Exit, and Percentage Difference from the current location to the exit on the 1st floor of the case study 2

Marker No.	**Distance (m.)**		**Exit**	**Distance Difference (m.)**	**Percentage Difference**
	Proposed System	The MATALL Laser distance meter			
101	10.25	10.65	1	0.40	4%
102	12.74	13.99	1	1.25	9%
103	12.56	13.43	1	0.87	6%
104	10.47	10.77	1	0.30	3%
105	7.78	8.67	1	0.89	10%

Table 7.2 Average The Distance, Exit, and Percentage Difference from the current location to the exit on the 1st floor of the case study 2 (continued)

Marker No.	**Distance (m.)**		**Exit**	**Distance Difference (m.)**	**Percentage Difference**
	Proposed System	The MATALL Laser distance meter			
106	5.89	6.60	1	0.71	11%
107	5.95	6.62	2	0.67	10%
108	8.85	9.09	1	0.24	3%
109	10.13	11.33	1	1.20	11%
110	5.44	5.66	1	0.22	4%
111	4.02	4.64	1	0.62	13%
112	5.56	5.93	1	0.37	6%
113	5.02	5.32	1	0.30	6%
114	2.54	3.02	1	0.48	16%

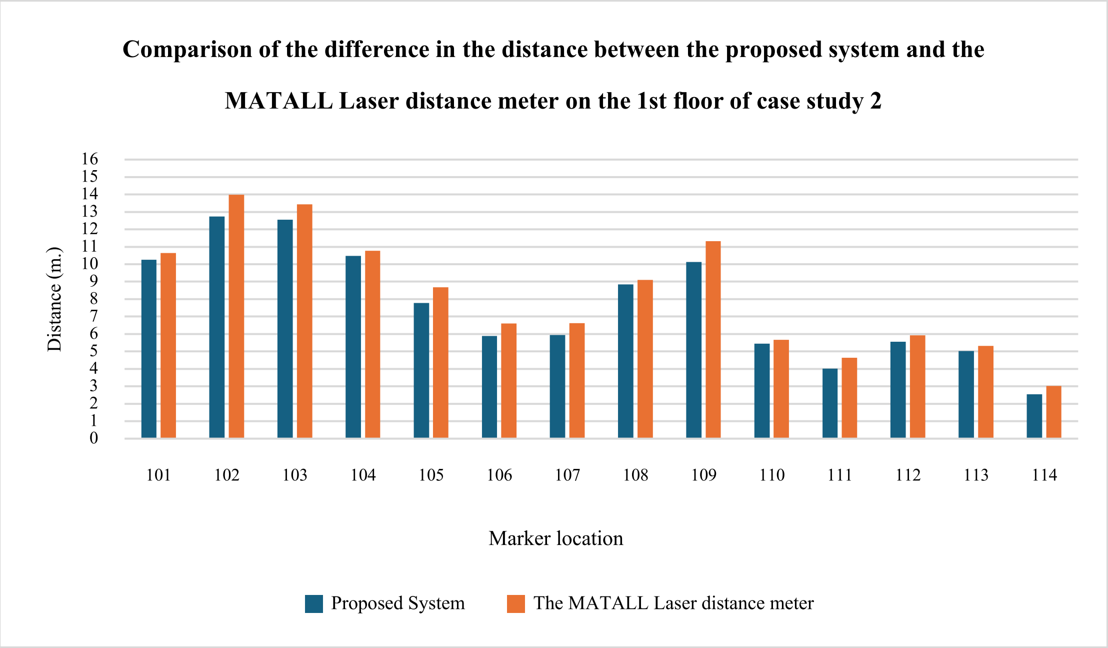


Figure 7.14 The comparison of the distance between the proposed system and the MATALL Laser distance meter on the 1st floor of case study 2.

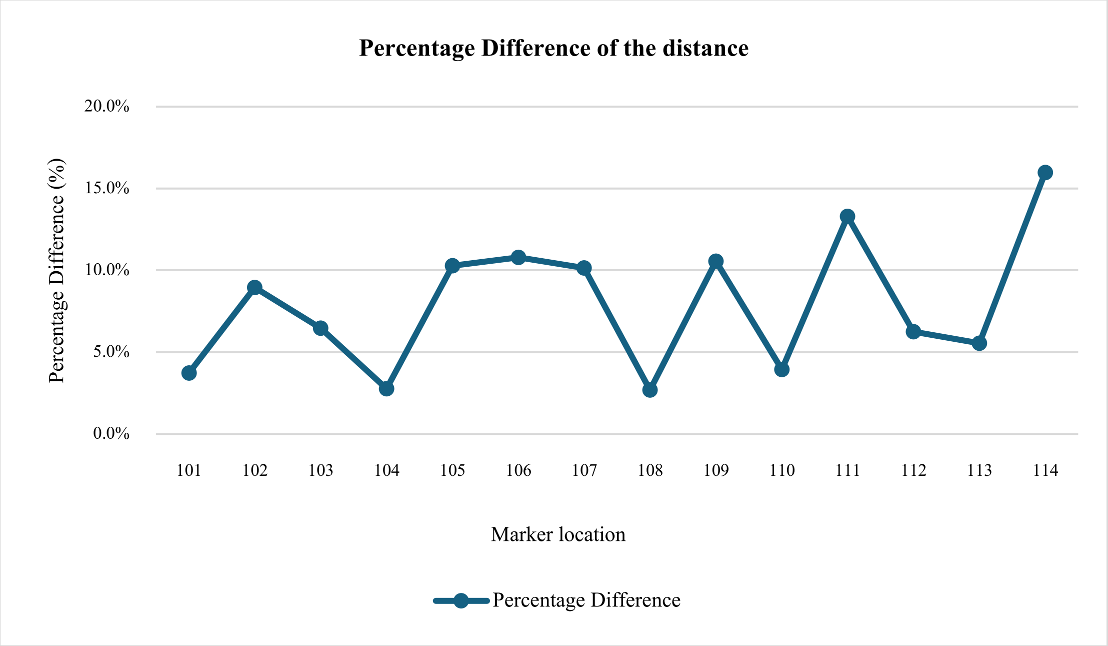


Figure 7.15 Summarizes the percentage difference of distance between the proposed system and the MATALL Laser distance meter on the 1st floor of case study 2.

Table 7.3 Average The Distance, Exit, and Percentage Difference from the current location to the exit on the 2nd floor of the case study 2

Marker No.	Distance (m.)		Exit	Distance Difference (m.)	Percentage Difference
	Proposed System	The MATALL Laser distance meter			
201	34.58	36.82	1	2.24	6%
202	34.33	32.87	1	2.09	6%
203	29.52	36.89	1	4.86	14%
204	26.10	29.68	1	3.58	12%
205	25.93	31.14	1	5.21	17%
206	26.06	28.55	1	2.49	9%
207	22.76	25.96	1	3.20	12%
208	23.18	23.69	1	0.51	2%
209	23.00	26.28	1	3.28	12%
210	30.17	30.19	1	0.02	0%
211	24.95	30.66	1	5.71	19%
212	25.62	27.16	1	1.54	6%
213	24.48	24.71	1	0.23	1%

Table 7.3 Average The Distance, Exit, and Percentage Difference from the current location to the exit on the 2nd floor of the case study 2 (continued)

Marker No.	**Distance (m.)**		**Exit**	**Distance Difference (m.)**	**Percentage Difference**
	Proposed System	The MATALL Laser distance meter			
214	22.64	23.49	1	0.85	4%
215	24.37	25.08	1	4.71	3%
216	21.07	21.41	1	0.34	2%
217	19.54	20.41	1	0.87	4%
218	20.23	21.01	1	0.78	4%
219	14.32	15.72	1	1.40	9%

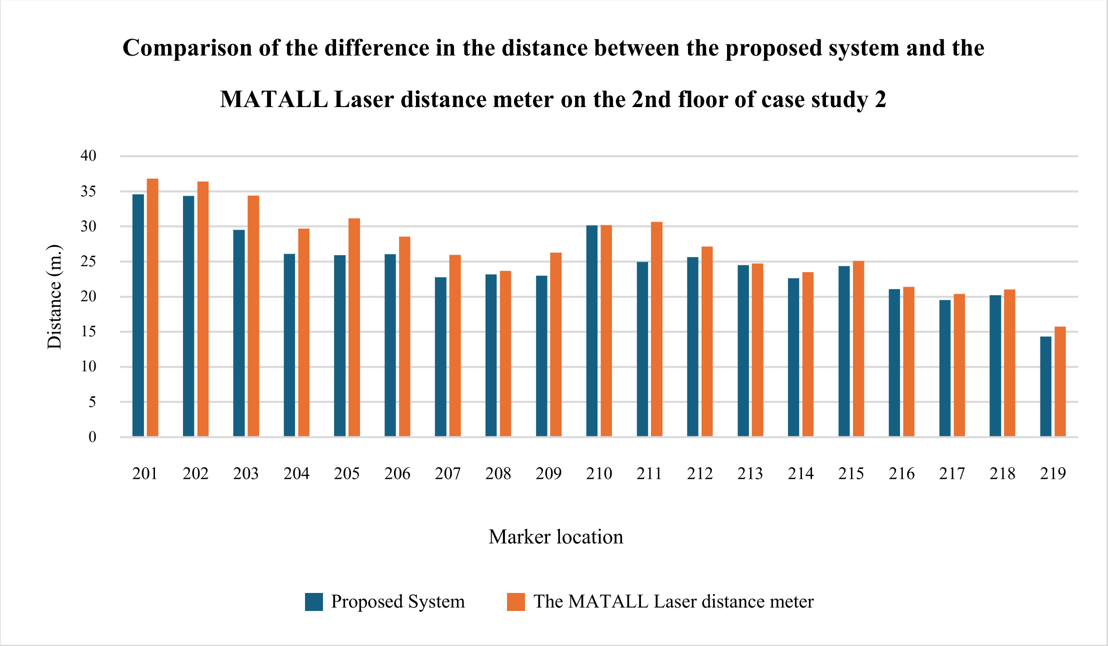


Figure 7.16 The comparison of the distance between the proposed system and the MATALL Laser distance meter on the 2nd floor of case study 2.

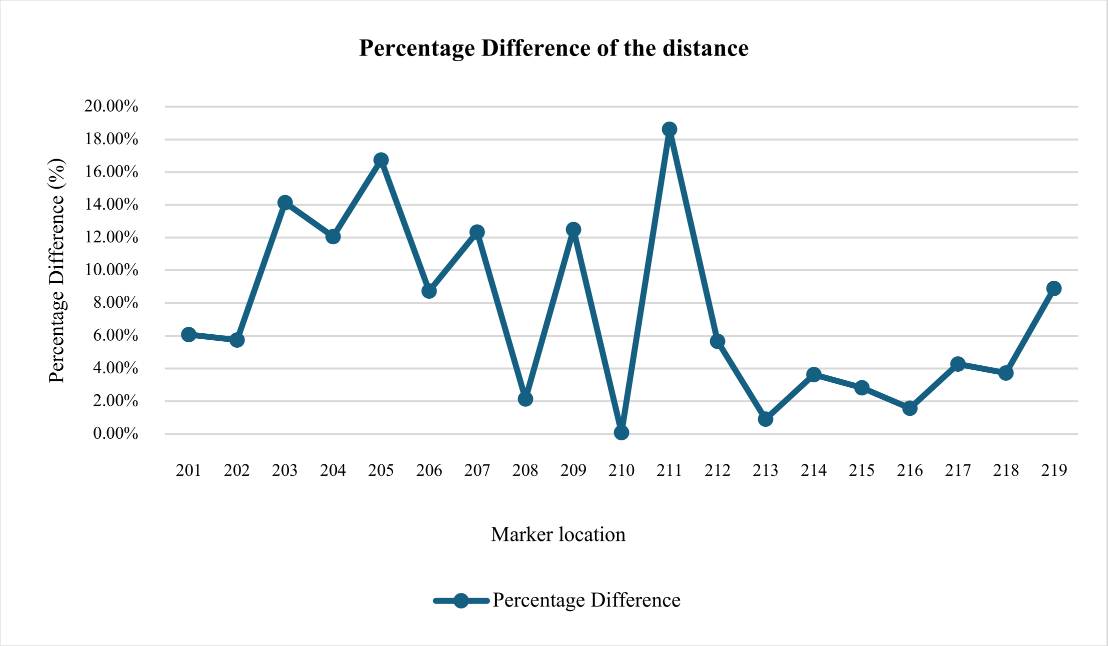


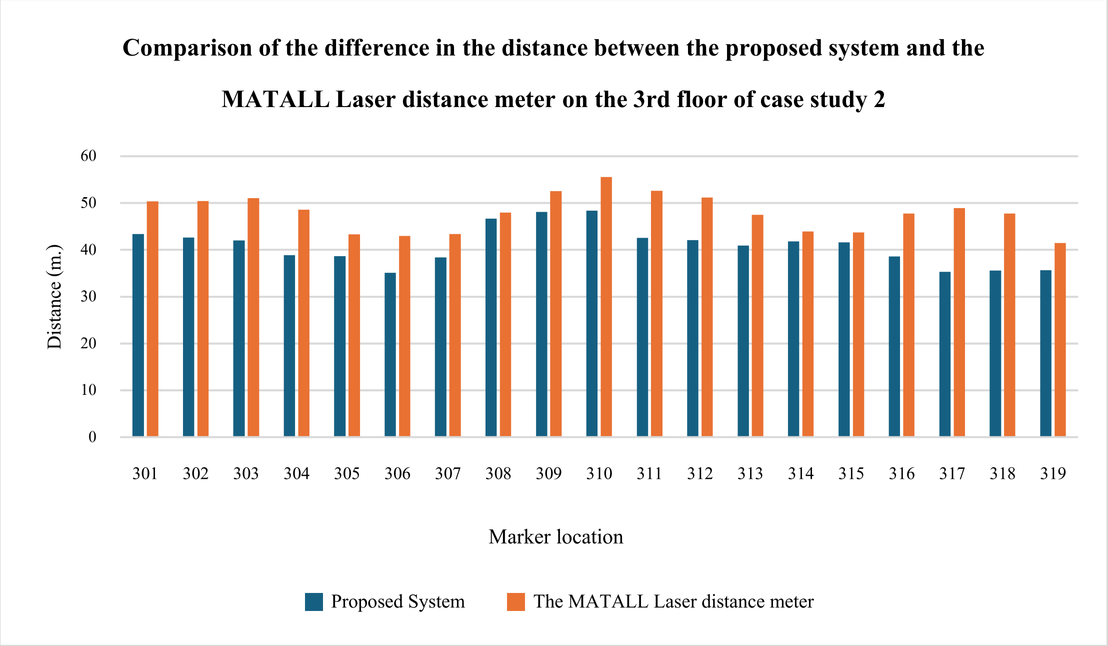
Figure 7.17 Summarizes the percentage difference of distance between the proposed system and the MATALL Laser distance meter on the 2nd floor of case study 2.

Table 7.4 Average The Distance, Exit, and Percentage Difference from the current location to the exit on the 3rd floor of the case study 2

Marker No.	**Distance (m.)**		**Exit**	**Distance Difference (m.)**	**Percentage Difference**
	Proposed System	The MATALL Laser distance meter			
301	43.39	50.38	1	6.99	14%
302	42.60	50.45	1	7.85	16%
303	42.05	51.08	1	9.03	18%
304	38.90	48.62	1	9.72	20%
305	38.64	43.32	1	4.68	11%
306	35.10	42.99	1	7.89	18%
307	38.42	43.40	1	4.98	11%
308	46.65	47.96	1	1.31	3%
309	48.10	52.55	1	4.45	8%
310	48.36	55.54	1	7.18	13%
311	42.59	52.63	1	10.04	19%
312	42.08	51.16	1	9.08	18%
313	40.89	47.46	1	6.57	14%

Table 7.4 Average The Distance, Exit, and Percentage Difference from the current location to the exit on the 3rd floor of the case study 2 (continued)

Marker No.	**Distance (m.)**		**Exit**	**Distance Difference (m.)**	**Percentage Difference**
	Proposed System	The MATALL Laser distance meter			
314	41.80	43.92	1	2.12	5%
315	41.61	43.75	1	2.14	5%
316	38.62	47.74	1	9.12	19%
317	35.33	48.95	1	13.62	28%
318	35.57	47.74	1	12.17	25%
319	35.65	41.44	1	5.79	14%



Comparison of the difference in the distance between the proposed system and the MATALL Laser distance meter on the 3rd floor of case study 2

Figure 7.18 The comparison of the distance between the proposed system and the MATALL Laser distance meter on the 3rd floor of case study 2.

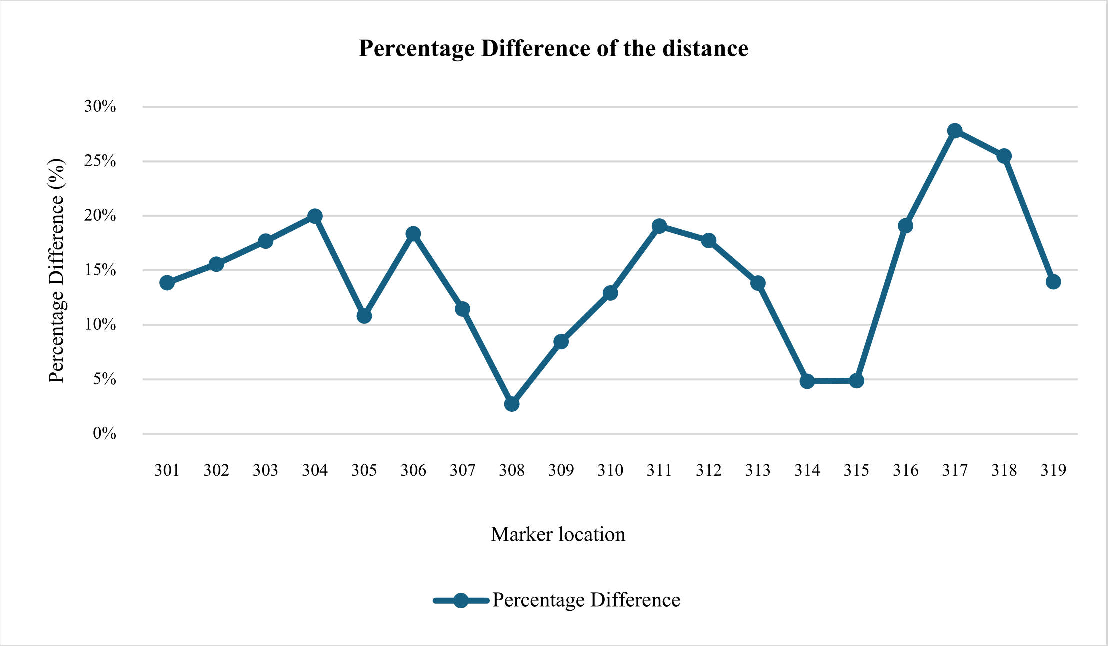


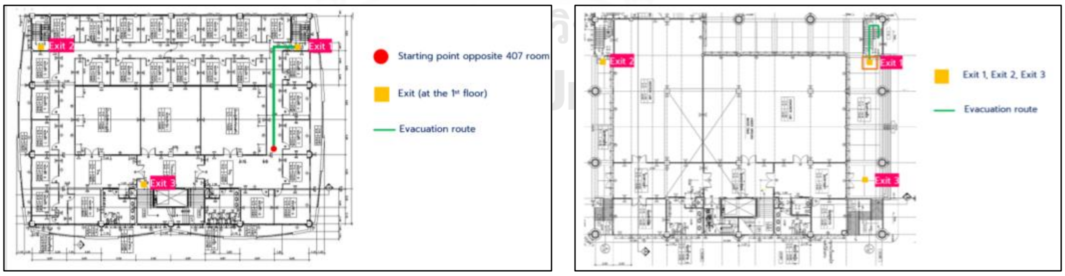
Figure 7.19 Summarizes the percentage difference of distance between the proposed system and the MATALL Laser distance meter on the 3rd floor of case study 2.

From both virtual and real environment testing, Table 7.1 to Table 7.4 and Figure 7.6 to Figure 7.19 presented the average and summarized the percentage difference of all markers measured by the proposed system and MATALL Laser distance meter. The results show that the Percentage Difference between all markers, the distance, the exit, and the average Percentage Difference from the current location to the exit measured by the proposed system are lower than those measured by the MATALL Laser distance meter, which was less than 8%, 7%, 15%, respectively. Therefore, this proposed system effectively provides real-time access to information such as the current location, exit, distance of the shortest route from the current location to the destination, and virtual green line, voice, and arrow direction for evacuation guidance. It is convenient for decision-making and helps users find destinations quickly and efficiently.

7.2.2 Testing on Scenario 1

In Figure 7.20 and Figure 7.21, the evacuation plan is two-dimensional (2D) and exits on the substances are on the 1st and 4th floors of scenario 1(a) and scenario 1(b) of case study 1, which is the Department of Civil Engineering building. Figure 7.22 and Figure 7.23 presents the user interface of the system, which generates the evacuation route and exit for the users. In addition, Figure 7.24 and Figure 7.25 present the 3D view of the evacuation route in the real-world scene, presenting the evacuation route with the vertical and horizontal route and correct position.

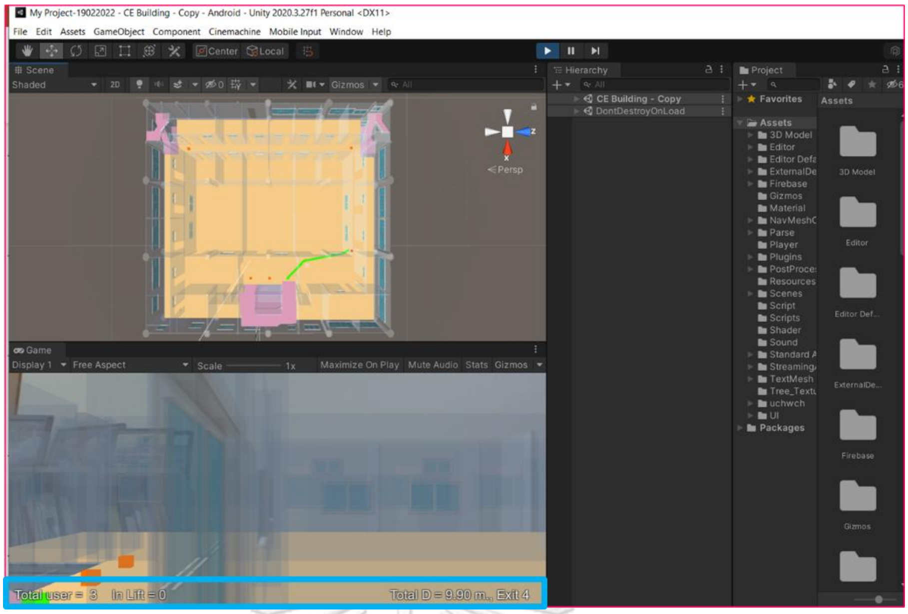
Figure 7.20 The evacuation plan and exits on the 4th floor of scenario 1(a).



(a) (b)

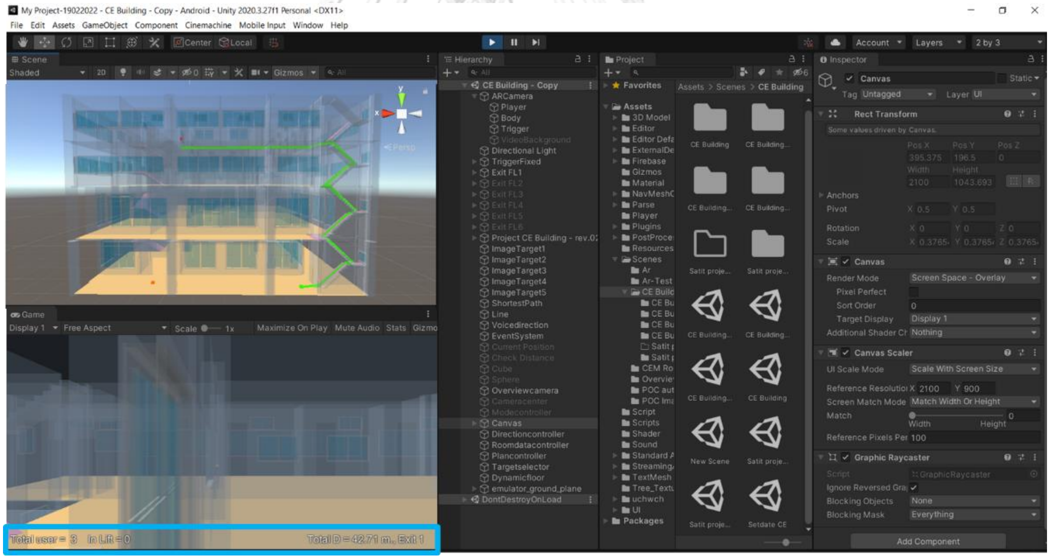
The evacuation plan and exits on the 4th floor The evacuation plan and exits on the 1st floor

Figure 7.21 The evacuation plan and exits on the 1st floor of scenario 1(b).



Total user = 3 In Lift = 0 Total D = 9.90 m., Exit 4

Figure 7.22 The user interface of the system presented the evacuation route of scenario 1(a) in the horizontal view.



Total user = 3 In Lift = 0 Total D = 42.71 m., Exit 1

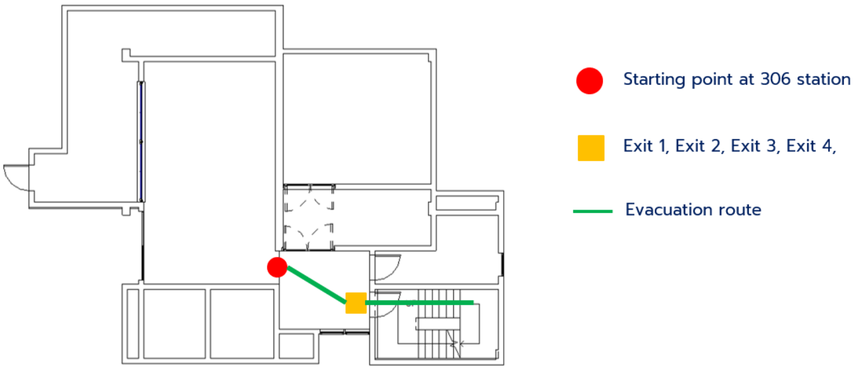
Figure 7.23 The user interface of the system presented the evacuation route of scenario 1(b) in the vertical view.

Figure 7.24 The 3D view of scenario 1(a) presents the evacuation routes in the horizontal view.

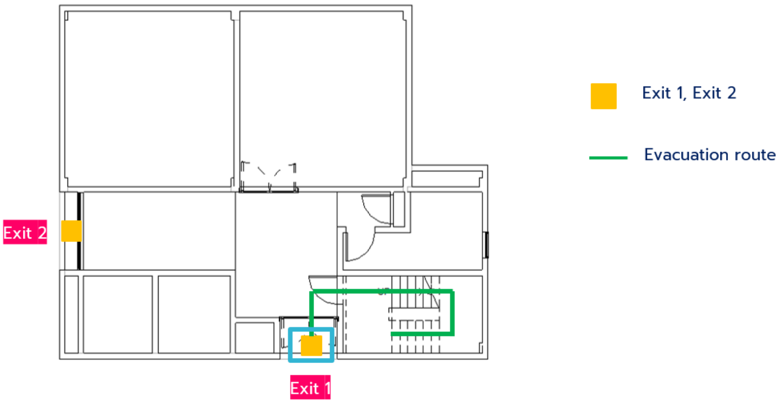
Figure 7.25 The 3D view of scenario 1(b) presents the evacuation routes in the vertical view.

7.2.2 Testing on Scenario 2

In Figure 7.26, the evacuation plan is two-dimensional (2D) and exits on the substances are on the 1st and 3rd floors of scenario 2 of case study 2, which is the Chulalongkorn University Demonstration Secondary School construction project. Figure 7.27 presents the user interface of the system, which generates the evacuation route and exit for the users. In addition, Figure 7.28 presents the 3D view of the evacuation route in a real-world scene, presenting the evacuation route with the vertical and horizontal route and correct position.

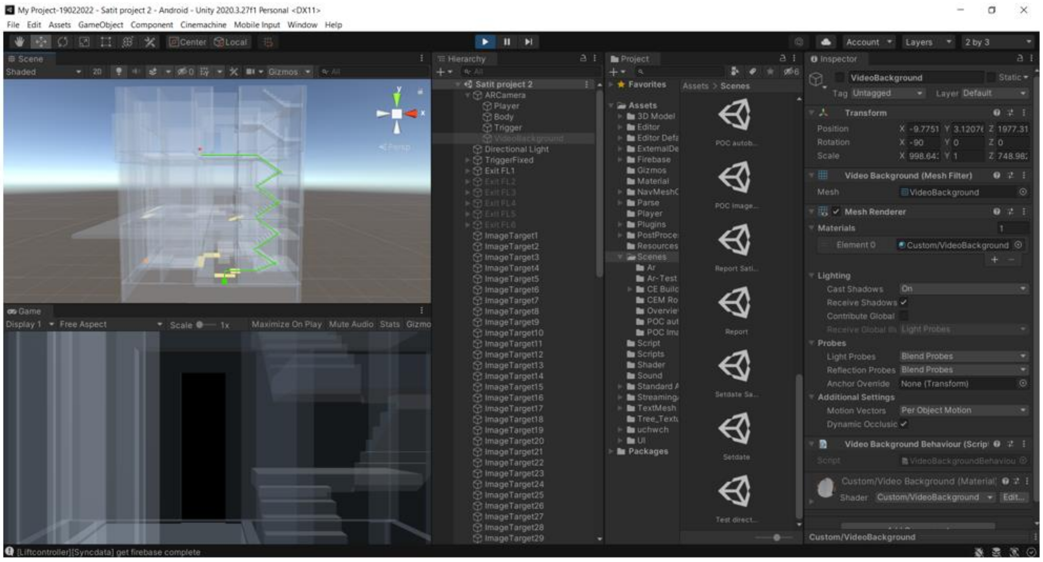


(a) The evacuation plan and exits on the 3rd floor of scenario 2.



(b) The evacuation plan and exits on the 1st floor of scenario 2.

Figure 7.26 The evacuation plan and exits on the 1st floor of scenario 2.



[Liftcontroller][Syncdata] get firebase complete

Figure 7.27 The user interface of the system presented the evacuation route of scenario 2 in the vertical view.

Figure 7.28 The 3D view of scenario 2 presents the evacuation routes in the vertical view.

7.2.3 Testing on Scenario 3

Construction site environments involve many temporary works and constantly changing workplaces. As a result, the number of occupants, spaces, and evacuation routes can vary daily (Marzouk and Daour, 2018), as shown in Figure 7.29 to Figure 7.31. In the event of an emergency situation occurring in the construction, the appropriate evacuation route can avoid obstacles. It is essential to help evacuate users from the construction site as safely as possible.

(a) (b)

Figure 7.29 Example of the temporary material area in the construction project.

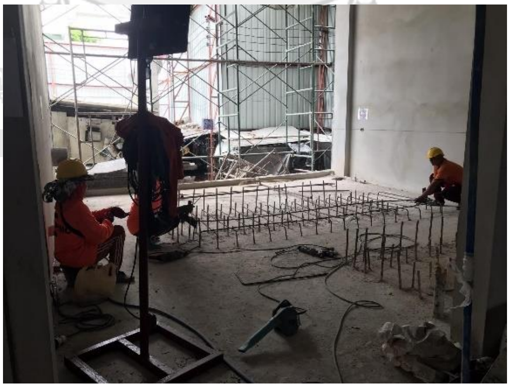
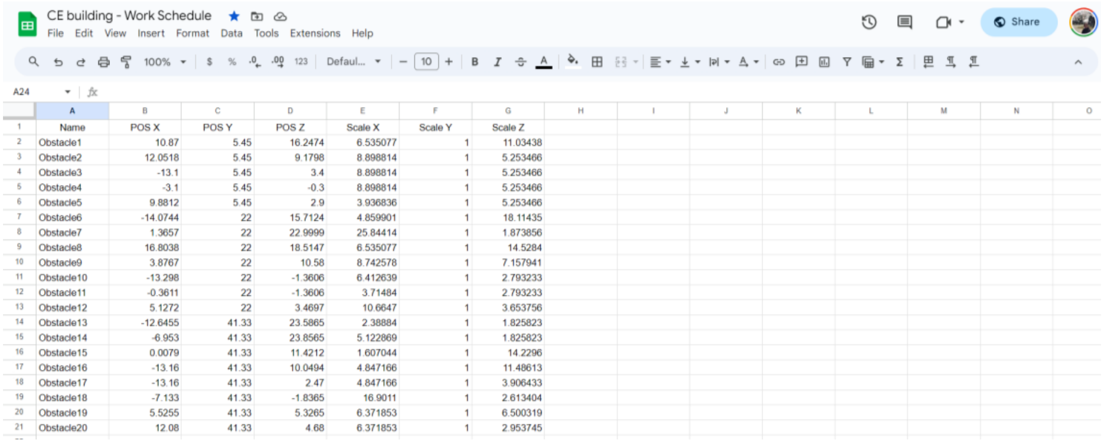


Figure 7.30 Example of the number of construction workers on day 1 in the construction project.

Figure 7.31 Example of the number of construction workers on day 2 in the construction project.

In the experiment, the dynamic work conditions as obstacles, such as the construction material area and continuously changed workplaces, were a case study. When the position of the obstacle changes and appears in the construction project, the area cannot be traversed by walking. However, the outputs of the proposed system, such as the real-time obstacle avoidance as an appropriate evacuation route while avoiding obstacles, were correctly rendered as expected. Furthermore, this proposed system intended to provide an appropriate evacuation route via a virtual green line in real-world scenes to users in order to support and evacuate users at the construction project. Therefore, the testing of the real-time obstacle avoidance system was carried out.

In this study, the proposed system would identify the position of obstacles and detect obstacles from a Google Sheet in real-time, which uses internet access to identify and update the position of obstacles, as shown in Figure 7.32. The proposed system uses the A* algorithm to find the shortest path from the starting node to the goal while avoiding obstacles. In addition, the proposed system calculated the shortest evacuation route based on distance and recommended the appropriate evacuation route to the user in real-time. If it was impossible to walk through due to obstructions, the proposed system could recommend the user to the next exit. In Figure 7.33, the output of the appropriate evacuation route was rendered on the device screen, and Figures 7.34 and 7.35 present a case of it being impossible to walk through due to obstructions. Therefore, the proposed system could be recommended to the user to the next exit instead.



Name	POS X	POS Y	POS Z	Scale X	Scale Y	Scale Z
Obstacle1	10.87	5.45	16.2474	6.535077	1	11.03438
Obstacle2	12.0518	5.45	9.1798	8.898814	1	5.253466
Obstacle3	-13.1	5.45	3.4	8.898814	1	5.253466
Obstacle4	-3.1	5.45	-0.3	8.898814	1	5.253466
Obstacle5	9.8812	5.45	2.9	3.936836	1	5.253466
Obstacle6	-14.0744	22	15.7124	4.859901	1	18.11435
Obstacle7	1.3657	22	22.9999	25.84414	1	1.873856
Obstacle8	16.8038	22	18.5147	6.535077	1	14.5284
Obstacle9	3.8767	22	10.58	8.742578	1	7.157941
Obstacle10	-13.298	22	-1.3606	6.412639	1	2.793233
Obstacle11	-0.3611	22	-1.3606	3.71484	1	2.793233
Obstacle12	5.1272	22	3.4697	10.6647	1	3.653756
Obstacle13	-12.6455	41.33	23.5865	2.38884	1	1.825823
Obstacle14	-6.953	41.33	23.8565	5.122869	1	1.825823
Obstacle15	0.0079	41.33	11.4212	1.607044	1	14.2296
Obstacle16	-13.16	41.33	10.0494	4.847166	1	11.48613
Obstacle17	-13.16	41.33	2.47	4.847166	1	3.906433
Obstacle18	-7.133	41.33	-1.8365	16.9011	1	2.613404
Obstacle19	5.5255	41.33	5.3265	6.371853	1	6.500319
Obstacle20	12.08	41.33	4.68	6.371853	1	2.953745

Figure 7.32 Example of the position of obstacles in the construction project.

Figure 7.33 Example of the appropriate evacuation route was rendered on a real-world scene.

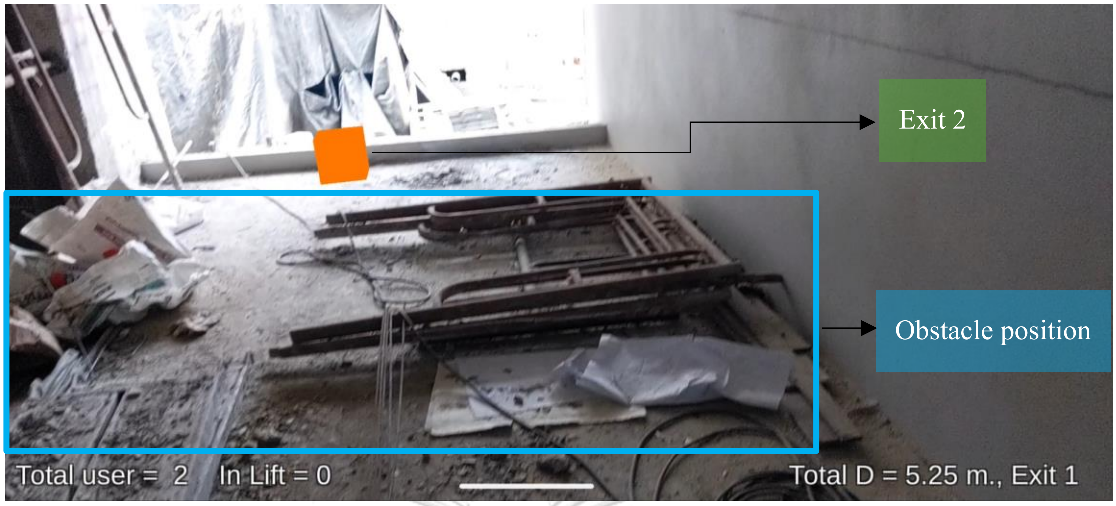


Figure 7.34 Example of the output in case it is impossible to walk through due to obstructions.

Figure 7.35 Example of the output of the proposed system could be recommended to the user to the next exit instead.

7.3 System Validation

In order to evaluate the proposed system, the experiment was designed and implemented in the construction project. A high-rise building construction project was selected to be a sample project, which is the construction project for an engine building, which was a construction project for Chulalongkorn University Demonstration Secondary School. This project is a six-story with a total area of 1,032.83 square meters and a height of 26.10 meters, as shown in Figure 7.36 to Figure 7.37.

Figure 7.36 Chulalongkorn University Demonstration Secondary School construction project.

Figure 7.37 The construction project for an engine building.

The experiments and questionnaires were designed and implemented at the construction project for an engine building. The designed questionnaires aimed at gathering qualitative rather than quantitative feedback were applied. The three engineers, four trainees, and five construction workers with experience in fire emergency procedures and who worked on this construction were selected to test and answer the questionnaires. Before respondents answer the questionnaires, a video will be shown on how to use the system and what functions can be performed. The designed questionnaires were divided into four parts, as presented in Appendix A. The first two parts were used to survey the respondents' demographic and background information regarding the fire emergency procedures in the construction project. The questionnaires' distribution and the respondents' demographic profile are presented in Table 7.5. Moreover, the proportion graphs for each respondent's demographic profile variable are presented in Figures 7.38 to 7.40.

Table 7.5 Demographic profile of the respondents

Variables	**Distribution (n = 12)**
Gender	
Male	67%
Female	33%
Age (years)	
Mean	34.67
Education	
Bachelor	58%
Other	42%
Work experience (years)	
< 5	33%
10 - 20	42%
> 20	25%
Job position	
Engineers	25%
Trainees	33%
Construction workers	42%

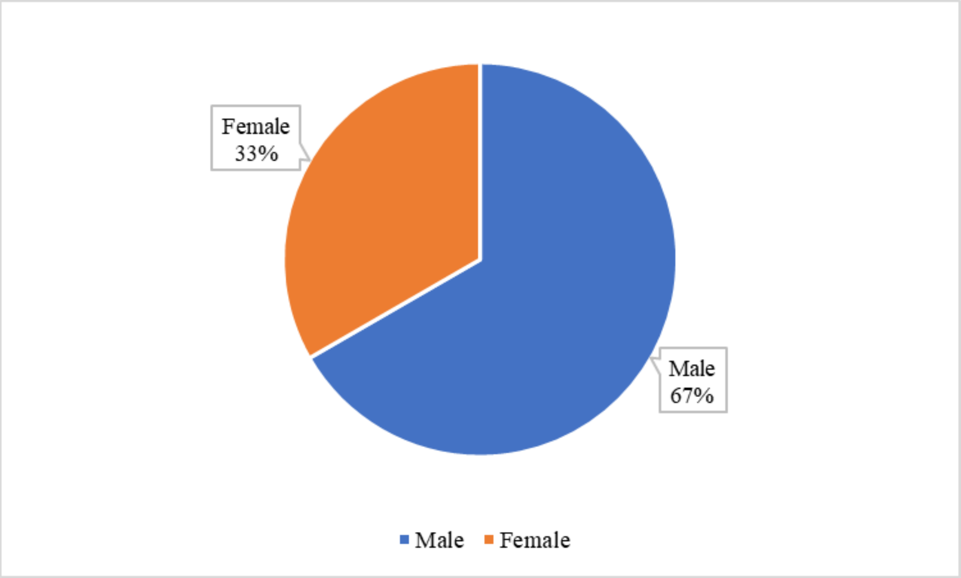


Figure 7.38 Gender of respondents.

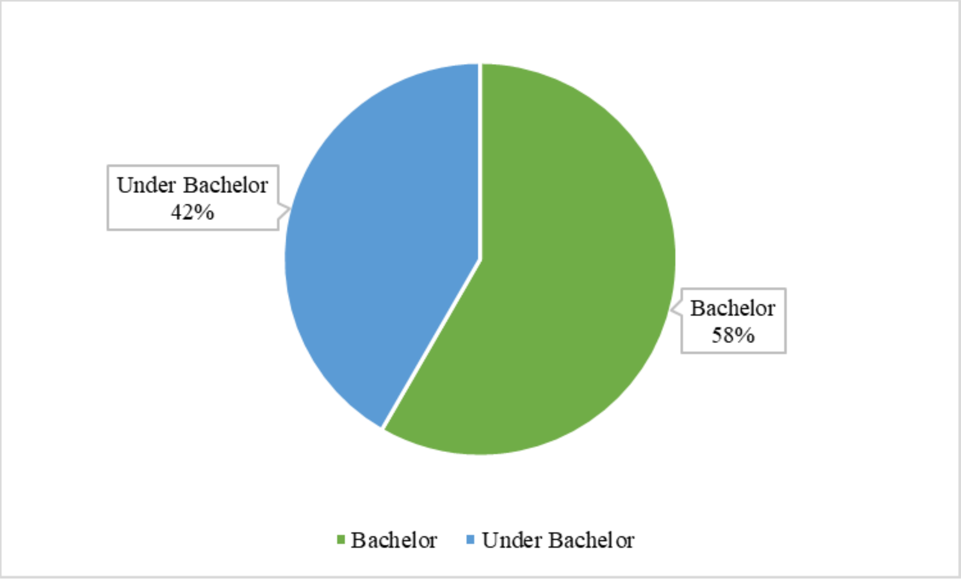


Figure 7.39 Educational level of respondents.

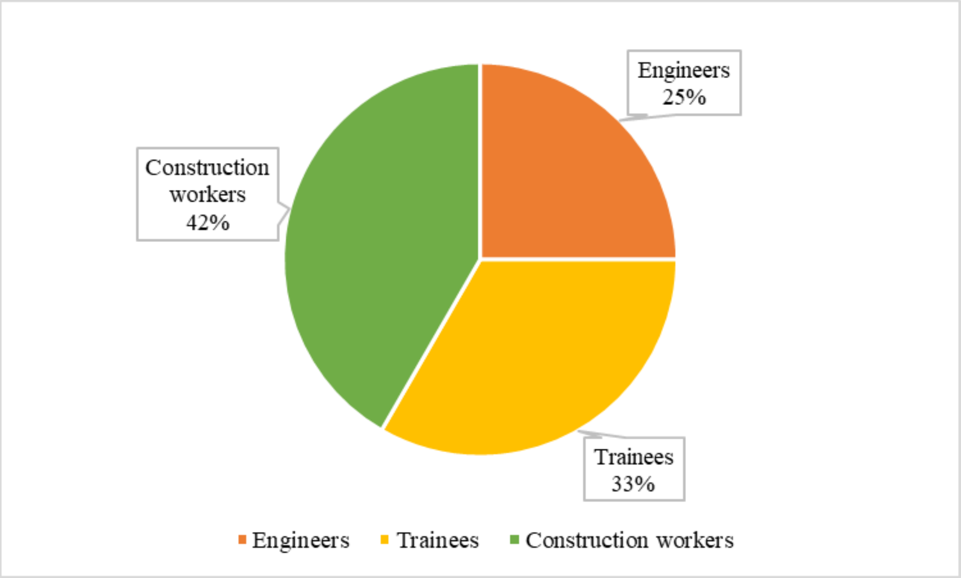


Figure 7.40 Job position of respondents.

The third part of the questionnaire asked the respondents how they evacuated from the construction project during an emergency by implementing the proposed system to experiment with the real construction project, as shown in Figure 7.41 to Figure 7.42. The respondents indicated they could easily perceive, understand, and execute the evacuation route by following the output as real-time access to information with the user in real-world scenes, as demonstrated in Figure 7.43 to Figure 7.44.

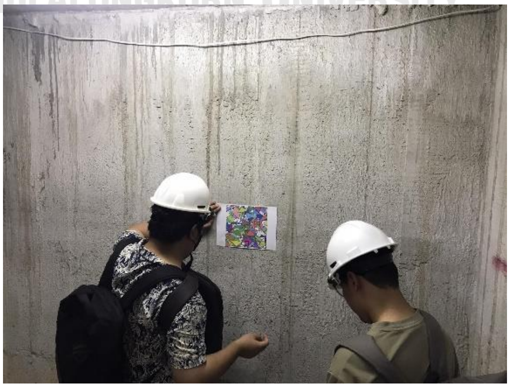


Figure 7.41 Installation of markers in the construction project.

(a) (b)

Figure 7.42 Implementation of the proposed system in the construction project.

Figure 7.43 Example of the output of the proposed system for respondent number 1 in the case of the 1st floor.

Figure 7.44 Example of the output of the proposed system for respondent number 2 in the case of the 1st floor.

Figure 7.45 Example of output of the proposed system for respondent number 3 in the case of the 2nd floor.

Figure 7.46 Example of the proposed system for respondent number 4 in the case of the 3rd floor.

The fourth part of the questionnaire dealt with evaluating the proposed system, where the respondents were asked to provide a score with a rating scale with five scales associated with the system's performance in eight questions. The meaning of the five scales consisted of 1 = very poor, 2 = poor, 3 = moderate, 4 = good, 5 = very good. The results of this part are presented in Table 7.6.

Table 7.6 Results of the evaluation of the proposed system by the respondents.

Question No.	Content	Average Score
1	I felt that the proposed system aided the perception of the evacuation route in the construction project.	3.25
2	I felt that the proposed system aided the perception of the appropriate evacuation route and could avoid obstacles.	3.33
3	I felt that the proposed system aided in understanding the evacuation route in the construction project.	3.25
4	I felt that the proposed system aided in understanding the appropriate evacuation route and could avoid obstacles.	3.08
5	I felt that the proposed system aided the execution of the evacuation route in the construction project.	3.00
6	I felt that the proposed system could provide appropriate access information.	3.00
7	I felt that the proposed system could evacuate from emergency situation	3.08
8	I felt confident about implementing this proposed system in my construction project.	3.17

Table 7.6 presents the results of the evaluation of the proposed system following the performance of the system to support the respondents in evacuating from hazardous locations in the construction project were approximately equal to 3.15/5.0, which means that the proposed system was moderate in terms of assisting and improving their decision-making process. In contrast, most respondents had moderate confidence in implementing the proposed system in their construction project.

In addition, the proposed system was evaluated by comparing it with the conventional method of the fire evacuation system, which used 2D drawings and fire exit signs based on the paper format. The respondents were also asked to rate with a rating scale of five scales the performance of the proposed system compared to the traditional method in seven questions. The meaning of the five scales consisted of 1 = totally disagree, 2 = disagree, 3 = moderate, 4 = agree, 5 = totally agree. The results of this part are presented in Table 7.7.

Table 7.7 Comparison results between the proposed system and the conventional method.

Question No.	Content	Average Score
1	I felt that the proposed system aided the perception of the evacuation route in the construction project **better** than the conventional method.	3.00
2	I felt that the proposed system aided the perception of the appropriate evacuation route and could avoid obstacles **better** than the conventional method.	3.17
3	I felt that the proposed system aided in understanding the evacuation route in the construction project **better** than the conventional method.	3.17
4	I felt that the proposed system aided in understanding the appropriate evacuation route and could avoid obstacles **better** than the conventional method.	3.33
5	I felt that the proposed system aided the execution of the evacuation route in the construction project **better** than the conventional method.	3.08
6	I felt that the proposed system could provide appropriate access information **better** than the conventional method.	3.17
7	I felt the proposed system could evacuate from emergency situations **better** than the conventional method.	3.17

Table 7.7 presents the comparison results of the evaluation of the proposed system following the performance of the system compared with the conventional method to support the respondents in evacuating from hazardous locations in the construction project were approximately equal to 3.17/5.0, which means that in the respondents' opinion, the proposed system can perceive, understand and improve their decision-making process better than the conventional method.

7.4 Discussion of the feasibility of the proposed system implementation

According to the experiment of the proposed system in the real environment and the construction project, the feasibility of the implementation in real practices was analyzed as described below.

The major benefit of this developed communication system is demonstrated by using visualization technology tools such as Building Information Modeling (BIM) and Augmented

Reality (AR) to provide the evacuation route in the dynamic nature of the construction project. It may guide the route of the material handling to support the decision-making of construction workers and staff unfamiliar with the route in the construction project. Therefore, the proposed system is feasible to implement in the BIM authoring process, which requires As-built construction drawings for understanding the position and exit information to create a virtual model in the virtual environment of the construction project. Likewise, a marker-based location process for spatial links displays the physical location and virtual information. Moreover, it can identify the user's location in the construction project to provide the evacuation route from the current location. However, it is difficult to identify the current location without scanning the marker and none of the internet. Although the problem of identifying and tracking the current user location can be created using CCTV cameras, it is an expensive and time-consuming installation. In addition, the application authoring process provides information for evacuating and guides the route of the material handling in the construction project; none of the tools can provide the visualization of the evacuation route and route for material handling in the construction project.

Although this system did not require resources, such as time and cost, as much as CCTV cameras to monitor and identify the user’s location in the construction project, the requirements of expertise in computer programming still existed.

7.5 Conclusion

The proposed system was tested in both the laboratory and the real environment to verify, and the developed algorithms were also tested. The information with the user’s augmented views, such as a virtual green line, voice and arrow direction, exit, distance from the current location to the exit, and the appropriate evacuation route in case of obstacle avoidance, was provided in a real-world scene via mobile phones. The results of the system verification showed that the proposed system could generate the correct real-time access information for testing case studies in the laboratory and the real environment.

As part of system validation, a high-rise building construction project was selected as a sample project, and four staff members, consisting of engineers, trainees, and construction workers, were chosen to be the subjects for testing. The questionnaires were applied to collect information on the respondents' demographic and background information regarding the evacuation system in the construction project. Then, the proposed system was implemented in the sample construction project according to the case study. The output for each case study was provided to the respondents, who were required to evaluate the performance of the proposed system. In addition, the proposed system was compared with the conventional evacuation system method, which used 2D drawings and fire exit signs based on the paper format in this construction project. The evaluation results indicated that the proposed system could perceive, understand, and improve their decision-making process. Finally, the feasibility of the proposed system implementation in the current practice was discussed.

Chapter 8

Research Conclusion and Recommendations

8.1 Conclusion of overall research

Communication is the heart of implemented projects. The construction process requires collaboration between people, and the contractor should be able to communicate in a clear and understandable platform between the receiver and sender. Communication is one of the most critical factors contributing to success because of the numerous parties involved working together and addressing the issues occurring on projects.

Construction is a high-hazard industry comprising a wide range of construction activities. The construction phases record high accidents compared to other phases. Because the characteristics of construction projects are extremely complex and often occur in an uncontrolled, unprepared, and dynamic environment where each project goes through several phases leading to completion continuously changed workplaces, the number of occupants, spaces, and evacuation routes change from one day to another. In the current practice, the construction project has one party responsible for monitoring and controlling the safety of the construction project. In an emergency, that party cannot control the communication system with stakeholders and provide the information to evacuate from the hazardous area directly and in real-time, which leads to injuries and casualties. However, the current communication system is not appropriate for the dynamic nature of the construction project and cannot provide the information for daily evacuation.

The convention evacuation plan also has limitations, and it still needs to be improved. Most construction projects have emergency exit signs, but these emergency signs are not enough to reach a safe place and are not installed in every position on every floor. Some fire exit signs were unclear and could not be modified according to the construction progress, which could have resulted in construction workers and staff not knowing the appropriate evacuation route. Furthermore, fire exit signs and evacuation plans may show the shortest route to the assembly point, but these routes are not considered risk locations, such as the obstacle location.

Therefore, the problem of the construction project has a non-interactive communication system as real-time communication will be solved by proposing a new communication system that can efficiently reduce potential hazards in the construction project by automatically generating appropriate evacuation routes as an effective tool is needed to support decision-making and enable construction workers and staff to perceive and understand information clearly and efficiently for evacuation purposes to assist common users in the evacuation process.

In order to explore the current practices, problems, and limitations of the fire emergency procedures in construction projects, Walk-in construction site surveys were performed to capture a fire emergency procedure. Photography and video recording were implemented. Most of the observed construction projects did not fully implement an evacuation system to reduce the number of injuries and fatalities in construction projects. In addition, the problems discovered from the site observation were that evacuation routes in construction drawings are insufficient to identify hazardous areas and evacuation routes. Consequently, the problem with the current evacuation plan is that it is not updated with the construction work schedule and environment, and being stuck by an object obstructed by materials and equipment would be improved by providing the appropriate evacuation route via the mobile application.

The proposed system concept was initiated from these mentioned problems and supported by a literature review. The proposed system, which was named The Self Care using Technology Evacuation System (SCT Evacuation System), was used to improve the decision-making process and provide information for evacuating and guidelines on the route for material handling to direct construction workers and staff in the construction project. The three elements, which consisted of 1) BIM authoring, 2) A marker-based location, and 3) Application authoring, were developed in this system.

The development and implementation of this system required a preparation process that included hardware and software. A laptop computer, mobile phone, and markers were prepared. The development system used for developing the application consisted of Microsoft Visual Studio and C# language. Likewise, AutoCAD software generated the construction project's two-dimensional (2-D) drawings. Then, the dimensional (3-D) model was created using Autodesk Revit software. The dimensional (3-D) model was saved in the Industry Foundation Classes (IFC) file format. The model was then exported to the Autodesk Naviswork (NWD) file format and saved in the Autodesk Filmbox (FBX) file format, making it suitable for data exchange between different BIM authoring software applications. Finally, the FBX file format was integrated into the Unity game engine with the assigned textures. Furthermore, a database containing information, such as user information, number of users, and status of users, including the coordination and sizing of the obstacle, was created using Firebase and Google spreadsheet, respectively.

This research applied the advantage of visualization techniques in order to improve fire safety management. Consequently, the proposed calculation and algorithm were developed to provide the information for evacuating and guideline the route for material handling to construction workers and staff from hazardous locations in construction projects. Firstly, the identification of users algorithm identifies each user who enters and exits the construction project and updates information in real-time. Secondly, the shortest evacuation route was calculated, which applied the A* algorithm formula. Thirdly, the shortest virtual evacuation route algorithm was classified as the shortest virtual evacuation route on a real-world scene. Fourth, the voice and arrow direction algorithms, which were classified into two types based on the scenario, consisted of 1) the voice direction algorithm and 2) the arrow direction algorithm. Fifth, the real-time obstacle avoidance algorithms, which were classified into two types based on the scenario, consisted of 1) the real-time obstacle avoidance algorithm to synchronize data on the Google spreadsheets and 2) the real-time obstacle avoidance algorithm for identifying and updating the position of materials and temporary works in the construction project. Lastly, the material handling route algorithm, which was classified into two types based on the construction work schedule, consisted of 1) The real-time material handling route algorithm to synchronize work schedule data on the Google spreadsheets and 2) the route of material handling algorithm for identifying and updating the construction activities and route of material handling followed the construction work schedule in daily. The proposed calculation and algorithm were implemented with the prototype application.

The Self Care using Technology Evacuation System (SCT Evacuation System) consists of three elements containing six algorithms to perform real-time evacuation functions at the construction project. Firstly, a BIM was authorized to design and enhance the interpretation and understanding of construction workers and staff regarding the evacuation route and to select appropriate evacuation routes in the construction project. This element was developed to generate and display the user's location in the virtual environment and superimpose 2D and 3D computer graphics onto real-world scenes. Thus, the following four sub-elements consist of a 3D architectural model of the building generated using Autodesk Revit 2022 based on as-built drawings. Therefore, the room and exit locations in the 3D model are the same as in the real world. Then, it is exported to the Autodesk Naviswork (NWD) file format, saved in the Autodesk Filmbox (FBX) file format, and linked to the FBX model and the Unity game engine. In addition, this element adopted a previously developed method of linking a digital model to support integrating the information in the 3D model, including 3-D rendering, physics, and collision detection.

Secondly, The developed marker-based location system utilizes a marker as a spatial index to connect physical locations with virtual information. The system functions as follows: Firstly, the camera captures an image with a marker on the mobile device. The image is then forwarded to the classifier algorithm, which is designed to classify data into different categories or classes and assumes a relatively balanced distribution of classes to create the marker ID by generating the code. Then, the marker code is sent to the database as a key value to look for associated information. Next, the system sets the location and direction in the virtual environment. However, the system does not display any data if the code is not recognized in the database. As the mobile device moves, the system transmits updated data concerning the location and direction to the real world in real-time. The system does not update any data if the mobile device has not moved.

Lastly, application authoring provides real-time information, such as the user's current location, which calculates the distance to the exit via a virtual green line. The system also provides voice and arrow directions to evacuate and guidelines for the route of material handling guidance, virtual green line, exit, and the distance from the current location to the exit. In addition, it recommends the appropriate evacuation route in case of obstacle avoidance for construction workers and staff.

Then, three elements contain six algorithms developed functions in the system, which present real-time information such as voice and arrow directions for evacuation and the route of the material handling guidance, virtual green line, exit, and distance from the current location to the exit, including the appropriate evacuation route in case of obstacle avoidance, were verified in both the virtual and the real environment. The proposed system was tested to verify its accuracy and demonstrated that it could satisfactorily provide the results, which were the information to evacuate to construction workers and staff in the construction project.

For validation, the proposed system was implemented with a real construction project, which was the construction project of a high-rise engine building. The twelve project participants, three engineers, four trainees, and five construction workers with experience in fire emergency procedures who worked on this construction were selected to be the samples. The questionnaires were used to collect data on the respondents' demographic and background information regarding the fire evacuation system in the construction project and to evaluate the proposed system. The subjects were required to consider the four case studies regarding the evacuation route in the construction project by using a text-based paper format to investigate the feedback between the before and after use of the proposed system in the construction project. After that, the outputs of the proposed system of each case study were provided to them for answering the questionnaires. The questionnaire results demonstrated that the proposed system could better perceive, understand, and improve their decision-making process than the conventional method. In addition, most respondents had moderate confidence in implementing this proposed system in their construction projects. Lastly, the feasibility of implementing the proposed system in the current practices at the construction project was discussed. In order to apply this system in the BIM authoring process, the design and development process is feasible. Moreover, a new communication system could support monitoring and identifying the user's location in the construction project.

8.2 Applications and benefits of the proposed system

The Self Care using Technology Evacuation System (SCT Evacuation System) can improve the decision-making process and provide information for evacuating and guidelines for the route for material handling at construction projects. This system can create and provide real-time access to information for evacuating and guideline the route for the material handling to construction workers and staff in construction projects by tracking a marker. The user can observe evacuation and get the appropriate route guidance representing information such as voice and arrow directions for evacuation and guideline the route guidance via the virtual green line, provide the exit and distance from the current location to the exit, including the appropriate evacuation route in case of obstacle avoidance. The following six algorithms were developed:

1. The Identification of Users
    - 1.1 Identify each user who enters and exits the construction project and updates information in real-time
2. The shortest evacuation route
    - 2.1 Present the shortest evacuation route
3. The shortest virtual evacuation route
    - 3.1 Display the exit object in green color
    - 3.2 Display the distance of the shortest evacuation route
    - 3.3 Render the shortest virtual evacuation route
4. The voice and arrow direction
    - 4.1 The voice direction
        - 4.1.1 Indicate the direction to the construction workers and staff when there is low visibility due to haze obstructing vision.
    - 4.2 The arrow direction
        - 4.2.1 Displays the arrow direction images on their mobile phones.
5. The real-time obstacle avoidance
    - 5.1 The real-time obstacle avoidance algorithm to synchronize data on the Google spreadsheets
        - 5.1.1 An online update capability to keep the fire evacuation routes up-to-date and display information following the changing construction project environment.
    - 5.2 The real-time obstacle avoidance
        - 5.2.1 Display the appropriate fire evacuation route
6. The material handling route
    - 6.1 The real-time material handling route algorithm to synchronize work schedule data on the Google spreadsheets

6.1.1 An online update of the construction activities followed by the construction schedule and display information following the changing construction project environment

6.2 The route of material handling

6.2.1 Display the appropriate material handling route

8.3 Research contributions

The research contributions comprise the following:

1) The output will be a new communication system considering the evacuation route, voice and arrow directions, and obstacle avoidance.

2) The algorithm developed for the evacuation system can be used in the dynamic nature of the construction project.

8.4 Recommendations and Limitations

The recommendations and limitations comprise the following:

1) The proposed system was developed to improve the decision-making process, provide information for evacuation, and guide the evacuation route in construction projects. Other types of construction projects were not included in this development.

2) The proposed system was developed in the individual laptop computer environment and was connected to the network for sharing information, such as using a database and Google spreadsheet.

3) A marker-based location system was applied in this development. Thus, the marker had to be captured all the time in order to run the system.

4) Some input data were required by the user, such as the user’s data and the coordination and sizing of the obstacle.

5) Other factors that may influence the evacuation process are the quality of the markers used, the internet signal, and the accuracy of the location-tracking technology.

8.5 Future research

Future research comprises the following:

1) An advanced device for measuring and tracking data, such as a 3D Laser Scanner and CCTV, should be applied to future research. Moreover, factors such as the internet signal and light should be included; therefore, all factors impacting the real-time evacuation system can be integrated.

2) At this time, more types of sensors can be embedded into future research, including smoke and flammable sensors, to prevent the system from selecting the next exit, which is safe from the smoke and fire area, and provide information to the user.

3) The concept of the proposed system can be applied to construction projects in other civil engineering domains, such as low-rise buildings and infrastructure. The system can benefit other construction projects, such as condominiums, office buildings, museums, hotels, and hospitals, where many common users cannot interpret the 2D drawing quickly.

Appendix A

Questionnaires form

แบบสอบถามเกี่ยวกับระบบสื่อสารเพื่อสนับสนุนเส้นทางอพยพในโครงการก่อสร้างอาคาร

คำชี้แจง :

แบบสอบถามฉบับนี้เป็นเครื่องมืองานวิจัยเรื่อง"ระบบสื่อสารเพื่อสนับสนุนเส้นทางอพยพในโครงการก่อสร้างอาคาร" โดยข้อมูลที่ได้จากแบบสอบถาม เพื่อนำไปใช้ในการทดสอบการพัฒนาระบบต้นแบบของงานวิจัย โดยความรู้ที่ได้จากงานวิจัยจะเป็นแนวทางในการพัฒนาสำหรับอุตสาหกรรมก่อสร้างในประเทศไทยต่อไป ทั้งนี้ผู้วิจัยขอรับรองว่าข้อมูลที่ได้รับจะนำเสนอเป็นภาพรวมโดยที่ไม่นำเสนอผลเป็นรายบุคคล (ข้อมูลจะถุกปิดเป็นความลับและใช้เฉพาะในงานวิจัยนี้เท่านั้น)

ขอขอบพระคุณเป็นอย่างสูงที่ให้ความร่วมมือเป็นอย่างดีมา ณ ที่นี้ด้วย

แบบสอบถามฉบับนี้แบ่งเป็น 6 ส่วน ประกอบด้วย
ส่วนที่ 1 ข้อมูลส่วนบุคคล
ส่วนที่ 2 คำถามเกี่ยวกับเกี่ยวกับการจัดการด้านอพยพหนีไฟในโครงการปัจจุบัน
ส่วนที่ 3 ทดสอบการจัดการด้านอพยพหนีไฟ จากสถานการณ์สมมุติ (ก่อนใช้ระบบ)
ส่วนที่ 4 ทดสอบการจัดการด้านอพยพหนีไฟ จากสถานการณ์สมมุติ (หลังใช้ระบบ)
ส่วนที่ 5 การประเมินระบบต้นแบบที่พัฒนาขึ้น เพื่อสนับสนุนการอพยพหนีไฟในโครงการก่อสร้าง
ส่วนที่ 6 การประเมินเปรียบเทียบระหว่างระบบต้นแบบที่พัฒนาขึ้นและวิธีการดั้งเดิม

ส่วนที่ 1 : ข้อมูลส่วนบุคคล

ชื่อ-นามสกุล ....

อายุ (ปี) ....

เพศ ....

ระดับการศึกษา ....

ตำแหน่ง ....

ประสบการณ์ในการทำงาน (ปี) ....

ประสบการณ์ในการทำงานอาคาร (ปี) ....

ส่วนที่ 2 คำถามเกี่ยวกับเกี่ยวกับการจัดการด้านอพยพหนีไฟในโครงการปัจจุบัน

1. ในโครงการของท่าน มีการใช้เครื่องมือใดในกระบวนการจัดการด้านอพยพหนีไฟ

☐ 2D-Drawing

☐ Building Information Modeling (BIM)

☐ Augmented Reality (AR)

☐ Virtual Reality (VR)

☐ สัญลักษณ์ป้ายทางหนีไฟ

☐ ไม่มี

2. ท่านคิดว่า ควรมีวิธีการสำหรับช่วยในการอพยพหนีไฟ โดยการนำเทคโนโลยี BIM และ AR มาประยุกต์ใช้ หรือไม่ อย่างไร

....

....

....

....

....

3. ท่านคิดว่า "หากมีการพัฒนาเครื่องมือที่ช่วยในการอพยพคนงานและผู้ที่เกี่ยวข้องจากเหตุการณ์ไฟไหม้ในโครงการก่อสร้างแบบเรียลไทม์" จะสามารถช่วยลดจำนวนของผู้บาดเจ็บหรือเสียชีวิตในโครงการก่อสร้างได้หรือไม่

☐ ได้

☐ ไม่ได้

☐ ไม่แน่ใจ

ส่วนที่ 3 ทดสอบการจัดการด้านอพยพหนีไฟ จากสถานการณ์สมมุติ (ก่อนใช้ระบบ)

1. ท่านสามารถรับรู้ เส้นทางการอพยพหนีไฟ ในโครงการก่อสร้างหรือไม่

☐ ทราบ

☐ ไม่ทราบ

☐ ไม่แน่ใจ

2. ท่านคิดว่า เมื่อเกิดเหตุไฟไหม้ ท่านจะสามารถอพยพหนีไฟในเส้นทางที่อพยพได้ถูกต้อง

☐ ทราบ

☐ ไม่ทราบ

☐ ไม่แน่ใจ

3. ท่านคิดว่า ป้ายอพยพหนีไฟในโครงการก่อสร้าง เพียงพอสำหรับช่วยในการอพยพหรือไม่

☐ เพียงพอ

☐ ไม่เพียงพอ

ส่วนที่ 4 ทดสอบการจัดการด้านอพยพหนีไฟ จากสถานการณ์สมมุติ (หลังใช้ระบบ)

1. ท่านสามารถรับรู้ เส้นทางการอพยพหนีไฟ ในโครงการก่อสร้างหรือไม่

☐ ทราบ

☐ ไม่ทราบ

☐ ไม่แน่ใจ

2. ท่านคิดว่า เมื่อเกิดเหตุไฟไหม้ ท่านจะสามารถอพยพหนีไฟในเส้นทางที่อพยพได้ถูกต้อง

☐ ทราบ

☐ ไม่ทราบ

☐ ไม่แน่ใจ

3. ท่านคิดว่า ป้ายอพยพหนีไฟในโครงการก่อสร้าง เพียงพอสำหรับช่วยในการอพยพหรือไม่

☐ เพียงพอ

☐ ไม่เพียงพอ

ส่วนที่ 5 การประเมินเปรียบเทียบระหว่างระบบต้นแบบที่พัฒนาขึ้นและวิธีการดั้งเดิม

กรุณาให้ประเมินระบบต้นแบบที่พัฒนาขึ้น ตามความเห็นของท่าน โดยระดับคะแนนมีความหมายดังนี้

ระดับคะแนน 1 หมายถึง แย่

ระดับคะแนน 2 หมายถึง ค่อนข้างแย่

ระดับคะแนน 3 หมายถึง ปานกลาง

ระดับคะแนน 4 หมายถึง ดี

ระดับคะแนน 5 หมายถึง ดีมาก

คำถาม	5	4	3	2	1
1.ระบบช่วยให้ท่าน **รับรู้** เส้นทางการอพยพหนีไฟได้					
2. ระบบช่วยให้ท่าน **รับรู้** เส้นทางการอพยพหนีไฟที่เหมาะสมจากสิ่งกีดขวางในโครงการก่อสร้าง					
3. ระบบช่วยให้ท่าน **เข้าใจ** เส้นทางการอพยพหนีไฟได้					
4. ระบบช่วยให้ท่าน **เข้าใจ** เส้นทางการอพยพหนีไฟที่เหมาะสมจากสิ่งกีดขวางในโครงการก่อสร้าง					
5. ระบบช่วยให้ท่าน สามารถตัดสินใจเลือก เส้นทางการอพยพหนีไฟที่ถูกต้อง					
6. ระบบสามารถให้ข้อมูลเกี่ยวกับการอพยพหนีไฟได้อย่างเหมาะสม					
7. ระบบสามารถช่วยท่านอพยพหนีไฟในโครงการก่อสร้างได้					
8. ท่านมีความเชื่อมั่นในการนำระบบไปใช้ เพื่อจัดการเรื่องการอพยพหนีไฟในโครงการก่อสร้าง ในระดับใด					

ส่วนที่ 6 การประเมินเปรียบเทียบระหว่างระบบต้นแบบที่พัฒนาขึ้นกับการใช้สัญลักษณ์ป้ายหนีไฟ รูปแบบ 2 มิติ

กรุณาให้ประเมินระบบต้นแบบที่พัฒนาขึ้น ตามความเห็นของท่าน โดยระดับคะแนนมีความหมายดังนี้

ระดับคะแนน 1 หมายถึง แย่

ระดับคะแนน 2 หมายถึง ค่อนข้างแย่

ระดับคะแนน 3 หมายถึง ปานกลาง

ระดับคะแนน 4 หมายถึง ดี

ระดับคะแนน 5 หมายถึง ดีมาก

คำถาม	5	4	3	2	1
1.ระบบช่วยให้ท่าน **รับรู้** เส้นทางการอพยพหนีไฟได้ <u>ดีกว่า</u> การใช้สัญลักษณ์ป้ายหนีไฟรูปแบบ 2 มิติ					
2. ระบบช่วยให้ท่าน **รับรู้** เส้นทางการอพยพหนีไฟที่เหมาะสมจากสิ่งกีดขวางในโครงการก่อสร้าง <u>ดีกว่า</u> การใช้สัญลักษณ์ป้ายหนีไฟรูปแบบ 2 มิติ					
3. ระบบช่วยให้ท่าน **เข้าใจ** เส้นทางการอพยพหนีไฟได้ <u>ดีกว่า</u> การใช้สัญลักษณ์ป้ายหนีไฟรูปแบบ 2 มิติ					
4. ระบบช่วยให้ท่าน **เข้าใจ** เส้นทางการอพยพหนีไฟที่เหมาะสมจากสิ่งกีดขวางในโครงการก่อสร้าง <u>ดีกว่า</u> การใช้สัญลักษณ์ป้ายหนีไฟรูปแบบ 2 มิติ					
5. ระบบช่วยให้ท่าน สามารถตัดสินใจเลือก เส้นทางการอพยพหนีไฟที่ถูกต้อง <u>ดีกว่า</u> การใช้สัญลักษณ์ป้ายหนีไฟรูปแบบ 2 มิติ					
6. ระบบสามารถให้ข้อมูลเกี่ยวกับการอพยพหนีไฟได้อย่างเหมาะสม <u>ดีกว่า</u> การใช้สัญลักษณ์ป้ายหนีไฟรูปแบบ 2 มิติ					
7. ระบบสามารถช่วยท่านอพยพหนีไฟในโครงการก่อสร้างได้ <u>ดีกว่า</u> การใช้สัญลักษณ์ป้ายหนีไฟรูปแบบ 2 มิติ					

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