# A System for Generating Fire Extinguisher Plan and Supporting Fire Evacuation Route in Construction Project

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ในช่วงระยะเวลาที่ผ่านมาพบว่า การเกิดไฟไหม้ในโครงการก่อสร้างสร้างผลกระทบต่อคนงานเป็นจำนวนมาก เนื่องจากลักษณะของโครงการก่อสร้างอยู่ในรูปแบบพลวัต ทำให้แผนการป้องกันและระงับอัคคีภัยจำเป็นต้องมีการปรับปรุงและอัพเดทตามความคืบหน้าของแผนงานก่อสร้าง ปัจจุบันรูปแบบการจัดการเพื่อพัฒนาแผนการป้องกันและระงับอัคคีภัยในโครงการก่อสร้างใช้ระยะเวลาและคนงานจำนวนมาก รวมถึงการติดตั้งป้ายทางออกทางหนีไฟในโครงการก่อสร้างที่ไม่ชัดเจนและแสดงเส้นทางการอพยพที่ไม่ถูกต้อง เนื่องจากลักษณะของโครงการก่อสร้างที่เปลี่ยนแปลงตามแผนงานก่อสร้าง เทคโนโลยีแบบจำลองสารสนเทศอาคารและยูนิตี เอนจิน สามารถแสดงวัตถุในรูปแบบ 3 มิติและนำเสนอรูปแบบการสร้างแบบจำลองตามมาตรฐาน ดังนั้นในงานวิจัยนี้มีวัตถุประสงค์เพื่อนำเสนอกรอบการพัฒนาแผนการป้องกันและระงับอัคคีภัยต้นแบบ เช่น แผนการติดตั้งถังดับเพลิงและแผนการอพยพหนีไฟ เป็นต้น รวมถึงพัฒนาแอพพลิเคชั่นสำหรับช่วยพนักงานดับเพลิงและคนงานในระหว่างกระบวนการกู้ภัยและอพยพ โดยคำนึงถึงลักษณะของโครงการก่อสร้าง จากการศึกษาพบว่ากรอบการพัฒนาแผนการป้องกันและระงับอัคคีภัยต้นแบบ ทำให้ผู้ใช้งานสามารถกำหนดพารามิเตอร์สำหรับแผนการติดตั้งถังดับเพลิงและแผนการอพยพ เช่น วัตถุที่ก่อสร้างแล้วแสร็จและวัตถุที่อยู่ระหว่างการก่อสร้าง ทางออก ตำแหน่งของถังดับเพลิงและสารไวไฟ เป็นต้น รวมถึงนำเสนอตำแหน่งการติดตั้งถังดับเพลิงที่เหมาะสม พื้นที่ไม่ปลอดภัย และเส้นทางอพยพที่ไวที่สุดในแผนการป้องกันและระงับอัคคีภัย รวมถึงแอพพลิเคชั่นสามารถแสดงเส้นทางการอพยพที่ไวที่สุด รายงานผู้อพยพและแจ้งตำแหน่งที่ผู้อพยพติดค้างอยู่ในโครงการก่อสร้างได้ โดยงานวิจัยนี้ได้ทำการตรวจสอบความถูกต้องของกรอบการพัฒนาแผนการป้องกันและระงับอัคคีภัยต้นแบบ จากการร่วมประเมินและทดสอบของวิศวกร เจ้าหน้าที่ความปลอดภัยจำนวน 4 คนและเจ้าหน้าที่ของโครงการก่อสร้างจำนวน 11 คน ผ่านเทคโนโลยีแบบจำลองสารสนเทศอาคารและโครงการก่อสร้างจริง



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KEYWORD: Fire safety plan, Evacuation route, A* algorithm, Game engine, Fire safety rule and regulation

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Fires in under-construction threaten worker safety and have a lot of negative impacts on many aspects of construction that were reported the past few years. Due to the dynamic nature of construction, the fire safety plan in construction needed to be reviewed and updated according to construction progress. The conventional approach or manual process to develop the fire safety plan for a construction project can be a time-consuming and enormous labor-intensive task. Furthermore, some of the emergency signs are unclear due to the nature of construction and some are not showing the correct evacuation route because of the structural design change based on the construction progress. BIM technology and the Game engine can present the object in 3D and provide programming for rule-based modeling. Therefore, this paper proposes a framework to develop the fire safety plan (such as fire extinguisher installation plan (FEIP) and evacuation route plan) and mobile application to assist the firefighters and people who are involved in construction during the rescue and evacuation process by considering the dynamic nature of construction. This research develops the prototype that enables the users to define the parameters for the fire extinguisher installation plan and evaluation route such as finished and unfinished building objects (walls, stairs, and slabs), exists, the locations of fire extinguishers (FE), and flammable substances (FS). This prototype provides the appropriate locations of fire extinguishers, the unsafe area, and the fastest evacuation route for a fire safety plan and the mobile application that can show the fastest evacuation route, report safe arrival and inform the location where the evacuee is stuck. To validate the proposed approach, the case study using the sample BIM model and real construction BIM model is executed. Moreover, 4 safety engineers or officers and 11 construction personnel participate in evaluating the proposed system.

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Thiha Nyimin

# TABLE OF CONTENTS

**Page**

# LIST OF TABLES

## LIST OF FIGURES

**Page**

# CHAPTER 1

# Introduction

## 1.1 Background Information

The construction industry has a negative reputation in the occurrence of accidents, based on the Health and Safety Executive (HSE) statistics, and a construction site is considered as a hazardous and dangerous workplace. A construction site has numerous features that make its uncommon and unanticipated structure. In a construction environment, changing is one of the characteristics that make it unique compared to others. Not only the progress of the construction but also the types of machines, crews, materials used and location are involved in the changes of a construction project, on a daily basis. Construction site workers have to adjust to these changing environments as well as the constantly altered obstacles and risky locations on site.

It is stated in HSE that 111 workers have lost their lives at work in the year 2019/2020. Regarding the statistical data shown in Figure 1.1, 40 deceased workers are from construction sites and it can be seen that the death rate of construction workers is the highest of all industries. As the survey also focuses on what is affecting the number of death as well as the injuries, the 86% of them are resulted from the following factors:

- one's balance and collapse from the building or structure
- confinement from collapse of objects and other materials
- hit forcibly by a moving vehicle or other implements
- electric shock.

Another 10% comes from:

- collapse and stumbles due to objects or slippery conditions on the same level
- wounds and bruises resulting from transporting or operating devices and materials
- falls from a high place
- harms from falling objects, which also involve hovering or dropping ones.

In the reports of the Federal Emergency Management Agency (FEMA) of the United States (US), about 4,800 fire accidents happen annually on construction sites. However, as regards the Occupational Safety and Health Administration (OSHA), surprisingly, fire in construction is not the main major source of death and injury while the number of workers, frequent occurrence, and the evacuation plan reflect the worker's safety. From the statistics of OSHA (2001), during a building construction, there exist other types of circumstances which are in need of immediate evacuation, such as crumbling building structures, weather changes, and earthquakes. Providing evacuation plans that can withstand the unforeseen encounters is crucial. To indicate an event in 2019, the evacuation of a high-rise construction site occurred due to the collision of a helicopter with a crane from a construction site because of the foggy weather. Therefore, large-scale construction sites should have a solid evacuation plan to ensure the safety of workers and timely emergency evacuation for whatever reason.

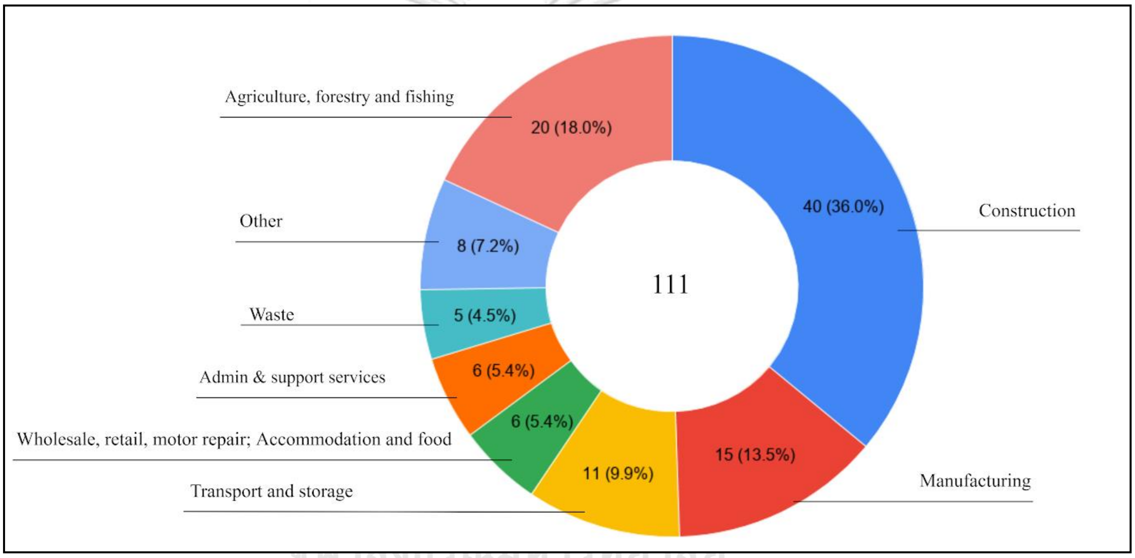



*Figure 1.1 Worker fatality rate from different industries*

Source: HSE (2020)

1.2 Problem Statement

As regards safety measures, an emergency, unexpected and dangerous circumstances that can cause a great impact on the surroundings and people are needed to be considered. In such cases, a quick and competent solution is necessary to guarantee the safety of all involved parties. To be specific, a suitable evacuation route plan and fire safety plan are needed to effectively evacuate people from a building before being exposed to the threat of loss or injury, in case of natural disasters or man-made destruction. This is necessary to consider, especially when it comes to complex and huge factories as well as high-rise constructions. Kim and Lee (2019) stated that planning the evacuation route in construction is challenging for individual workers, safety engineers and construction personnel since the construction sites are known to be active and mobile. The current practice depends solely on the personal intuition and experiences of safety engineers on organizing the construction site and arranging moving paths for construction workers, facilities, supplies and machines (Soltani et al., 2002). Choe and Leite (2017) have claimed that current practices of fire safety heavily rely on timely updates and reviews in the construction industry. Moreover, it can be quite time consuming and requires in-depth physical work if the safety planning is performed manually. Kim and Lee (2019) have presented that the fire safety planning involves several aspects to consider such as escape routes, firefighting equipment installation, and safety training to workers. In many building construction projects, feasible and modernized fire safety plans are not available.

According to FEMA of the United States (US), the number of the occurrence of fire accidents that happen annually on construction sites reaches about 4,800. The fire in construction is not the major factor of death but it can impact the construction duration and cost. Khan et al. (2020) has stated that construction burn lesions as well as explosions are liable accidents for equipment operators, electric technicians, carpentry trades, and HVAC mechanics. Moreover, it is undeniable that buildings that are still under construction have to depend on either fire extinguishers or temporary water storage tanks, as there are no adequate protection systems for fire incidents. Furthermore, current practice of safety procedures are inconvenient and mostly rely on manual mode with less consideration for people who are not familiar with the operating procedures, such as the positioning or placement of fire extinguishers in a specific building structure. Hence, it is a necessity to provide a user-friendly method with more creativity to approach this situation. The locations of fire extinguishers should be in a good position.

In this era, modern cities and high-rise buildings are inseparable due to an effort to get more commercial and residential space on accessible land resources. With the rising scale of project size and buildings, a considerably huge number of workers are in need during construction. This results in the evacuation during the construction phase of a high-rise building as one of the most complex works due to the dynamic character of construction progress and environments. It involves changing the building model or layout, location of material, and switching the workers, and many more. Moreover, the population of workers on-site and the height of the building can make the evacuation challenging. There are several challenges for a worker to achieve successful evacuation and the crucial factors are as follows:

(a) Changing building objects and the locations of various non-building objects (Galea et al., 2019)

During the construction phase, building objects (e.g., walls, columns, floors) and the locations of various non-building objects (e.g., workers, equipment, and temporary structures) are always changed with regard to the progress of construction. Whereas, in most of the construction sites, the emergency signs and emergency route maps are not adapted according to the changing of the physical environment. So, evacuees may face difficulties in making the decision to choose the evacuation route and escaping from the construction site.


*Figure 1.2 Constant changing connectivity*

Source: (Galea et al., 2019)

(b) Worker unfamiliarity with a construction environment (Galea et al., 2019)

There may be new workers and some workers who may need to work only a few days in a month in the construction site. Those workers may not be familiar with the building layout and cannot know the current construction environment. It points out that the evacuation route of those workers mainly depends on the evacuation signs. Some of the evacuation signs may not be installed or may not be obvious to the eye due to the construction works. In the case of unclear and improper evacuation route signs, those workers may face difficulties to leave the construction site in time.

*Figure 1.3 Obscure emergency exit sign on the construction site*

Source: (Galea et al., 2019)

(c) Lack of suitable Communication tools for emergency

The construction site of a high-rise building is reflected in the number of workers on-site and the population of workers is probably to be made up of many divergent nationalities. As a result, different communication languages may influence the workers' evacuation. In addition, there is no proper communication system for informing the fire locations to all of the workers. Due to the nature of construction, miscommunication may occur between the firefighters and workers when the latter send information about the locations that they are stuck.

(d) Different nature of the terrain (Deere et al., 2020)

In construction sites, different types of terrain (rebar and concrete floors, and temporary stairs and ladders are involved (Figure 1.4). So, the evacuees may make the wrong decision in selecting the evacuation routes. Moreover, the evacuation routes are less likely to provide a safe path for workers, involving the rebar floors or the temporary stairs and ladders that have steep slopes and narrow widths. These kinds of terrain have a negative impact on evacuation performance.


*Figure 1.4 Different types of terrain in construction site*

Moreover, the convention evacuation plan also has limitations and it still needs to be improved. All of the traditional emergency guidance plans (the emergency signs and evacuation route maps) are the static way of expression (Ma et al., 2017). The two-dimensional evacuation sketch maps are the current form of guideline for the construction of evacuation guidance, although this method has poor visibility. For the aspect of large buildings with complex structures, which also involve numerous safe exits as well as inconsistent fire points will have a direct effect on the choices of evacuation route (Lim and Rhee, 2010). Moreover, most of the construction has emergency exit signs but these emergency exit signs are not enough to reach a safe place. Moreover, these signs are not modified according to the construction progress. Those signs and maps may show the shortest route to reach the assembly point but these routes are not regarded as the risk locations and conditions of the surfaces that can affect the walking speed (rebar floor, temporary ladder, temporary stairs, and so on). So, traditional emergency guidance plans have no capability to show safe and time-saving routes.

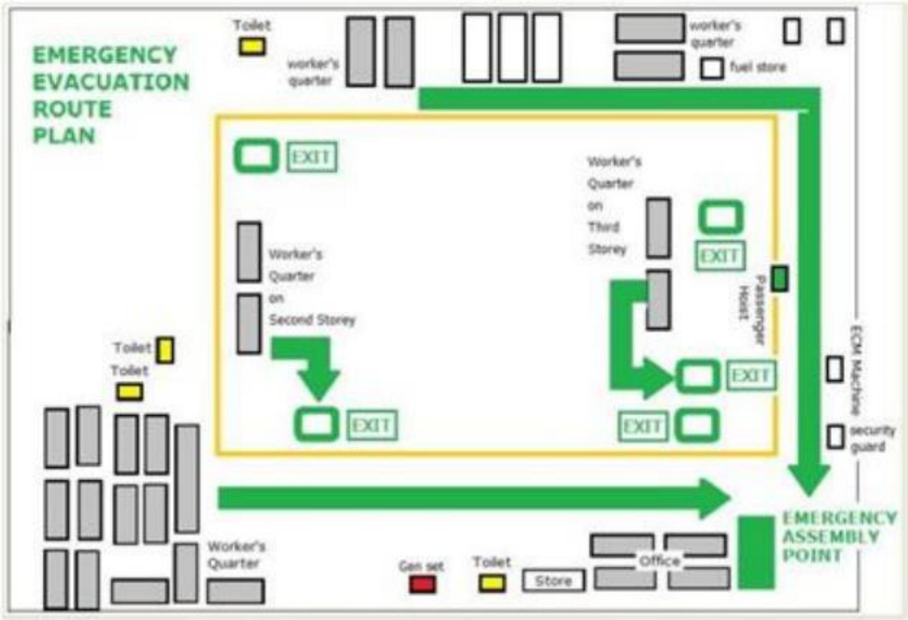



*Figure 1.5 Emergency evacuation route plan*

Regarding the health and safety handbook, the fire warden from the workplace needs to collect the number of people who are evacuated. In current practice, the assigned person has to collect the data manually with paper and the real-time data cannot be acquired for other authorities and the firefighters. The number and location of occupants are the main challenge for the resource deployment sector, also affecting the capability of firefighters in surveying the scene and rescuing tasks (Chou et al., 2019). The timeliness of rescue and evacuation is heavily downgraded by the lack of accurate and immediate instructions.



In this study, A new approach in planning the evacuation route system, that can effectively handle the dynamic nature of the construction site which has a direct influence on the evacuation route and different types of terrain that can impact the evacuation performance, will be created. Moreover, the problem of producing the suboptimal path in creating the evacuation route and human error in checking the fire safety plan will be solved by proposing a system that can efficiently reduce it by automatically generated evacuation routes and the fire safety plan. Furthermore, a mobile application will be built to assist the workers, safety engineers, construction personnel, and firefighters in the evacuation and communication process. For workers or people in the construction site, the mobile application can show the fire locations and the optimal evacuation routes (the fastest route among the safe routes) that are adapted to the real-time construction environment. In addition, the function allows workers to inform their safe arrival. The data of the workers' arrival can be viewed by many people simultaneously. The problem of miscommunication between evacuees and firefighters, regarding the locations of where the evacuees are stuck and the locations of fire, will be solved by displaying the specific locations in the mobile application.

## 1.3 Objectives of the study

The main objectives of this research are as follows;

- Develop a system that can be used as the generation and assessment of the fire extinguisher installation plan.
- Develop a system that can be used as the generation of the evacuation route plan
- Develop a mobile application that can assist the people who are in construction sites and firefighters, in case of an accident during construction.

## 1.4 Scopes of the study

This study mainly focuses on the following elements:

- The fire extinguisher installation plan and evacuation process in construction,
- Thailand rules and regulations and OSHA are applied.
- The update interval is daily.
- The three-dimension (3D) visualization technique is applied in the system development process.



## 1.5 Expected Research contribution

The main contribution of this research is as follows:

- The outcome will be a new evacuation route planning system that can consider not only the distance but also the velocity on different terrain.
- The developed algorithm for the fire extinguisher installation plan can be used in different types of building design.

# CHAPTER 2

## Literature Review

This section will discuss the previous research related to the fire safety plan and evacuation procedures, technology-aided evacuation plans and components of high-rise construction. Moreover, this chapter will share the knowledge about the usefulness of the building information model (BIM), conventional evacuation plans and components of high-rise construction. This section assists in identifying the theoretical framework and the scope or goal of the study, based on the previous research. The primary intention of this chapter is to search the methods and technology for the evacuation plan to achieve the objective.

### 2.1 Literature review relating to the fire safety plan and evacuation plan

#### 2.1.1 General emergency procedures for building crisis

During an emergency inside a building, it is important to find the nearest exit or alternate ones if it is blocked. Except for cases such as the hostage crisis, where a stay-in-place type of solution is crucial, it is best to leave the dangerous site immediately while the situations are still good. Unnecessary use of emergency phone calls can cause delays in delivering emergency resources to the most vulnerable places. Generally, the elevators are of no use when an emergency strikes, and hallways and stairs are the essential options.

#### 2.1.2 Regulations and guidelines relating to the evacuation plan

Nowadays, there are a lot of rules, regulations and guidelines for evacuation plans. The following facts highlight the requirements for the evacuation route:

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

❖ Regulation 31 (Emergency route and exit)

- Each emergency route or exit must be indicated by suitable signs.
- An emergency route or exit must lead as directly as possible to an identified safe area
- An emergency route or exit must be kept clear and free from obstruction.
- The number of exit routes must be adequate.

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

- Standard Number - 1926.150(c)(1)(i)
    - For every 3,000 square feet of the protected building area or a major fraction, a fire extinguisher rate which is not less than 2A shall be provided. Travel length shall not exceed 100 feet from any point of the protected area to the nearest fire extinguisher.
- Standard Number - 1926.150(c)(1)(i)
    - If more than 5 gallons of combustible liquids or 5 pounds of flammable gas are being used on the job site, a fire extinguisher with a rate not less than 10B, shall be provided within 50 feet of wherever. However, this does not apply to the integral fuel tanks of motor vehicles.

III. Ministerial Regulation No.33, BE 2535 (1992) (Thailand)

- Clause 19
    - High-rise buildings or special large-scale buildings must be equipped with handheld fire extinguishers which are of appropriate type and size to extinguish fire which occurs from the type of material used in each floor. On every floor, at least one fire extinguisher must be provided, located at every 1,000 square meters or less and at a maximum distance of 45.00 meters.
    - Fire extinguisher must contain at least 4 kilograms of chemicals. (e.g., 2A and 10B fire extinguishers)

2.1.3 Fire extinguisher classification

Every fire extinguisher has an alphanumeric rating that shows the fire class as well as the size of fire it can put out. According to the OSHA [standard number 1926.150(c)(1)(x)], the fire class and the appropriate fire extinguisher are shown in Table (2.1). The amount of fire that can be extinguished by a fire extinguisher is represented by numbers. Every number before the A is equally effective as the 1 ¼ gallon of water. To be exemplified, the fire extinguisher rating 2A represents the effectiveness of 2 ½ gallons of water. For Type B fire extinguishers, the numbers indicate the specific square feet they can cover in putting out the fire. For instance, a 10 square feet area of fire is covered by a 10B fire extinguisher. 2A:10B specifies that the fire extinguisher has an effect of 2½ gallon of water while being used on class A fire and can extinguish a fire over 10 sq ft when it is used on class B fire.

*Table 2.1 Fire class and fire extinguishers data*

| | WATER TYPE | | | | FOAM | CARBON DIOXIDE | DRY CHEMICAL | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | SODIUM OR POTASSIUM BICARBONATE | | MULIT-PURPOSE ABC | |
| | STORED PRESSURE | CARTRIDGE OPERATED | WATER PUMP TANK | SODA ACID | FOAM | CO2 | CARTRIDGE OPERATED | STORED PRESSURE | STORED PRESSURE | CARTRIDGE OPERATED |
| CLASS A FIRES WOOD, PAPER, TRASH HAVING GLOWING EMBERS | YES | YES | YES | YES | YES | NO (BUT WILL CONTROL SMALL SURFACE FIRES) | NO (BUT WILL CONTROL SMALL SURFACE FIRES) | NO (BUT WILL CONTROL SMALL SURFACE FIRES) | YES | YES |
| CLASS B FIRES FLAMMABLE LIQUIDS, GASOLINE, OIL, PAINTS, GREASE, ETC. | NO | NO | NO | NO | YES | YES | YES | YES | YES | YES |
| CLASS C FIRES ELECTRICAL EQUIPMENT | NO | NO | NO | NO | NO | YES | YES | YES | YES | YES |
| CLASS D FIRES COMBUSTIBLE METALS | SPECIAL EXTINGUISHING AGENTS APPROVED BY RECOGNIZED TESTING | | | | | | | | | |
| METHOD OF OPERATION | PULL PIN-SQUEEZE HANDLE | TURN UPSIDE DOWN AND BUMP | PUMP HANDLE | TURN UPSIDE DOWN | TURN UPSIDE DOWN | PULL PIN-SQUEEZE LEVER | RUPTURE CARTRIDGE-SQUEEZE LEVER | PULL PIN-SQUEEZE HANDLE | PULL PIN-SQUEEZE HANDLE | RUPTURE CARTRIDGE-SQUEEZE LEVER |
| RANGE | 30'-40 | 30'-40 | 30'-40 | 30'-40 | 30'-40 | 3'-8' | 5'-20' | 5'-20' | 5'-20' | 5'-20' |
| MAINTENANCE | CHECK AIR PRESSURE GAUGE MONTHLY | WEIGH GAS CARTRIDGE ADD WATER IF REQUIRED ANNUALLY | DISCHARGE AND FILL WITH WATER ANNUALLY | DISCHARGE ANNUALLY -RECHARGE | DISCHARGE ANNUALLY -RECHARGE | WEIGH SEMI-ANNUALLY | WEIGH GAS CARTRIDGE-CHECK CONDITION OF DRY CHEMICAL ANNUALLY | CHECK GAS PRESSURE GAUGE AND CONDITION OF DRY CHEMICAL ANNUALLY | CHECK GAS PRESSURE GAUGE AND CONDITION OF DRY CHEMICAL ANNUALLY | WEIGH GAS CARTRIDGE-CHECK CONDITION OF DRY CHEMICAL ANNUALLY |

Source: OSHA (1970)



2.1.4 Movement speed in different physical characteristics

A number of scholars have analyzed horizontal and vertical walking speeds and explored the influence of physical characteristics on walking speed. Fruin (1971) has stated that the horizontal walking speed of individuals depends on several factors including age, gender, nature of footwear, the slope of inclination, and crowd density. The research also measures the free flow stair walking speed of 700 males and females with various age groups using two different stairs, the descending and ascending ones. The first one has a slope of 31.9° and the other one with a slope of 26.5°. The average speeds for descending stairs are shown in the Table.

*Table 2.2 Average speed on descending stairs*

| | Age – 29 or under | | Age – 30 to 50 | | Age – Over 50 | |
|---|---|---|---|---|---|---|
| | 32° angle | 27° angle | 32° angle | 27° angle | 32° angle | 27° angle |
| Males (ft/min) | 163 | 83 | 136 | 160 | 112 | 118 |
| Females (ft/min) | 117 | 132 | 100 | 128 | 93 | 111 |
| Group Average (ft/min) | 149 | 160 | 127 | 153 | 108 | 117 |

Source: Fruin (1971)

Yeo and He (2009) made an analysis about the walking speed on stairs in Mass Rapid transport stations in Singapore. Data suggests that the vertical travel speeds for adult males in the down and up direction are 0.42 m/s and 0.32 m/s, respectively, while that of females are 0.36 m/s and 0.30 m/s. Fang et al. (2012) conducted an experiment in a high-rise building to measure the stair walking speed and a total of 163 people participated. They found that the average walking speed on stairs is 0.81 m/s.

Galea et al. (2019) stated that different surface conditions and devices affect the evacuation time. The research collected the walking speed of a worker on different floor surfaces such as concrete, decking, and decking with rebar. It also gathered the ascending and descending speeds of the worker on different devices (e.g., temporary dogleg, parallel scaffold stairs and ladders) from an experiment conducted in a tall construction site. Four full-scale evacuation trials and five walking speed experiments were conducted and 1,078 participants were involved. The temporary stairs, that have the depth of the tread 0.189 m and the riser height 0.202 m (47° angle), are used in this experiment. In this research, the walking speed on the standard stair is not collected and the comparison is made with their walking speed and male stair walking speeds that Galea et al. derived from Fruin data (average over two different stair slopes (31.9° and 26.5°)) (Galea et al., 2019). The descending speed on various devices is shown in Table (2.3) and the walking speed on different surfaces is mentioned in Table (2.4). These walking speeds will be applied in developing a new approach pathfinding system that can consider the nature of the terrain.

*Table 2.3 Descent speed on various devices*

| | Dogleg stairs (m/s) | Parallel stairs (m/s) | Ladder (m/s) | Standard stairs average (Fruin) (m/s) |
|---|---|---|---|---|
| **Min** | 0.42 | 0.36 | 0.29 | (Male 51–80) 0.67 |
| **Average** | 0.72 | 0.64 | 0.45 | (Male 30–50) 0.86 |
| **Max** | 1.21 | 1.15 | 0.61 | (Male 17–29) 1.01 |

Source: Galea et al. (2019)

*Table 2.4 Walking speed data for the four types of surface*

| Surface type | Min (m/s) | Max (m/s) | Average (m/s) | Standard deviation |
|---|---|---|---|---|
| **Concrete** | 1.43 | 2.52 | 1.89 | 0.23 |
| **Across decking** | 0.93 | 2.25 | 1.50 | 0.24 |
| **Rebar** | 0.64 | 2.29 | 1.41 | 0.29 |
| **Along decking** | 0.45 | 2.23 | 1.36 | 0.27 |

Source: Galea et al. (2019)

2.1.5 Physical challenges for workers in high-rise construction during an evacuation

A high-rise construction site can be divided into two regions: the main part of the building and the formwork (see Figure 2.1). The main part of the building consists of the core and core under construction. The core under construction consists of the completed and partially completed floor. The floor space can be littered with scaffolding, equipment and building materials, and it is difficult to navigate around the floor.



During building construction, we can categorize the working population into two main parts. The first one is the workers from formworks and the second one is the workers in the main part. To consider a building crisis, workers from formworks possibly have to use ladders to relocate themselves to the main part and then with stairs or sometimes a temporary one to the ground. The workers who are working in the main part have to use the hallways, ladders, stairs or floor surfaces, which may be permanent or temporary, to make their way to the ground (Deere et al., 2020).

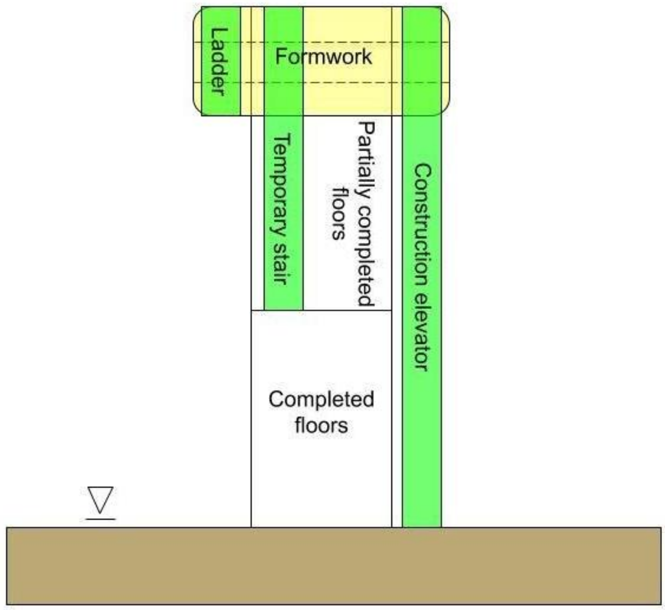



*Figure 2.1 General plan for high-rise construction*

(Adapted from Galea et al. (2019))

2.2 Technology review relating to assistance tools for fire safety and evacuation

2.2.1 Building Information model (BIM)

Building information modeling (BIM) is the digital representation of physical and functional characteristics of places and BIM technology allows storing both geometric information and rich semantic information of building models, as well as their relationships, to support lifecycle data sharing (Liu et al., 2015). BIM-based virtual models can assist in managing and controlling cost and time by creating the virtualized construction process through 4D simulation.

Moreover, researchers also put their efforts into combining traditional issues regarding the escape plan with BIM. They developed the system by converting the rules and regulations into visual language and integrated with the BIM. There is a development by Wang et al. (2012), who has used Revit's (Autodesk 2012) application programming interface (API), and elaborated an add-in toolbox on it. The system makes an approximate judgment on evacuation using two factors: capacity and time. It uses the standard factor as a reference and decides if the public space meets this standard or not during the pre-design phase of a workspace, to prevent jams and congestion during escape planning, Wang et al. (2012) have conducted research implying BIM models. Also, it is used to check evacuation rules and regulations in high-rise buildings, as well as complex ones by Choi et al. (2014).

2.2.2 Game engine in the evacuation training

Integrating game engines with BIM is one of the effective technologies for the evacuation process. 3D game engines can provide real-time and interactive visualization, using first or third person perspectives (Kumar et al. (2011); Yan et al. (2011)). Yan et al. (2011) have introduced a prototype that uses the Unity 3D game engine and BIM for virtual walkthroughs. They mentioned using game engines for creating virtual walkthroughs has several advantages such as low cost, a navigation system, network support, equipment simulation and visualization, collision detection, and support for a higher frame rate per second.

Making the reaction speed and standardized operation as factors, a simulated guidance system is organized by the researchers of the Naval Research Laboratory for training the fire fighters. While comparing the emergency response between workers who participated in the virtual guidance system and other workers who did not, it is concluded that the ones who have attended the training system have a low error rate in searching paths and the overall reflection is also quicker than the rest.

A BIM-based virtual environment is introduced by Wang et al. (2014) to overcome a number of problems in building emergency management and to provide real-time fire evacuation guidance, where the proposed system is reinforced by virtual reality (VR) and a serious game engine. Bourhim and Cherkaoui (2018) have developed the virtual environment simulation for pre-evacuation emergencies. The result shows that the player's action in the simulation is almost the same as real human behavior and using virtual environment simulation as the emergency drill can improve the evacuation process. In conclusion, the game engine can effectively improve the evacuation process.

2.2.3 Evacuation route and fire safety planning

Several methods to enhance safety planning in construction sites have emerged after the appearance of new technologies including BIM, big data, and computer-aided simulations (Zhang et al., 2015). Researchers are dedicated to enhancing the conventional system of safety assessment by focusing on elementary research studies, which are leading to the design of safety concepts. As an example, Hadikusumo and Rowlinson (2004) have developed the design for safety process (DFSP), which is a tool to identify the hazard during the construction process and component. Zhang et al. (2015) has developed a BIM-based safety rule checking system to identify fall hazards through automated checking of 3D models in the design phase.

Specific commercial software for evacuation modeling is capable of taking coupling factors and complex conditions into consideration. Peng et al. (2019) has stated that EXODUS, Pathfinder from Thunderhead Engineering, and SIMULEX are the popular evacuation analysis software. However, the performances of these software are limited in terms of time consumption because of the huge calculation burden, it may take more than ten minutes for running a single simulation. If the circumstance changes, generating new paths will take an unacceptably long time. Therefore, these varieties of software become vulnerable to the dynamic nature of the construction site.

Kim and Lee (2019) have introduced a platform that can generate the daily evacuation path in 4D BIM. The building structure and the evacuation plan will be changed in terms of the construction progress. The author created the user input in terms of the key parameters that can impact the possible calculation such as exit, work area, object that can block the pathways and the rebar surface area. In this study, the location of temporary stairs and ladders are assumed. Furthermore, the authors didn’t consider windows that can be used as the access evacuation route and walls that can impact on the path planning. Moreover, it also needs the BIM managers to change the 4D BIM when the state of BIM does not meet with the current construction environment. Furthermore, this system does not have functions to check fire-fighting equipment installation plans.

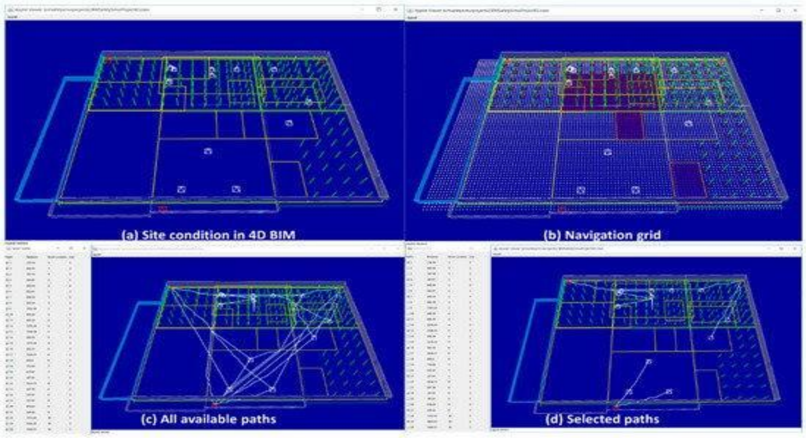



*Figure 2.2 Generation of the daily evacuation path in 4D BIM*

Source: Kim and Lee (2019)

Fire safety planning plays an important role in the construction emergency planning field. Current practices of fire safety which are used in the construction industry heavily rely on the timely updates and reviews (Choe and Leite, 2017). Moreover, if the safety planning is performed manually, it can be quite time consuming and requires in-depth physical work. Usually, the fire safety planning involves several aspects to consider such as escape routes, fire fighting equipment installation, and safety training to workers. In many building construction projects, feasible and modernized fire safety plans are not available (Kim and Lee, 2019).

Khan et al. (2020) has introduced a Con-fire Safety Planning system that uses visual language to generate the fire-fighting equipment installation plan and evacuation route plan. The text-based data, which are the manually extracted regulations relating to fire protection, are converted into mathematical logic. The converted mathematical data becomes the input for visual programming to check the locations of fire extinguishers. In Figure (2.3), the visual programming language is created in terms of the past accident case, best current practices in safety management, OSHA regulations and fire safety rules. After that, the visual programming language is integrated with BIM. To generate the initial installation plan for PFEs according to the OSHA fire safety rules (3000 $ft^2$), the algorithm is designed to divide that centerline (CL) on the value gained from the division of the total building area divided by the area. After that the system generates the starting point (A) in order to check the initial installation plan that complies with the rule and regulation (distance between any area and fire extinguisher should not exceed the 100 feet. If the distance is over 100 feet, an additional fire extinguisher is added. In this system, the temporary ladders, stairs, storage location, and dynamic building model are not considered and this system is not suitable for construction.

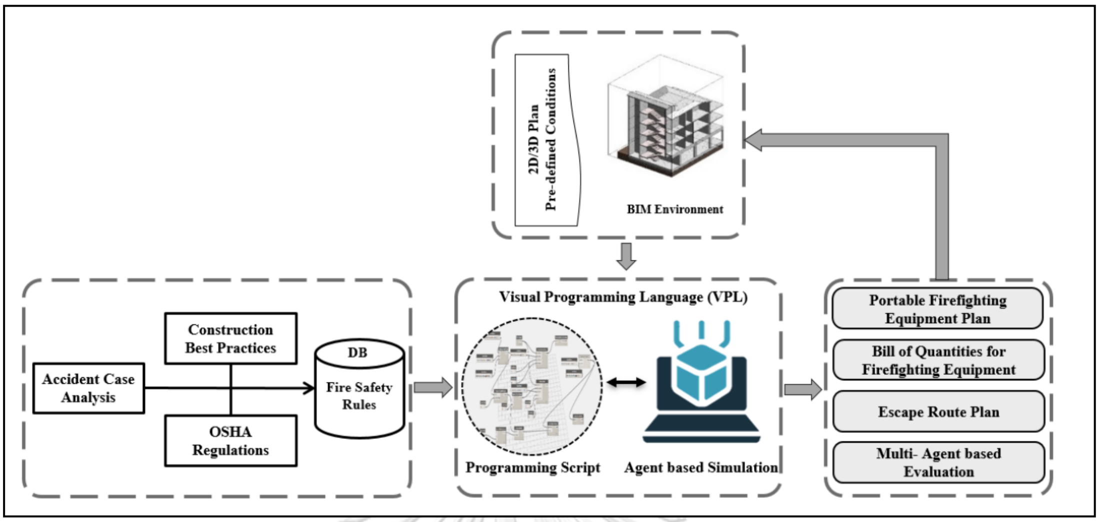



*Figure 2.3 The framework of the fire safety planning system*

Source: Khan et al. (2020)

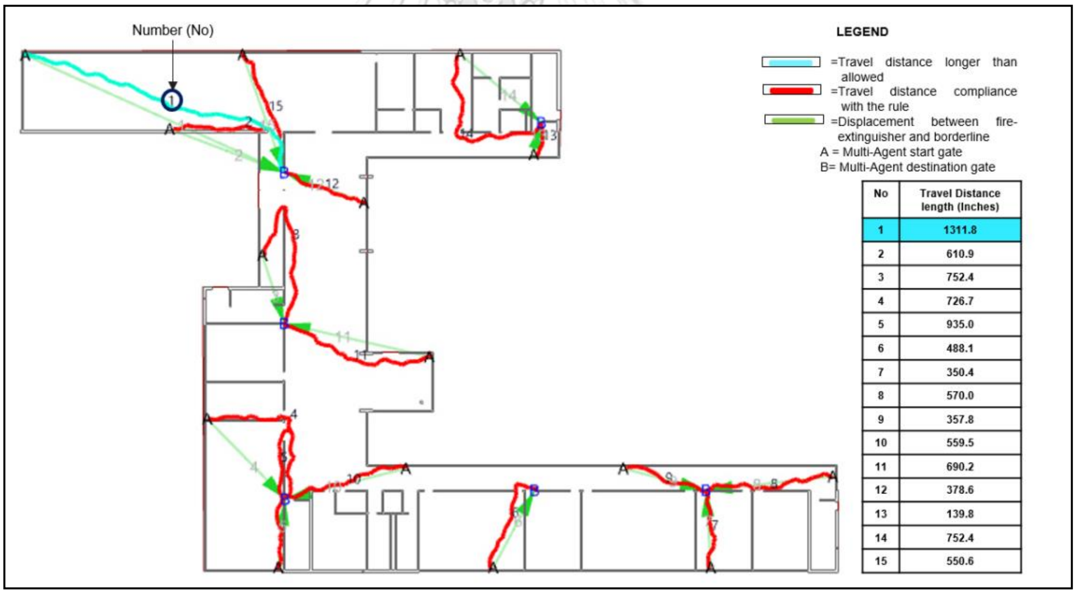



*Figure 2.4 Multi-Agent Simulation for the Con-fire Safety Planning*

Source: Khan et al. (2020)

On the contrary, some studies have focused on the technology-aided application in fire evacuation assessment design, escape route planning (Kim and Lee, 2019), safety education (Bourhim and Cherkaoui, 2018), and firefighting equipment installation planning Khan et al. (2020). However, their systems do not consider the temporary facilities, storage location, and walking speed on different surfaces and devices.

2.2.4 Evacuation route-finding system

The main objective of evacuation pathfinding is to improve the evacuation process in order to reduce the number of fatalities and injuries and accelerate the evacuation process (Gan et al., 2016). has mentioned that improving the choices of a route for the evacuees is one of the aspects to improve the evacuation process.

Soltani et al. (2002) has discovered the advantages and disadvantages of three algorithms: Dijkstra, A*, and Genetic Algorithms, in terms of the distance, route space and time consumption. The research uses each algorithm to develop the application of path planning and generates optimized paths in terms of visibility, travel distance and safety risks. Cui and Shi (2011) have stated that A* algorithm is appropriate in pathfinding for large spaces since it reduces complexity in search space hierarchy.

Wang et al. (2012) have proposed a 3D geometric network model which applies the Node-Relation-Structure (NRS) method in representing an indoor territory. For acquiring the shortest evacuation route, an ant colony optimization algorithm is used. Han et al. (2013) has introduced the evacuation route planning method that can be integrated with sensors. A wireless network handles the transmission and communication between all sensors. Ikeda and Inoue (2016) have developed an outdoor evacuation route system that shows the safe route in case of natural disasters. In this system, the Multi-Objective Genetic Algorithm is used for pathfinding and the safe route is determined in terms of average walking distance, walking speed and pedestrian traffic.



Chan and Armenakis (2014) have proposed the 3D evacuation route modeling. This system finds the route in terms of risk and distance. Multicriteria Decision Making (MCDM) and Analytic Hierarchy Process (AHP) are used to find the optimal route although route finding algorithm is not mentioned.

To send an efficient exit route amidst the crisis, Ahn and Han (2012) have developed the “RescueMe” system for mobile phone users. Aiding with AR and real-time speed, the system detects and guides routes to users, avoiding crowded hallways and blocked paths. It also tracks the walking speed of the user. If the speed is significantly slowed down, recalculation of the shortest route is automatically performed and recommends the resulting route to the user.

However, this system only relies on the photos captured by the mobile users for tracking, while no sensor data is applied or available from building monitoring systems.

Hamieh et al. (2020) has proposed the BIM-based path planning system where a path is determined according to the MOoP (Mobile object or person) such as visitors, workers, drones, and pallet trucks. Dijkstra’s algorithm is used for pathfinding here. Koch et al. (2014) has developed a BIM-based augmented reality application, augmented with indoor markers such as exit signs or fire extinguishers. The application aims to help maintenance workers in finding a possible path.

Ma et al. (2017) have stated that there are some disadvantages in traditional evacuation guidance plans. All of the evacuation route maps from every construction are illustrated with 2D drawings that have poor intuition. The 2D evacuation route map for a complex construction site is not truly effective on the evacuation process and it also takes a lot of time to understand the structure of the building. Another point is that the traditional evacuation guidance plans show the shortest route, however, cannot show the safe one. As a result, the authors have developed a method that can generate the safe route based on BIM and the fire location is added manually.

*Figure 2.5 BIM-based building evacuation path for evacuation guidance*

Source: Ma et al. (2017)

Kim and Lee (2019) have introduced a platform that can produce a daily evacuation path in 4D BIM. The building structure and evacuation plans will be changed in terms of the progress of the construction. A* algorithm is used for route finding. The limitation of this platform is that the location of the materials or storage area, and temporary structures are not considered.

Table (2.5) concludes various approaches by distinct scholars regarding virtual expression, focus area, and factor consideration for the pathfinding system.

*Table 2.5 Summary of evacuation route finding*

| Authors | Model dimensions | Study area | Factors consideration |
|---|---|---|---|
| Wu and Chen (2012) | 3D | Building | Distance and smoke concentration |
| Ikeda and Inoue (2016) | 2D | Outdoor | user average walking speed, time, distance and pedestrian traffic |
| Chan and Armenakis (2014) | 3D | Building | Hazard location and distance |
| Jiang (2019) | 2D | Building | Distance, temperature, smoke concentration and carbon monoxide concentration |
| Ahn and Han (2012) | 3D | Building | Distance and speed |
| Hamieh et al. (2020) | 3D | Building | Distance and Profile of mobile object or person (visitors, worker, drone and pallet truck) |
| Koch et al. (2014) | 3D | Building | Distance and smoke concentration |
| Ma et al. (2017) | 3D | Building | Distance and fire point |
| Kim and Lee (2019) | 4D | Construction | Distance and building structure changed in terms of construction progress |

2.2.5 A* Algorithm theory

The main purpose of any path-finding algorithm is to provide a route from a given starting point to a final point across a given area or world. The path that is generated with a path-finding algorithm has to consider the result of the combination of demands and restrictions. The paths generated by the algorithm must include the conditions which are too steep or even impossible. The paths that use roads or other easy/quick forms of transport are preferable. These factors are designed into a single 'cost function' to calculate an estimated cost between a starting point and the final one. An ideal path includes all the terrain properties into the most 'efficient' or 'economic' path that has the lowest overall cost to travel. According to Brand (2009). 'A*' algorithm is the most popular choice that combines all these properties. The path is evaluated based on the following equation;

$$f(n) = g(n) + h(n), \quad (1)$$

that is, g(n) = the cost of the path from starting node to node n,

h(n) = the cost of the cheapest path from node n to exit node, and

f(n) = the final cost for the path.

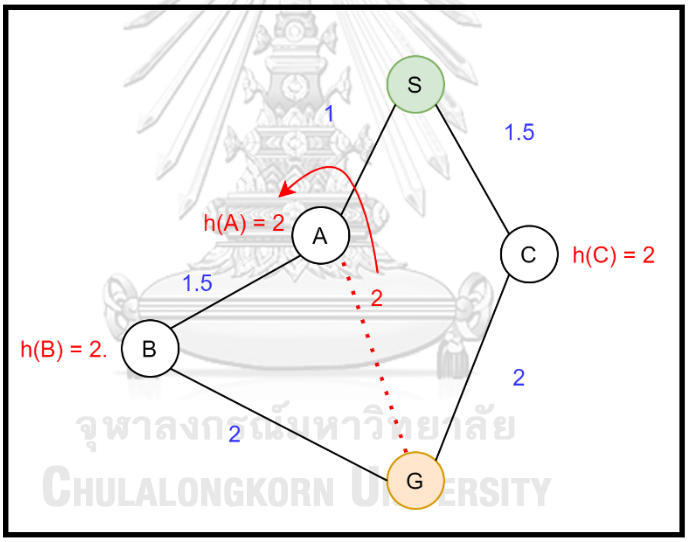



*Figure 2.6 Example of A* algorithm calculation (0)*

In Figure (2.6), the example values of the g(n) and h(n) are shown. The blue numbers represent the value of the g(n), while the red numbers are the value of the h(n). In this figure, the red dot line is the cheapest path from node A to exit node (G), and the cost of this straight line is the value of the h(n). The example of cost calculation for choosing the path is as follows;

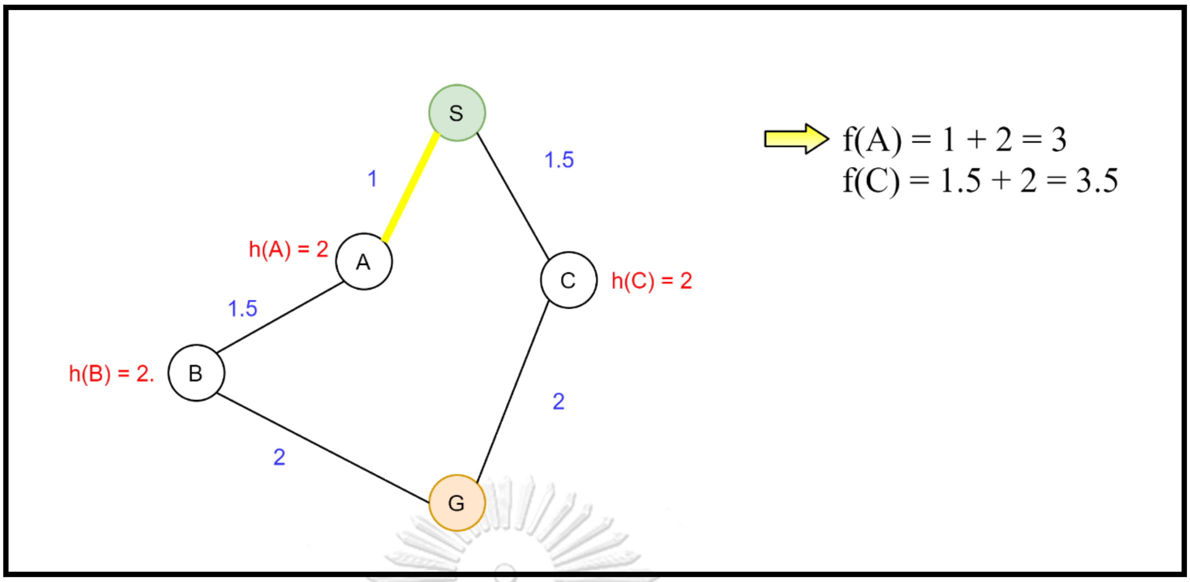



*Figure 2.7 Example of A* algorithm calculation (1)*

In Figure (2.7), the total costs of the S-A and S-C are calculated by using the A* algorithm (f(n) = g(n) +h(n)). At the current step, the total cost of the S-A is the lowest. So, this segment is selected.

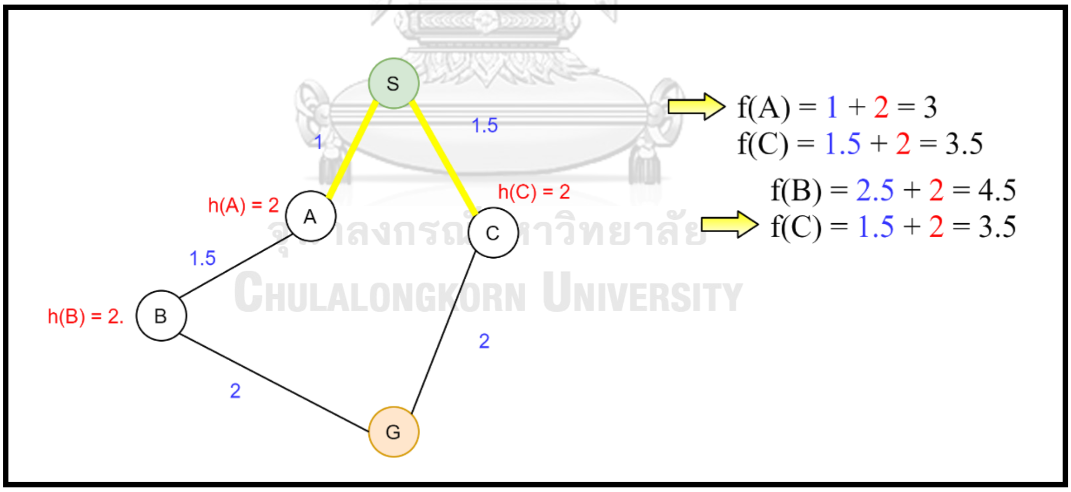



*Figure 2.8 Example of A* algorithm calculation (2)*

The total cost of the A-B segment is calculated because S-A is the selected route. In Figure (2.8), the total cost of the S-A-B and S-C is calculated and the S-C is lower than the S-A-B. So, the S-C is the selected route. And then, in Figure (2.9), the total cost of S-C-G is 3.5 and S-A-B is 4.5. Hence, the final route is determined as S-C-G.

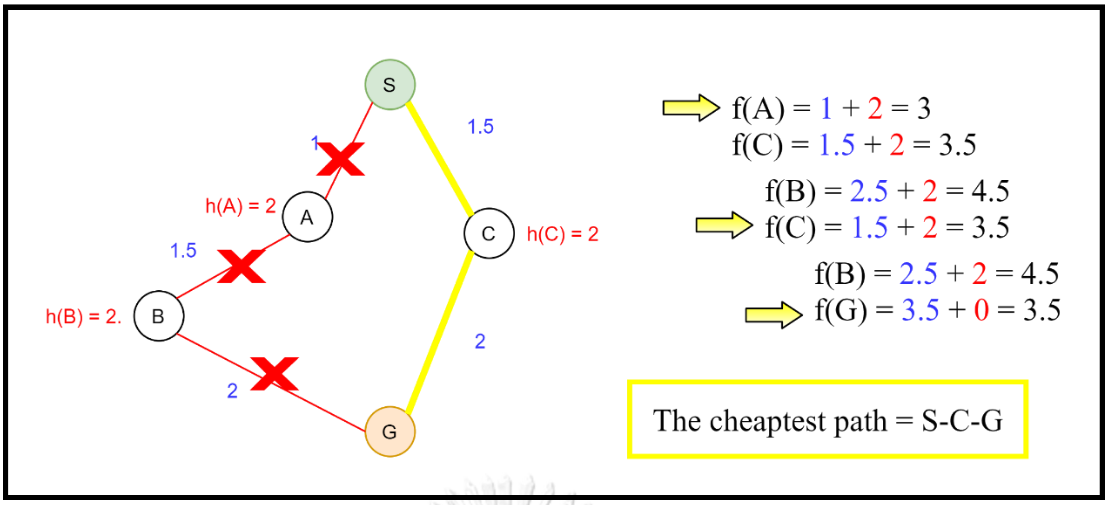



*Figure 2.9 Example of A* algorithm calculation (3)*

2.2.6 Navigation mesh in Unity

Navigation mesh (NavMesh), the shortest pathfinding system in 3D games, has become a popular concept because polygon structures are mostly used in the 3D environment. In Navigation Mesh, if a game character is on the same polygon of objects or terrain, the polygon can provide the walkable area or free walk. Several algorithms can be implemented for finding the route process in navigation mesh, but the A* algorithm is the most effective and popular today for the shortest pathfinding system (Cui and Shi, 2011).

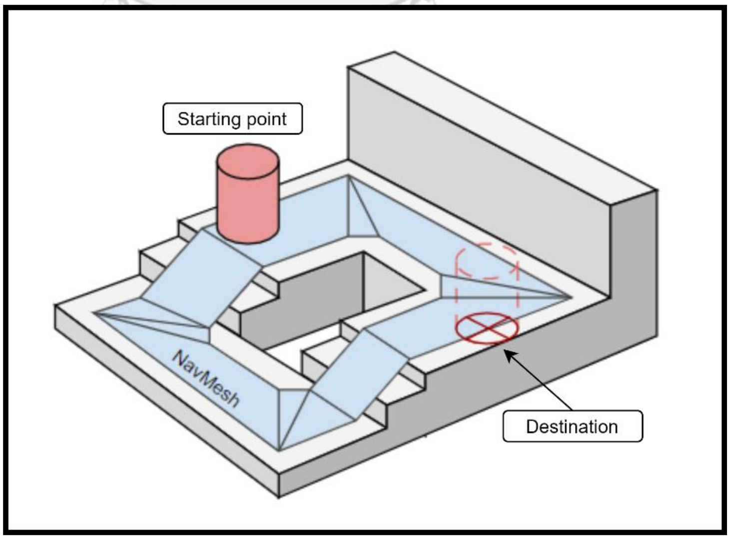



*Figure 2.10 Walkable area of NavMesh*

Source: Unity Manual (2020)

The navigation mesh or NavMesh is shown with a blue surface in Figure (2.10). to find the path between the starting point and destination, these two points must be mapped on the NavMesh. Then, the system starts searching from the start location, visiting all the neighbors until reaching the destination polygon. Tracing the visited polygons and finding the sequence of polygons which will lead from the start to the destination (Figure 2.11). After that, the path is described by connecting the corner of the sequence of polygons that is called a corridor in Unity (Figure 2.12).

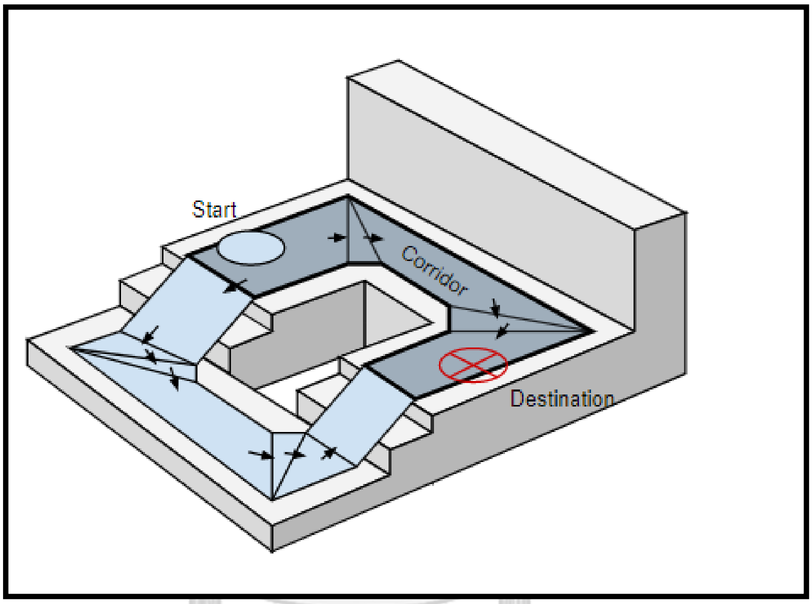



*Figure 2.11 Finding the path on the NavMesh*

Source: Unity Manual (2020)

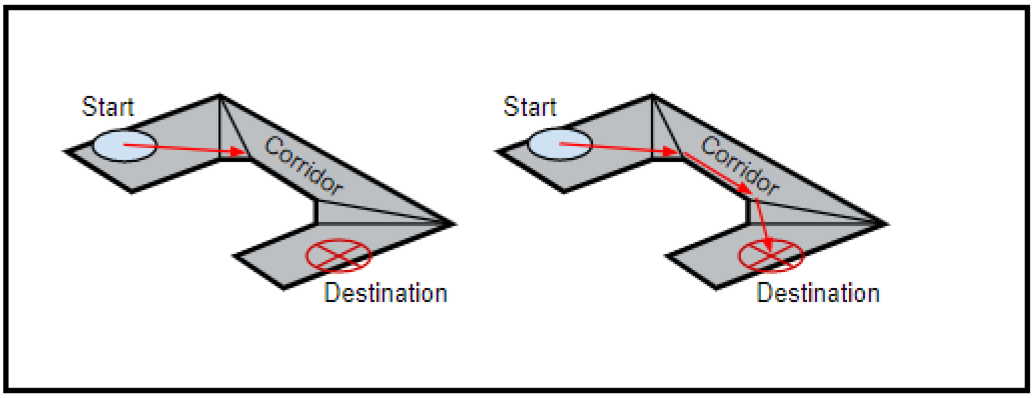



*Figure 2.12 The path that connecting the corner of the sequence of polygons*

Source: Unity Manual (2020)

2.3 Research gap

Regarding the literature review, diverse evacuation route planning systems and fire extinguisher installation systems are introduced by numerous intellectuals. Furthermore, a developed system for fire extinguisher installation is not appropriate for the dynamic nature of the construction and does not consider the non-building. However, these path-finding systems are not suitable for specific conditions where the dynamic nature of the construction site environment and the varying nature of the terrain have an enormous impact on the evacuation time. Moreover, their evacuation path planning systems recommend the path that only considers the short distance route and don't take the velocity on different terrains into account. Moreover, most of the scholars only focus on the fire safety plan and evacuation route planning. The mobile application to assist the workers, safety engineers, construction personnel, and firefighters during evacuation is neglected, while mobile phones become a trend and an essential thing for daily life. Therefore, the application for evacuation route planning and fire safety planning that suitable for construction sites and mobile applications will be developed in this study.

# CHAPTER 3

# Research Methodology

3.1 Introduction

This chapter discusses the framework that will be used in this study to reach the research aim and objectives. The research methodology consists of six steps: (1) Related literature review, (2) Technological review, (3) Construction site observation (4) Conceptual framework development (5) System design and development (6) Testing the prototype in sample building, (7) Implementation of the prototype in real construction site, (8) validation of the prototype, and (9) Discussion and conclusion.

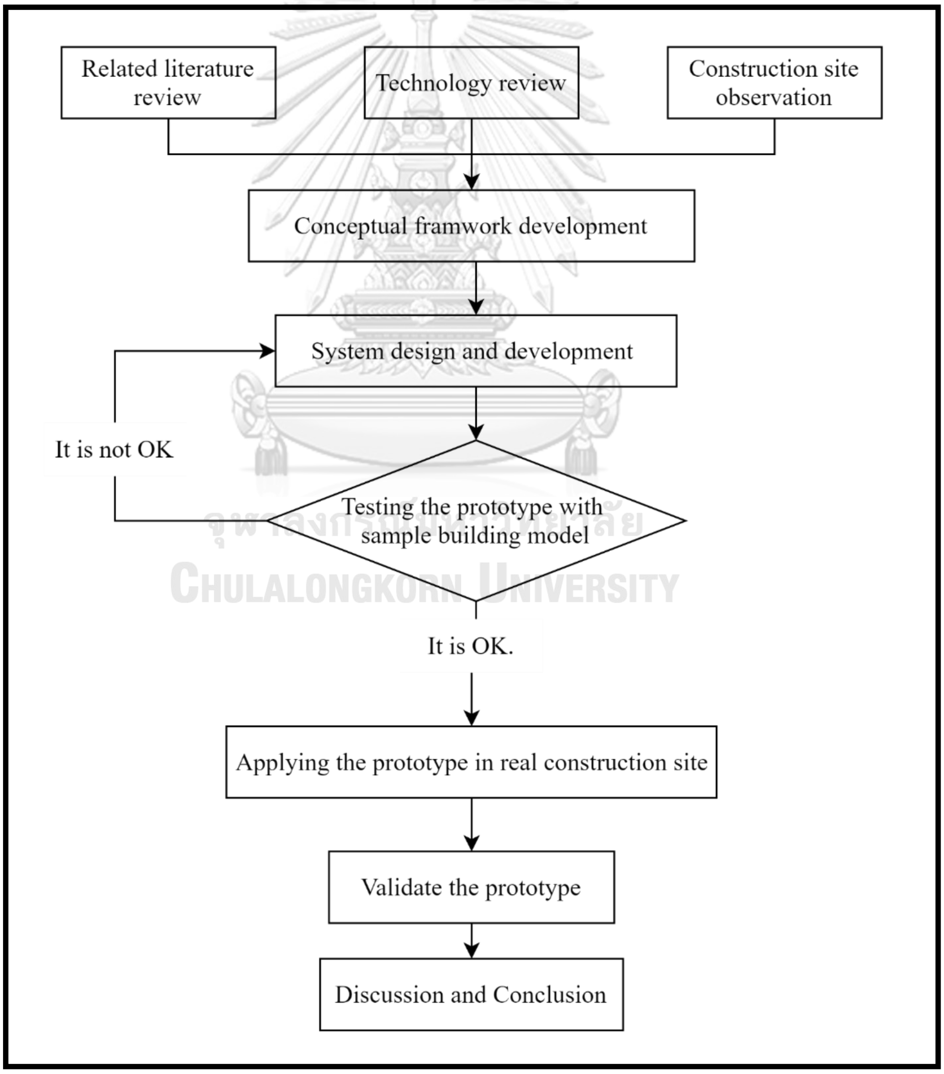



*Figure 3.1 Research methodology of the research*

3.2 Research methodology

3.2.1 Related literature review

In the related literature review section, journal articles, textbooks, conference proceedings, theses, dissertations, and other documents relating to this research are reviewed in order to explore knowledge about the processes of safety management such as evacuation plan and procedures, fire safety plan, and rules and regulations that are related to the emergency route and exit, and prevention of fire.

3.2.2 Technological review

In this session, the previous research that has mentioned the technology-aided approach which can assist in construction safety management are reviewed. The abilities of the various software, API and programming languages will be mainly discovered from websites such as YouTube, GitHub, Unity community, Stack Overflow, and so on.

3.2.3 Construction site observation

According to the data published by the Federal Emergency Management Agency (FEMA) of the United States (US), approximately 4,800 fire accidents annually happen on construction sites, and this topic is selected as the case study in this research. During site observation, Current methods in planning the evacuation route, analyzing the safety plan, emergency evacuation procedures and the limitation of the conventional approach will be discussed with the project organizers.



3.2.4 Conceptual framework development

The main objective of this research is to reduce the time-consuming, labor-intensive, and human errors in fire safety planning and to develop the assistance tool for evacuation in order to rid of the limitations of traditional evacuation plans (emergency sign and evacuation route plan). In order to enhance the level of construction fire safety management and reduce accidents, the site personnel should be able to develop the plan for fire prevention and protection, the plan for the evacuation, and provide appropriate knowledge for the workers. Figure (3.2) shows the conventional approach to develop the above plans. To perform these mentioned tasks, various and numerous information is required. When the in-charge personnel develop a fire safety plan and evacuation route plan, they should not consider only construction layout plans and fire safety requirements. They should also consider other factors which influence worker safety, such as different types of nature and resources. However, the majority of information is presented in two-dimensional, text-based, paper format. After the safety engineers and construction personnel obtains all of the information, they convert, interpret, and integrate that which they consider being of concern to them. The capability to perform these tasks depends upon the level of experience, knowledge, and individual perspective of the engineers and the supervisors. They mentally transform and generate combined pictures. Then they make decisions and produce the results of the fire safety plan and evacuation route plan. Due to the nature of the construction, the safety engineers and construction personnel need to collect the information and develop the plan on a daily basis.

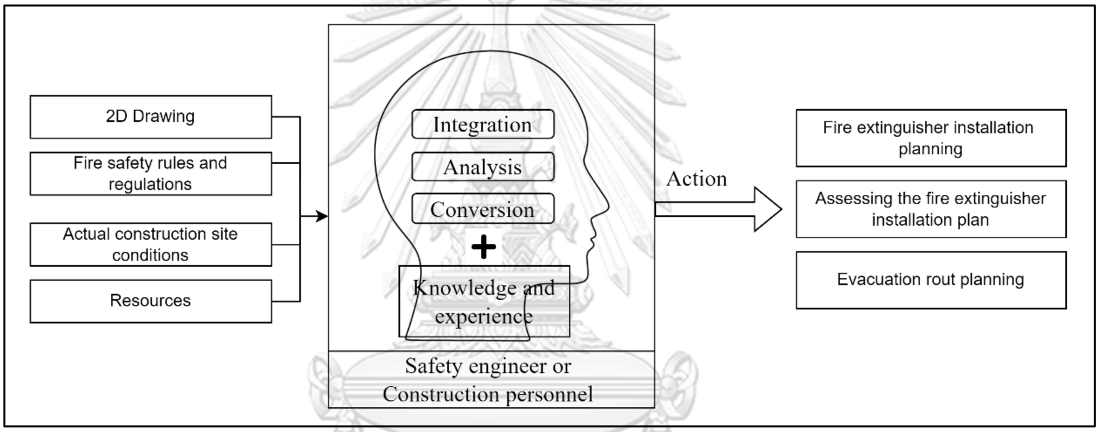



*Figure 3.2 Conventional approach for construction safety planning*

In order to execute the evacuation route plan at the construction site, a lot of labor and time is required and the assistance tools for evacuation should lead the evacuee to a safe place and evacuation route. However, the lion share of the construction site uses the traditional evacuation guidance plans that are incapable of showing the optimal evacuation route. Moreover, in-charge personnel should update and check the traditional evacuation guidance plans based on the construction progress.

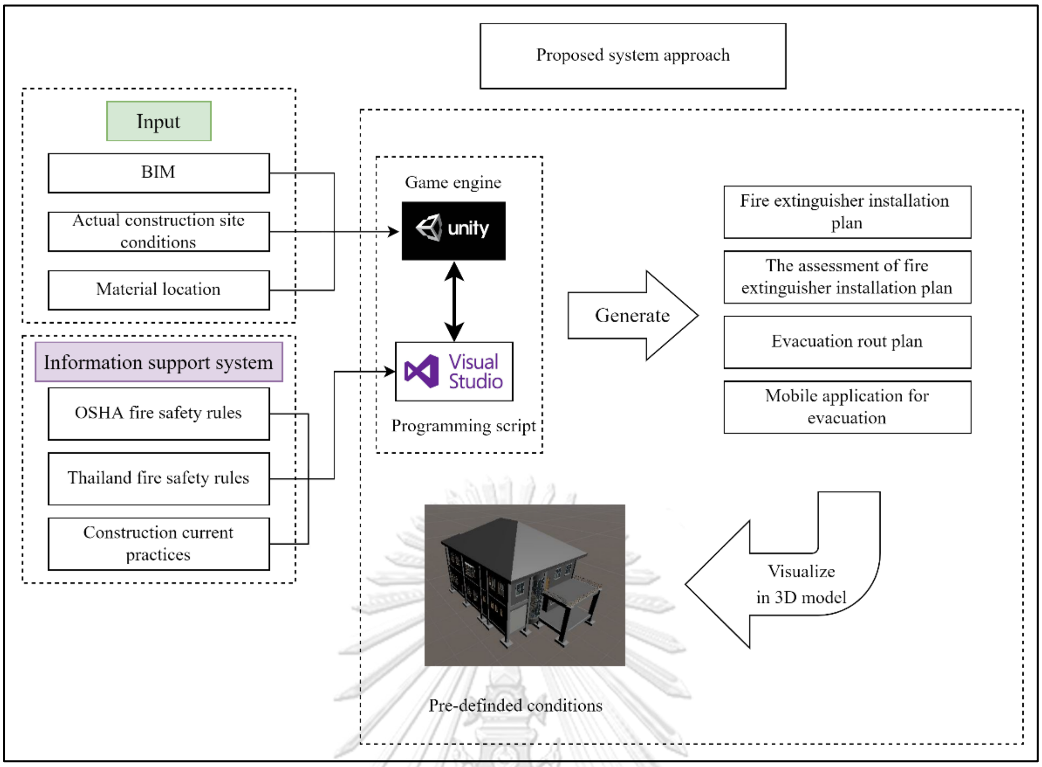



*Figure 3.3 Conceptual framework of the proposed system*

Therefore, this research gains ideas from the mentioned problems to improve the safety management process for fire safety and emergency evacuation. The proposed system reduces the time-consuming, labor-intensive, and human errors in planning and makes the decision making in choosing the safe path during the evacuation. All essential information is transformed, integrated, and generated in this proposed system by implementing the virtual environment, as shown in Figure (3.3). The advantages of virtual environments are that virtual environment technology is supported in every mobile phone.

(A) Idea for development of evacuation route planning system

In order to develop an effective emergency evacuation route plan, travel time, which is one of the factors to consider in route planning for construction because the construction site contains the different nature of the terrain and these terrains have different effects on the evacuation process. The proposed system supports the safety engineers and construction personnel in developing the evacuation route plan and in decision-making for selecting the appropriate evacuation route.

(B) Idea to use the technology for generating and assessing the fire extinguisher installation plan

The ideas to improve the fire extinguisher installation planning process came from the documents which were text-based. To perform this task, it requires the time, knowledge, and experience of the in-charge personnel to identify the correct locations. The proposed system contributes to the safety engineers and construction personnel in creating the fire extinguisher installation plan and assessing the old fire extinguisher installation plan.

(C) Idea to use modern technology instead of using the traditional evacuation guidance plans

Conventionally, the assistance tools for evacuation are emergency signs and floor layout plans, and a lot of workers are needed to update and check these tools. Moreover, these tools also have limitations in order to provide a safe evacuation route and visualization that take some time to understand. The proposed system provides the alternative assistance tool for evacuation as a mobile application and the evacuation route shows in the 3D model.

3.2.4 System design and development

Regarding the related literature and technological reviews, the concept of the system design will be chosen. The limitations of the previous research (e.g., the dynamic changing of building structure, temporary facilities and different types of terrain) and some functions that can make improvements will be noted. The problems of current practices in the evacuation planning process are analyzed and the limitations and advantages of the prototype will be examined.

According to the previous studies, the virtual 3D model is selected as the presentation style. The main benefit of the virtual 3D model expression is the visibility which is better than the two-dimensional one whereas the latter not only has poor visibility but also takes time to understand the drawing of large construction sites. This is due to the dynamic building structures and changing the evacuation route of complex construction sites, in terms of the construction progress. The framework of the proposed system is shown in Figure (3.4).

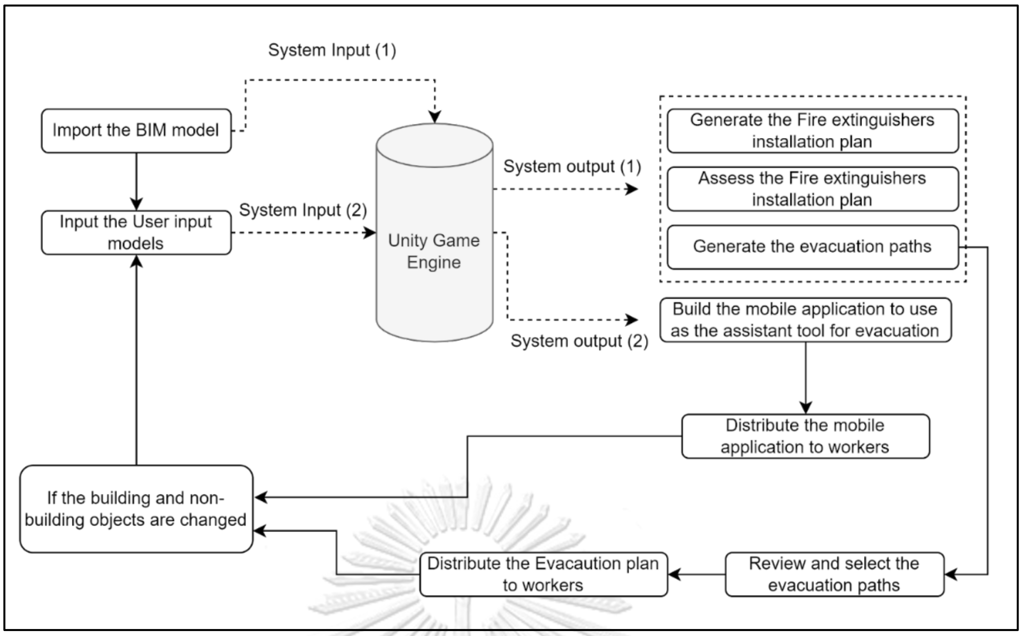



*Figure 3.4 Flowchart of the proposed system*

According to the framework, there are two system inputs such as the BIM model and user input. In this system, the BIM model is used as the 3D model because BIM technology allows storing both geometric information and rich semantic information of building models, as well as their relationship. User inputs can be divided into two types. The first one will be determined with key parameters that have a great impact on the calculation of possible paths. The following parameters are mainly used to develop rule-checking features for finding the fastest path inside a building or a construction site. The considerable parameters of evacuation route finding that have been identified by the previous researcher from the case study involve the following factors:

1. Dynamic changing of the construction site that can impact on searching the paths,
2. Exits that allow working crews to escape from a construction structure and a job site,
3. Surface conditions that have impacts on the walking speed (e.g., the rebar surface condition is not an ideal pathway),
4. Objects that can block the escape route of workers,
5. Temporary structures such as temporary stairs and temporary ladders,
6. fire locations.

The second user inputs which are used to create the fire safety plan are as follows:

1. Fire extinguishers,

2. Flammable gas (more than 5 pounds) or liquid (more than 5 gallons).

A prototype system that can handle the dynamic building structure and changing of material location and temporary facilities will be designed and developed. This system can be divided into three parts due to the previous studies. The first part is the evacuation route planning and the second one is the fire extinguisher installation plan. The last part is the mobile application that can assist the evacuees, safety staff, and firefighters during the evacuation. Both parts are developed to enable users to define parameters for pathfinding, such as changing building objects, material storage areas, and temporary structures to automatically identify the accessible evacuation paths.

The first and second part is developed for the automation process for evacuation paths plan and fire extinguisher installation plan throughout the construction processes in order to reduce the human errors, time-consuming and labor-intensive in creating the evacuation path, and making the fire extinguisher installation plan manually. For evacuation route planning, the fastest paths from every area will be provided to use as the evacuation routes. Moreover, the system provides the recommended evacuation route (fastest route) and the other alternative routes. After that, the contractor or project manager reviews the recommended evacuation route and all possible evacuation routes to be used as the evacuation route during construction. All of the evacuation routes visualization in 3D and the quantitative evaluation (travel time and distance) assist in the decision-making process for selecting the most accessible and secure path because the proposed system doesn't consider the congestion point and risk factor (flammable gas or chemical should not be on the evacuation route). The selected evacuation route can be distributed or communicated with workers in various channels, including the printed paper and hand-held computer.



For generating and assessing the fire extinguisher installation plan, two sections are carried out based on the fire safety rules and regulations of Occupational Safety and Health Standards (OSHA) (1970) and Ministerial Regulation No.33, BE 2535 (1992) (Thailand).

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

- Travel length shall not be over 100 feet starting from any point of the protected area to the nearest fire extinguisher. [Standard Number - 1926.150(c)(1)(i)].

- If more than 5 gallons of combustible liquids or 5 pounds of flammable gas exist on the job site, a fire extinguisher with a rate not less than 10B shall be provided within 50 feet.

The user input of the locations of fire extinguishers and fuel storage locations will be checked whether these locations are complied with the above rules and regulations or not. Moreover, the system can also generate the fire extinguisher plan according to the current practices (fire extinguisher should be at corridor and entrance) and rules and regulations. According to the OSHA, failure to provide the 2-A rating of fire extinguisher within 100 feet of an area where class A fire hazard exit in the building is one of the most frequently cited fire hazard violations. Therefore, for Standard Number - 1926.150(c)(1)(i), only the travel distance between the fire extinguisher and every area within the building is 100 meters or not, will be checked.

B. Ministerial Regulation No.33, BE 2535 (1992) (Thailand)

- On every floor, at least one fire extinguisher must be provided, located at every 1,000 square meters or less and at a maximum distance of 45.00 meters.
- Fire extinguisher must contain at least 4 kilograms of chemicals. (e.g., 2A and 10B fire extinguishers)
- Fire extinguishers which are of appropriate type and size to extinguish fire which occurs from the type of material used in each floor.



In this fire safety rules and regulations, the system calculates the required number of 2A fire extinguishers based on the area of floor and the 2A fire extinguishers will be placed at the location which has the maximum distance of 45 meters from any points of the construction building. Thailand fire safety rules don't mention the location of fire extinguishers for the flammable substances in detail like OSHA fire safety rules. Therefore, it is assumed that the distance between a 10B Fire extinguisher and flammable substances must be less than 45 meters.

The second part is the mobile application that can assist the evacuees, safety staff, and firefighters during the evacuation. In order to reduce the evacuees' worries and confusion in choosing the right evacuation paths and to get rid of human error in choosing the route, the evacuation guidance expression will be in the form of a 3D building model. The provided evacuation routes are also considered about the location of fire and it will be shown in evacuation guidance. To solve the problem of miscommunication between the evacuees and firefighters about the locations that evacuees are stuck, the information about those locations will be shown on the firefighters' evacuation guidance plan. In addition, as for safety staff, they should have information such as the number of workers who are at a safe place and workers who are still inside the building. In order to assist this condition, the workers can inform their status to safety staff through the internet whether they are already at a safe place or still inside the building.

3.2.5 Testing the prototype in sample building

During the testing process, the facts whether the evacuation routes can point out the exit, the travel time is shortened, fire extinguisher installation plan and assessment and real-time data (fire locations, evacuees' locations and workers' status) can show the correct data or not will be tested by changing the condition of construction such as exit, material locations and properties of floor that influence on the result. The accuracy result or output of this prototype will be collected and used for the internal validation or the verification process of this proposed system.

3.2.6 Implementation of prototype in real construction site

After testing the prototype in a sample building, the prototype will apply in real construction. Due to the Covide19, the system cannot test in the real construction project but the system tests on the real building design of the construction project by creating the different scenarios. Moreover, BIM will be collected. If the BIM model is not available, the design drawing will be collected to develop the BIM. After that, create the virtual environment in Unity software by using the created user input model.

3.2.7 Validation of the prototype

In this section, the external validation will be performed. According to the rule of thumb from Cohen et al. (2007), the minimum sample size is selected as 15. The safety engineers and construction personnel from these construction projects are selected as samples. If the total respondents from these construction projects does not meet the target sample size, the safety engineers and construction personnel from other construction projects will be selected as samples. Questionnaire surveys and interviews will be the data collection methods. The purpose of the interview is to obtain recommendation for future refinement for the model and factors. Questionnaire surveys are used to evaluate the proposed system and the safety engineers and construction personnel from Myanmar will be asked about the comprehensive and execution of the proposed system in order to collect their consideration.

The questionnaire surveys will be used at different Likert scales. Those two Likert's scales are shown in Table (3.1).

*Table 3.1 Likert's scales for two different questionnaires*

| Description | Poor | Fair | Average | Good | Excellent |
| --- | --- | --- | --- | --- | --- |
| Scale | 1 | 2 | 3 | 4 | 5 |

Mean score of each question will be calculated and Likert scale will be analyzed by using the evaluation criteria Table (3.2) that is calculated by using the mean range method (Naoum, 2012). The mean range method are as follows:

$$Mean\ Range = \frac{Largest\ scale - Smallest\ scale}{5} \qquad (2)$$

$$= \frac{5-1}{5} = 0.8$$

*Table 3.2 Evaluation criteria for Likert's scale*

| Description | Poor | Fair | Average | Good | Excellent |
| --- | --- | --- | --- | --- | --- |
| Mean Value | 1.00 – 1.80 | 1.80 – 2.60 | 2.61 – 3.40 | 3.41 – 4.20 | 4.21 – 5.00 |

3.2.8 Discussion and conclusion

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

# CHAPTER 4

## System Design and Development of the Output

### 4.1 Introduction

In this chapter, design and development of the proposed system is presented based on the system design and development from chapter 3. In accordance with the current practices, this prototype is designed not only to support the process of safety management, such as evacuation route planning and fire safety plan, but also to assist the evacuees during the evacuation. The three-dimension (3D) visualization technique is applied in the system development process. The Unity game engine and the Visual Studio software will be used as the major ones to create the user interface, computer-based calculations and algorithms. The procedures for prototype development are also mentioned.

### 4.2 System design

In this article, the system to assist the processes of safety management, such as planning the evacuation route, analysis of the fire safety plan, and assistance application during the evacuation, is presented. The hardware components in developing this system consist of a laptop computer and a mobile phone. In order to assist the construction site safety regarding the evacuation, this system is composed of three main modules:

(I) The generation and assessment of the fire extinguisher installation plan, and

(II) The generation of the evacuation route plan



(II) The mobile application during the evacuation and rescue process

The first and second modules are targeted to benefit the safety engineers and construction personnel. The first module is the fire extinguishing plan and assists in checking the locations of fire extinguishers whether they comply with the rule and regulations (OSHA and Thailand rules) or not, while the second module provides the evacuation route plan. Safety engineers and construction personnel can use this module in laptops or personal computers that have Unity software, making the system easily accessible. Also, safety engineers and construction personnel are allowed to change the building structure and the locations of temporary facilities according to the up-to-date condition of the construction.

The third module is dedicated to mobile users who are inside the construction site during the emergency, mainly construction workers and fire fighters. In this system, automated tracking of the location is out of scope. Hence, users have to input their current locations and the alphanumeric markers will be placed according to the information about their respective areas. The mobile users can access the fire location after the safety engineers and construction personnel have added the specific information about it: using their laptops and the internet server. Moreover, fire fighters can see the locations of fire and locations where the evacuees are stuck. The mobile application also provides the fastest route from the exit to evacuees' locations. The system architecture is summarized and shown in Figure (4.2).

The first module can generate the fire extinguisher installation plan and check the rules and regulations of OSHA Standard (Standard Number - 1926.150(c)(1)(i) and 1926.150(c)(1)(iv)) and Thailand fire safety rules (Clause – 19). Based on the above user input and another user input that can affect the rules and regulations of fire safety plans. For Standard Number - 1926.150(c)(1)(i), whether only travel distance from any point of the protected area to the nearest fire extinguisher shall not exceed 100 feet, is checked. In the second module, measuring the travel distance between two locations or points, show the fastest route from every starting point to exits, and showing the fastest route from every starting point can be performed from user inputs, having different impacts on selecting the pathways.

There are also two modes under the assistance application for the evacuation as illustrated in Figure (4.1): the evacuee mode and the firefighter mode. In the evacuee mode, the evacuee can get information about the optimal route (fastest and safe) which shows the nearest exits and locations of the fire extinguishers. Moreover, the evacuee can inform the location where he/she remains, and the status of the safe arrival. In the firefighter mode, firefighters can obtain information about the optimal route (fastest and safe) that shows the destination location where the starting point is the exit. In addition, firefighters can also check the report showing the locations and the number of people stuck. This application will be designed not only for users who have internet access but also for those who do not have access to the internet.

The user interfaces are created for communication between the users and the proposed system. In order to develop and implement the proposed system, it requires both hardware and software preparation. Moreover, the calculation will be performed for finding the fastest evacuation path, the nearest exits, and fire extinguishers.

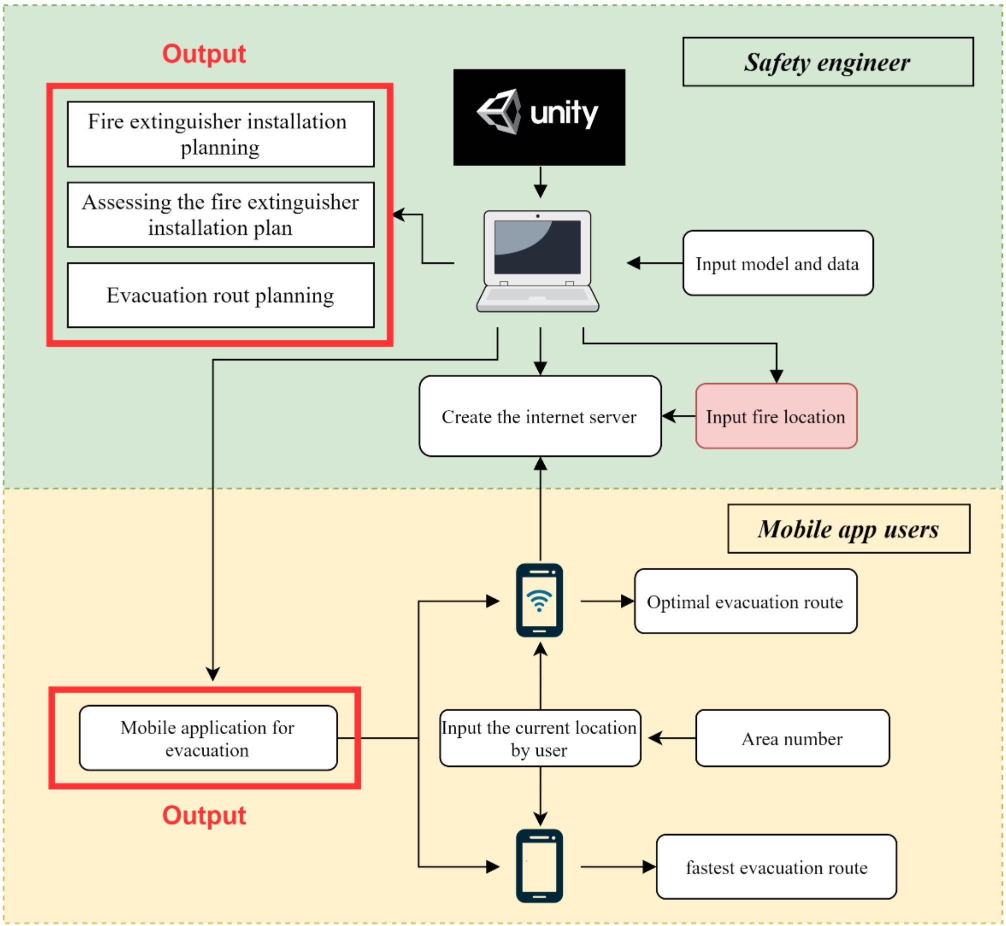



*Figure 4.1 The architectural model of the proposed system*

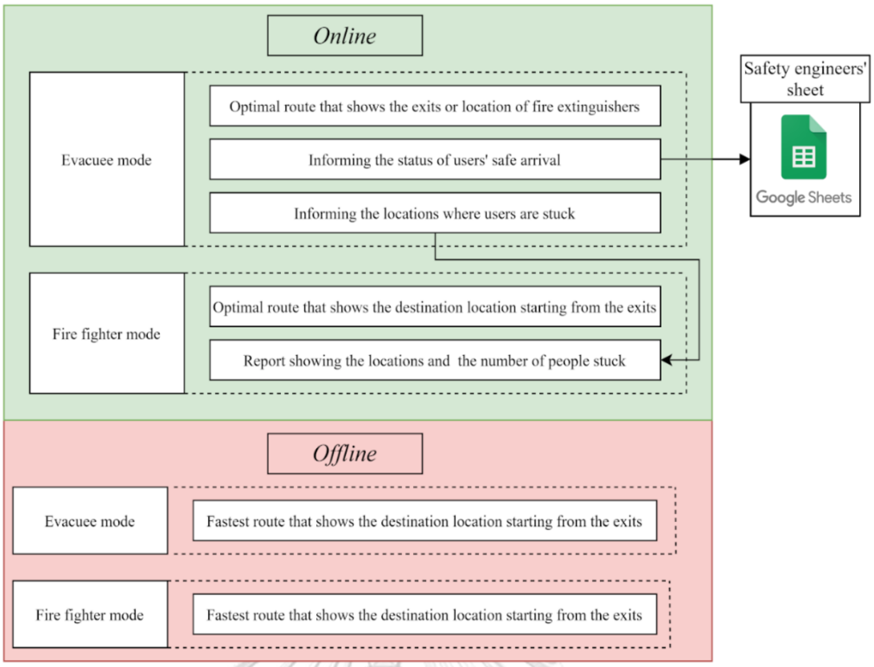



*Figure 4.2 Two modes of the assistance application for the evacuation*

## 4.3 System development

In this article, the software, hardware, and procedures of system development that will be applied in the proposed system will be discussed. They will be determined in order to meet specifications of the design and develop the prototype. The 3D building model preparation and development of modules are also described in this article.

### 4.3.1 Required software and tools

In this section, the development environments which are prepared for proceeding the proposed system are described. The following software and tools will be used in developing the prototype.

A. Autodesk Revit (2019) and Navisworks (2019)

B. Unity (Game Engine) (2019)

   a) NavMesh build components tool

   b) Multiplayer HLAPI package

   c) Android build support module

C. Visual Studio (2017)

   a) Game development with Unity tool

D. Google Form

A. Autodesk Revit (2019) and Navisworks (2019)

Revit is a typical and popular BIM software. It is used to create the 3D model of the building. In order to export the 3D model to unity, the 3D model file type must be the FBX file. The exported FBX file from Revit only shows the name of the material of the components, while the exported FBX files from Navisworks can provide rich information, showing the components with categories such as level (floor), wall, door, and so on. The differences between the exported FBX file from Revit and Navisworks are shown in Figure (4.3). Therefore, the FBX file from Navisworks will be used in this prototype. The Revit converts the RVT file to NWC file, and then imports it to Navisworks to generate the FBX file. So, Navisworks is used as the data convertor to import the FBX file to Unity (Figure 4.4).

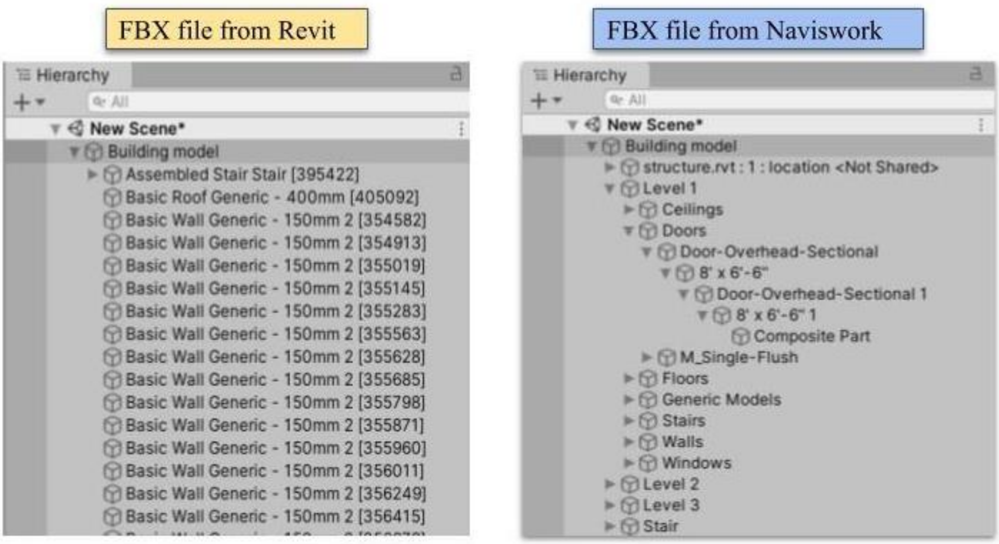



*Figure 4.3 The differences between the exported FBX file from Revit and Navisworks*

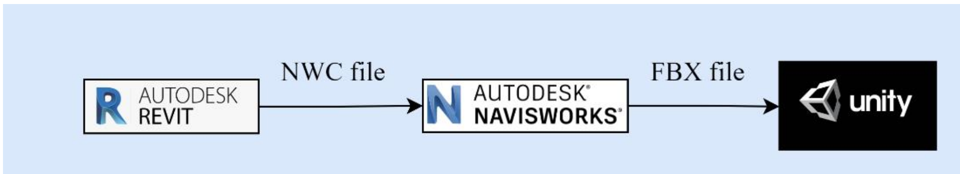



*Figure 4.4 Exporting BIM model to unity*

B. Unity (Game Engine) (2019)

Unity is the cross-platform game engine and it supports more than 25 platforms. It has a powerful engine and is easily operable. In order to achieve the objectives, (a) Navmesh building components tool, (b) Multiplayer HLAPI package, and (c) Android build support module are installed in unity.

(a) NavMesh building components

Navigation mesh or NavMesh building components tool is easy to use in generating the NavMesh compared to the navigation function from Unity. It can be downloaded from GitHub and will be used to find the fastest and safe route in this system. There are four scripts in the NavMesh build components tool which are stated as follows:

- NavMesh Surface - is used for building and generating the NavMesh surface for one type of agent. It will be used to identify the walkable floor and obstacles in this study. NavMesh is shown in Figure (4.5) and an example of agent type is displayed in Figure (4.5).
- NavMesh Modifier - is used to contribute to the NavMesh generation of NavMesh area types based on the transform hierarchy or component of the building. It will be mainly used in identifying the rebar area in this study.
- NavMeshModifierVolume - is to provide an effect on the generation of NavMesh area types based on volume. It is applied to identify the fire or risky locations in this research.
- NavmeshLink - is used for connecting the same or different NavMesh surfaces for one type of agent. In this study, it will be used in windows, temporary stairs, and temporary ladders. NavmeshLink is shown in Figure (4.6).

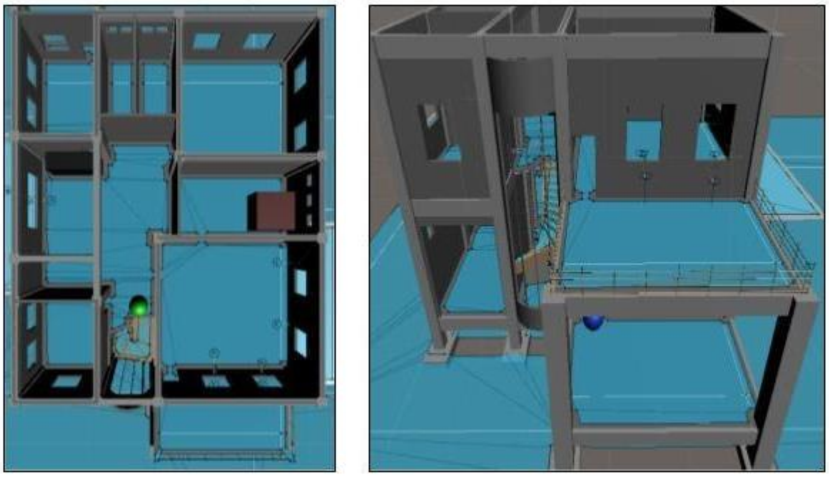


*Figure 4.5 NavMesh or navigation mesh*

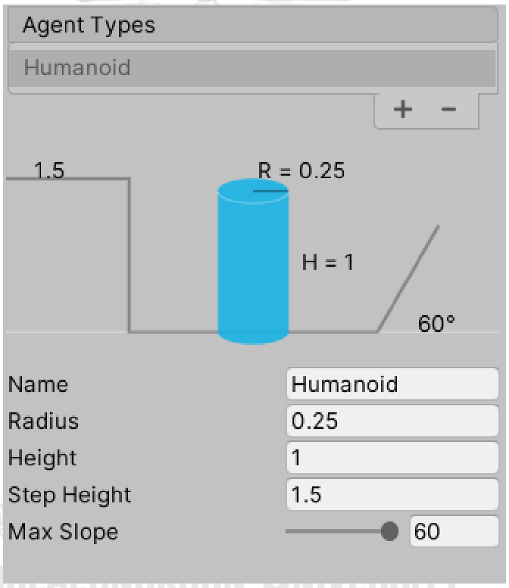



*Figure 4.6 The capacity of the agent type*

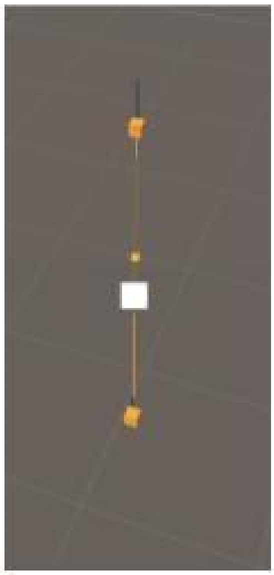


*Figure 4.7 NavmeshLink*

(b) Multiplayer HLAPI package

Unity's multiplayer High-Level API (HLAPI) is a system for building multiplayer capabilities for Unity games. It is built on top of the lower-level transport real-time communication layer and handles many of the common tasks that are required for multiplayer games. The Multiplayer HLAPI package can be downloaded from the package manager in Unity. In this study, this package is used to create the internet server and deliver the location of fire to all mobile application users who have cellular data. Moreover, it is also used to inform the locations where evacuees are stuck.



(c) Android build support module

The Android build support module is an essential part in building mobile applications. The Unity Hub is used to install Android Build Support and the required dependencies: Android SDK & NDK tools, and OpenJDK.

C. Visual Studio (2017)

Microsoft Visual Studio is an integrated development environment (IDE) that supports 36 different programming languages. In order to integrate with Unity, Game development with Unity tools is needed to be installed in Visual Studio. C# programming language, a powerful language for creating a number of different programs and applications like mobile applications, desktop applications, cloud-based services, websites, enterprise software and games, is used to contribute to the prototype.

D. Google Form

Google Form is used in informing the status of evacuees' safe arrival. The Google Sheet is created to get the responses from the Google Form. Safety engineers and construction personnel can get the number of workers who have safely arrived to the designated area by looking at the data from Google Sheets.

4.3.2 Hardware requirement

In this research, the laptop will be the major hardware component to develop the prototype. The android mobile phone is needed to test the mobile application during the development stage. The specifications of the laptop and mobile phone are shown in Table (4.1).

*Table 4.1 Specifications of the laptop and mobile phone*

| Hardware components | Specifications |
| --- | --- |
| Laptop (MSI GF 63 Thin 9RCX) | System processor - Intel(R) Core (TM) i7-9750H CPU @ 2.60GHz |
| | RAM - 8GB |
| | System type - 64-bit |
| | Video Graphics Array - NVIDIA GEFORCE GTX 1050 TI |
| Mobile phone (Mi note 2) | Android version - 8.0.0 |
| | Ram - 6GB |

4.3.3 User input model and data Creation

The user input model and data will be created in terms of key parameters that are mentioned in Chapter 3. The input models are temporary facilities, the material locations and exits. Fire extinguishers, temporary ladders and stairs, and planes are the models for the temporary facilities. The class of the fire extinguisher will be determined based on the site observation. The actions of some models will be added to the respective models by using the scripts that are coded with Visual Studio (2017). The representative models of the input are shown in Figure (4.8).


*Figure 4.8 Various types of input mode*

The input data is applied in identifying the surface conditions (concrete or rebar), and finished and unfinished components for the dynamic building structure in terms of the construction progress. The actions and effects are mentioned in Table (4.2). The action of the finished part and the unfinished part for the navigation system will be created by using the NavMesh Surface. In order to make the unfinished components or meshes disappear, Visual Studio will be applied while also using it to produce the actions of rebar and starting points.

*Table 4.2 The actions of the input data*

| Layers names | Actions |
|---|---|
| Finished part | Workers cannot pass through. |
| Unfinished part | Mesh will disappear (Figure 4.9) and workers can pass through. |
| Rebar | Increase the cost value (cost value is explained in 4.3.4) for the navigation system (Figure 4.10). |

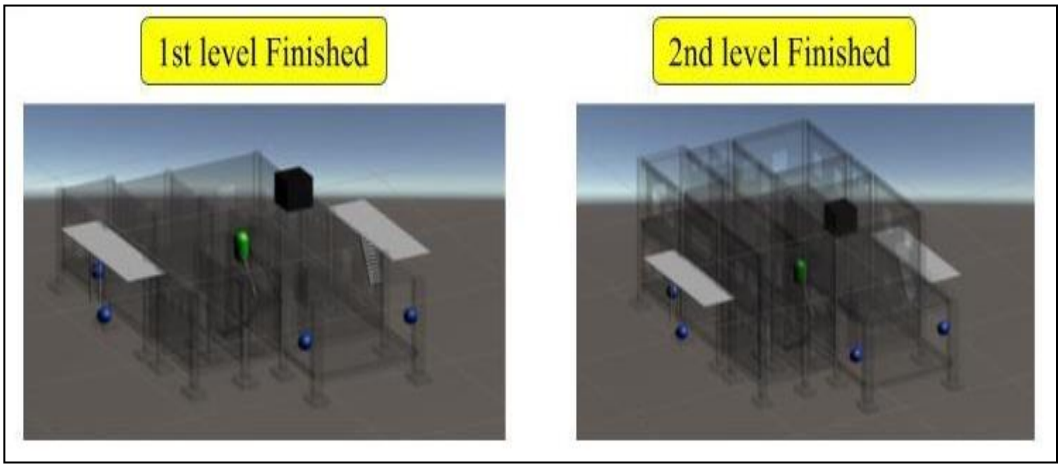



*Figure 4.9 The action of unfinished part for mesh*

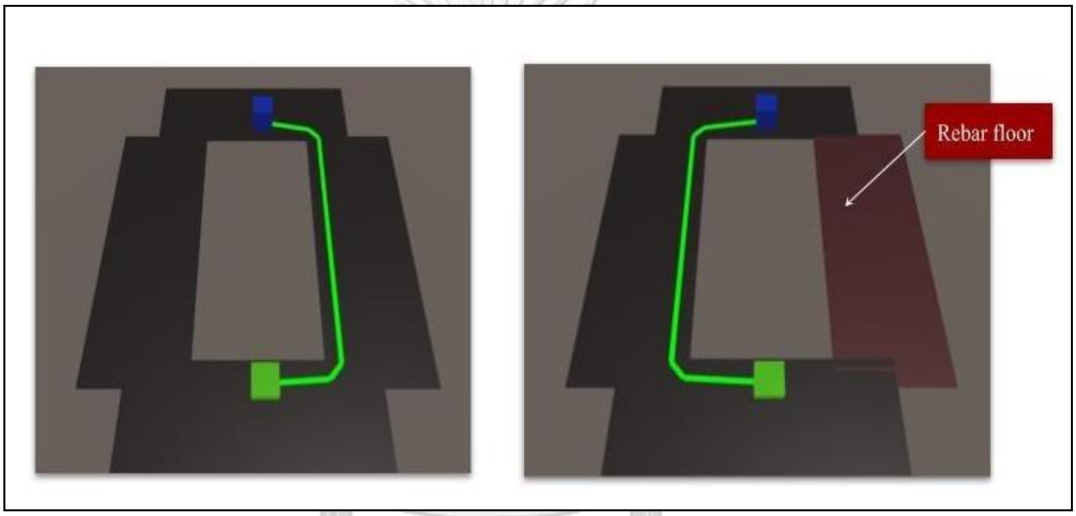



*Figure 4.10 The action of the rebar for the navigation system*



4.3.4 A* algorithm and Area Cost

A* algorithm is used for the navigation function in Unity. At first, the grid nodes are created based on distinct site conditions. They can be divided into four parts: starting node, exit node, walkable node, and unwalkable node (Figure 4.11). The starting node represents the starting point (specific area) and the exit node is the location of the exit. Unwalkable nodes correspond to the inaccessible regions such as finished walls, columns, and material locations. Walkable nodes correspond to the accessible regions such as concrete and rebar floors, windows locations, temporary stairs and ladders, and locations of fire.

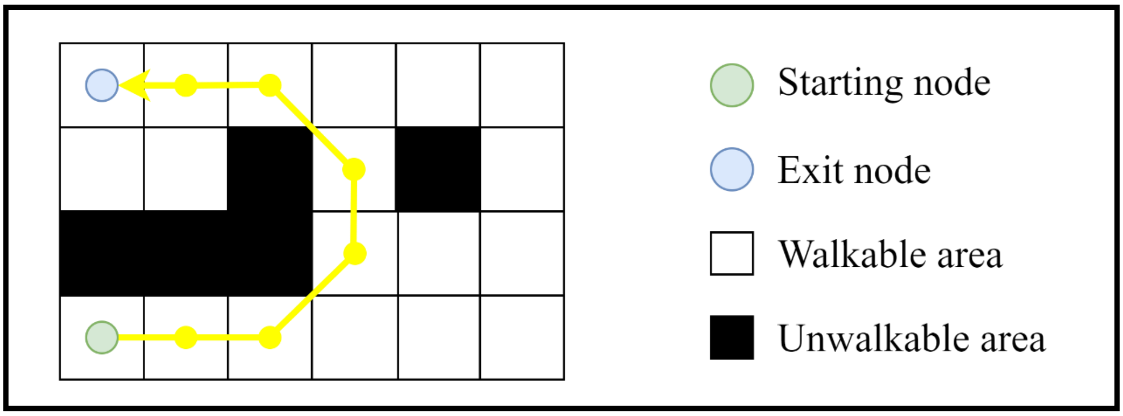



*Figure 4.11 Accessible region and inaccessible regions*

In the algorithm, the path is selected based on the total cost value. The path that has a lower travel cost is selected. In this proposed system, the travel time is used instead of the cost. The locations that are on fire will not be passed through when there is an alternative route, however, if there is no other route, the system shows the route that passes through the fire location.

In this study, the walking speed is converted into the travel time value in order to get the fastest route. The data of walking speeds on different surface conditions and devices are taken from the previous research. These walking speeds can be divided into the two types of walking speed such as horizontal, vertical walking speeds and walking speed on slope.

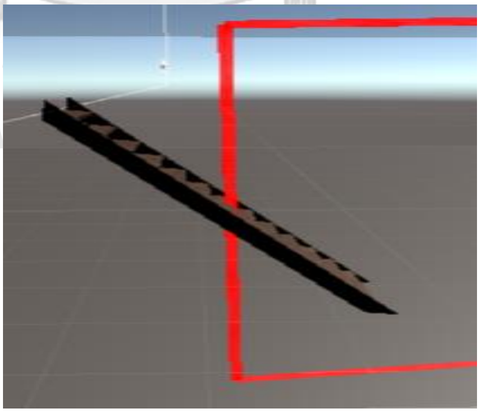


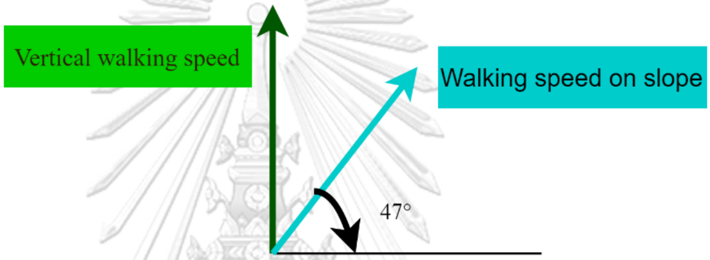
*Figure 4.12 The evacuation route at temporary stair*

The horizontal walking speed on the rebar and concrete floor, and stair walking speed will be directly used in this study. Galea et al. (2019) has mentioned the walking speed on the slope of the temporary stair. In this system, only one type of temporary stair is created due to system limitations. The walking speed on the slope of the temporary parallel and dogleg stairs have a disadvantage on the pathfinding system because the angle of the temporary stairs from the system cannot be the same as a real-world angle. In order to remove the angle of the temporary stair, the walking speed on the slope of the temporary stair needs to convert to the vertical walking speed (Figure 4.11). The vertical waking speed of the temporary stair is the average of the waking speeds on the dogleg and parallel stairs. The calculation of converting to vertical walking speed from the walking speed on the slope is shown as follows.

Walking speed on slope (47°) of temporary dogleg stair = 0.72 m/s (Galea et al., 2019)

Walking speed on slope (47°) of temporary parallel stair = 0.64 m/s (Galea et al., 2019)

Average walking speed on slope (47°) of both temporary stairs = 0.68 m/s




The vertical walking speed of the temporary stairs = 0.68 x sin (47°) = 0.5 m/s.

The walking speeds on different floors and devices are converted into travel time for 1m (s) by using the following equation and the data are shown in Table 4.3.

$$t = \frac{s}{v} \tag{3}$$

Where, t = travel time

s = travel distance

v = walking speed.

*Table 4.3 The walking speeds and the converted travel time*

| | Area | Walking speed (m/s) | Travel time for 1m (s) |
|---|---|---|---|
| E R Galea et al. (2019) | Concrete floor | 1.89 (horizontal) | 0.53 |
| | Rebar floor | 1.41 (horizontal) | 0.71 |
| | Main stair | 0.93 (slope) | 1.04 |
| | Temporary ladder | 0.45 (vertical) | 2.22 |
| | Temporary stair | 0.5 (vertical) | 2 |
| Assumption of this study | Fire | - | 100 |

The examples of the optimal route considering the nature of terrain and fire location are shown in Figure (4.12). The evacuation time reflects the safety of the evacuee. So, the optimal route must not only be the safe route but also the fastest one. In this figure, the width and length of one grid are assumed as one meter each. In these three scenarios, there are two routes to reach the exit and these routes have the same travel distance. During scenario (1), The first route involves the concrete floor and the second route mainly involves the rebar floor. In this condition, the system selects the path that passes through the concrete floor as the optimal path because this path complies with the optimal route standard (safe and the fastest route). The fire location is added on the concrete floor in scenario (2). In this situation, the safety of the evacuee is the first priority. So, the route on the rebar floor is selected as the optimal route (safe and the fastest route) because the route involves a concrete floor. In scenario (3), there is only a walkable route and the system shows the route that passes through the fire. In this case, the evacuee has to determine the situation from the fire conditions and decide whether they can pass through or not.

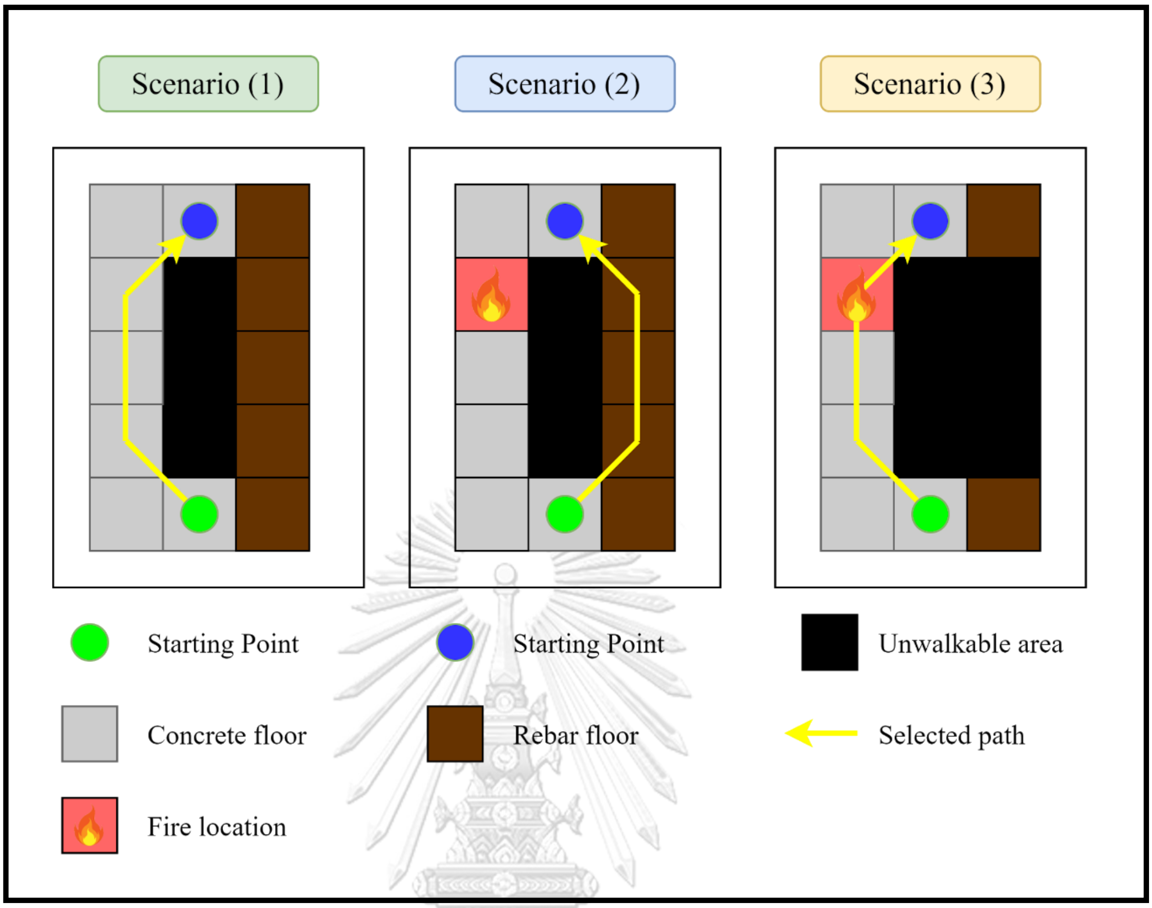



*Figure 4.13 Path finding system in different conditions*

Figure (4.14) presents three routes that have the same travel distance to the exit. The fire route (blue route) comprises the concrete floor and fire point. The second route (red route) involves the rebar floor, while the last route (yellow route) includes the concrete floor and rebar floor. The blue route and red route do not comply with the standard of the optimal route. Although the blue route is the fastest one among the three routes, it is not safe. Also, the red route is safe but it is not the fastest one considering the safe routes. Hence, the yellow route which is the safe route and the fastest route among them is selected as the optimal route.

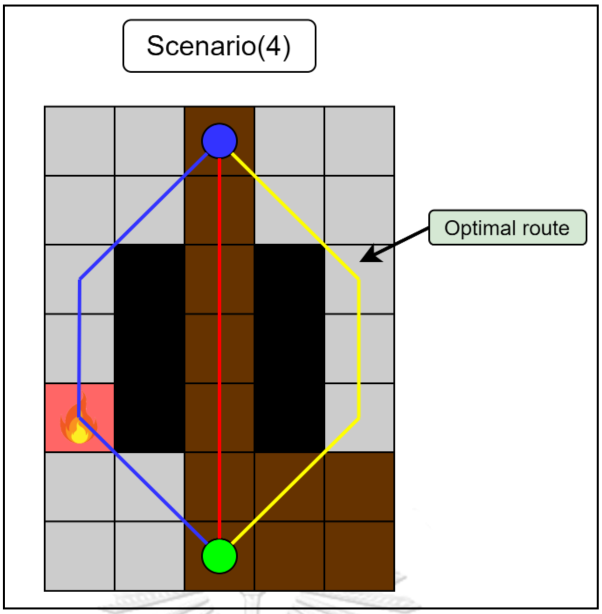



*Figure 4.14 Decision making in selecting the route*

4.3.5 3D building model preparation

Before the implementation stage, a 3D building model will be prepared. During preparation, doors and windows will be deleted in order to be used as the evacuation route. After that, the input model and data will be added with the intention of getting the current physical environment of the construction site. The process of the preparation of the 3D building model is presented in Figure (4.15).

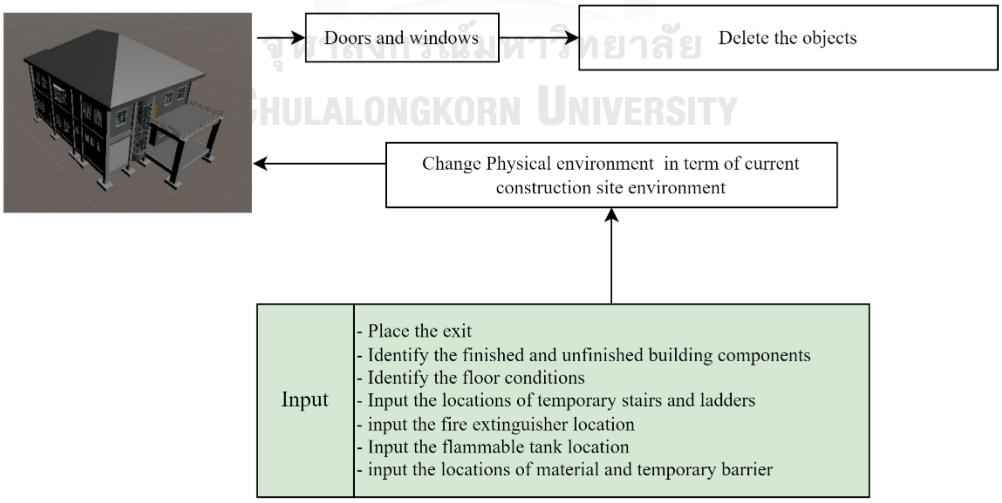



*Figure 4.15 3D building model preparation procedures*

4.3.6 Determination of the directions

The cross-product (left-hand-rule) is used to determine the directions that the next waypoint is on the right-hand site or left-hand site. If the next waypoint is on the right-hand side, the y-axis value of the cross-product of two vectors is positive (see Figure 4.16). The next waypoint is on the left-hand side, the y-axis value is negative (see Figure 4.17).

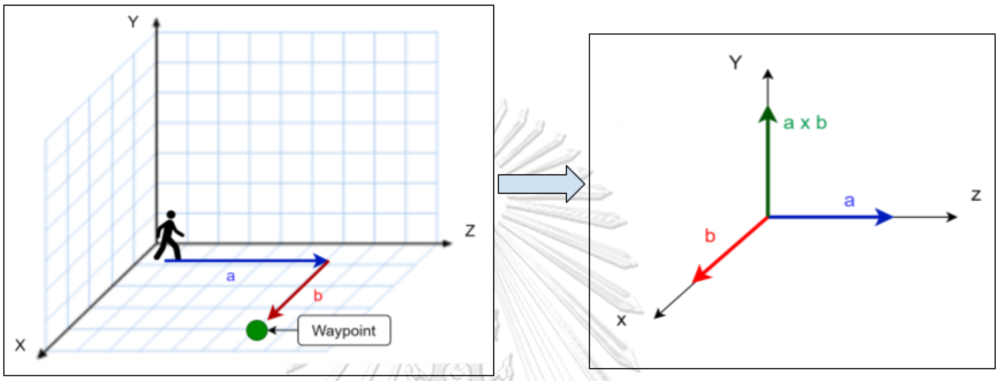



*Figure 4.16 Waypoint is on the right-hand side of the current vector*

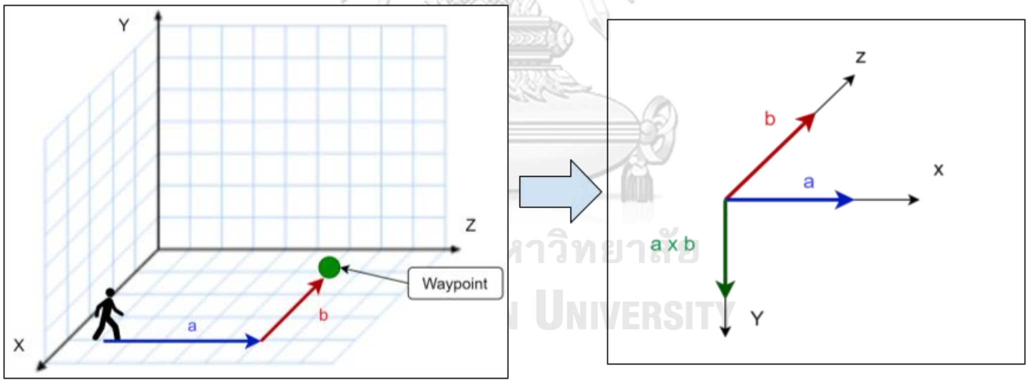
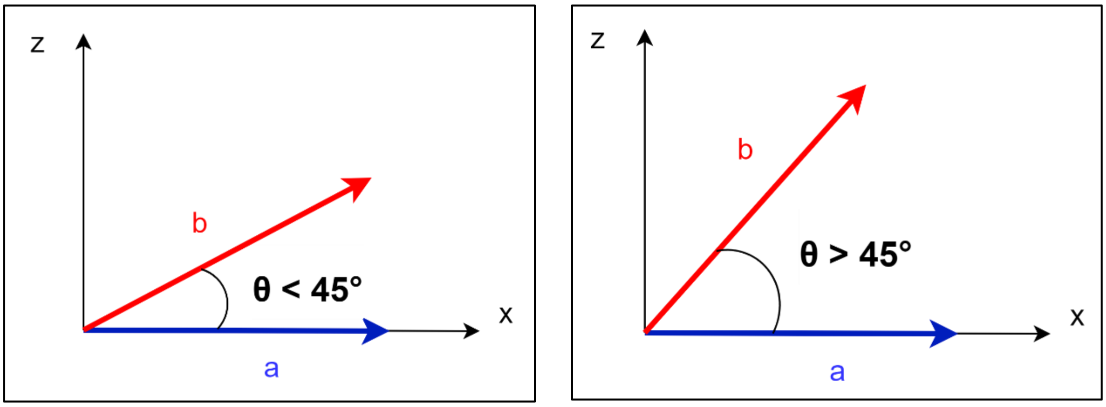



*Figure 4.17 Waypoint is on the right-hand side of the current vector*

In order to determine that the waypoint is straight from the current vector, the angle between current vector (a) and waypoint vector (b) is calculated. If the angle is lower than 45 degrees, the system assumes that the direction of the waypoint is straight (see Figure 4.18).




(a) Go straight (b) Turn left or Turn right

*Figure 4.18 Determination of the direction of waypoint is straight or Turn left and right*

To know the direction of the next waypoint is “Go up” or “Go down”, the difference between y value of current point and y value of waypoint is calculated. If the difference is larger than 1, the direction is “Go up”. If the difference is lower than -1, the direction is “Go Down”. Table 4.4 shows the Summary of determination of directions to waypoint.

*Table 4.4 Summary of determination of directions to waypoint*

| Steps | Directions | Equation |
|---|---|---|
| 1 | Go up | $\|a.y\| - \|b.y\| < -1$ |
| | Go down | $\|a.y\| - \|b.y\| > 1$ |
| 2 | Go straight | $\theta < 45°$ |
| | Turn right or left | $\theta > 45°$ |
| 3 | Turn right | $(a \times b).\ y > 0$ |
| | Turn left | $(a \times b).\ y < 0$ |

4.4 Development of Algorithm for the proposed system

4.4.1 The algorithm of fire extinguisher installation plan for OSHA

In the construction site, fire extinguishers play an important role in fighting the fire since under-construction buildings do not contain permanent and adequate fire protection systems. The incorrect position of the fire extinguisher can affect the fire extinguishing process. Hence, this proposed system provides the fire extinguisher installation plan based on the OSHA rules and regulations, and current practice. The flow chart of the new algorithm is revealed in Figure (4.19).

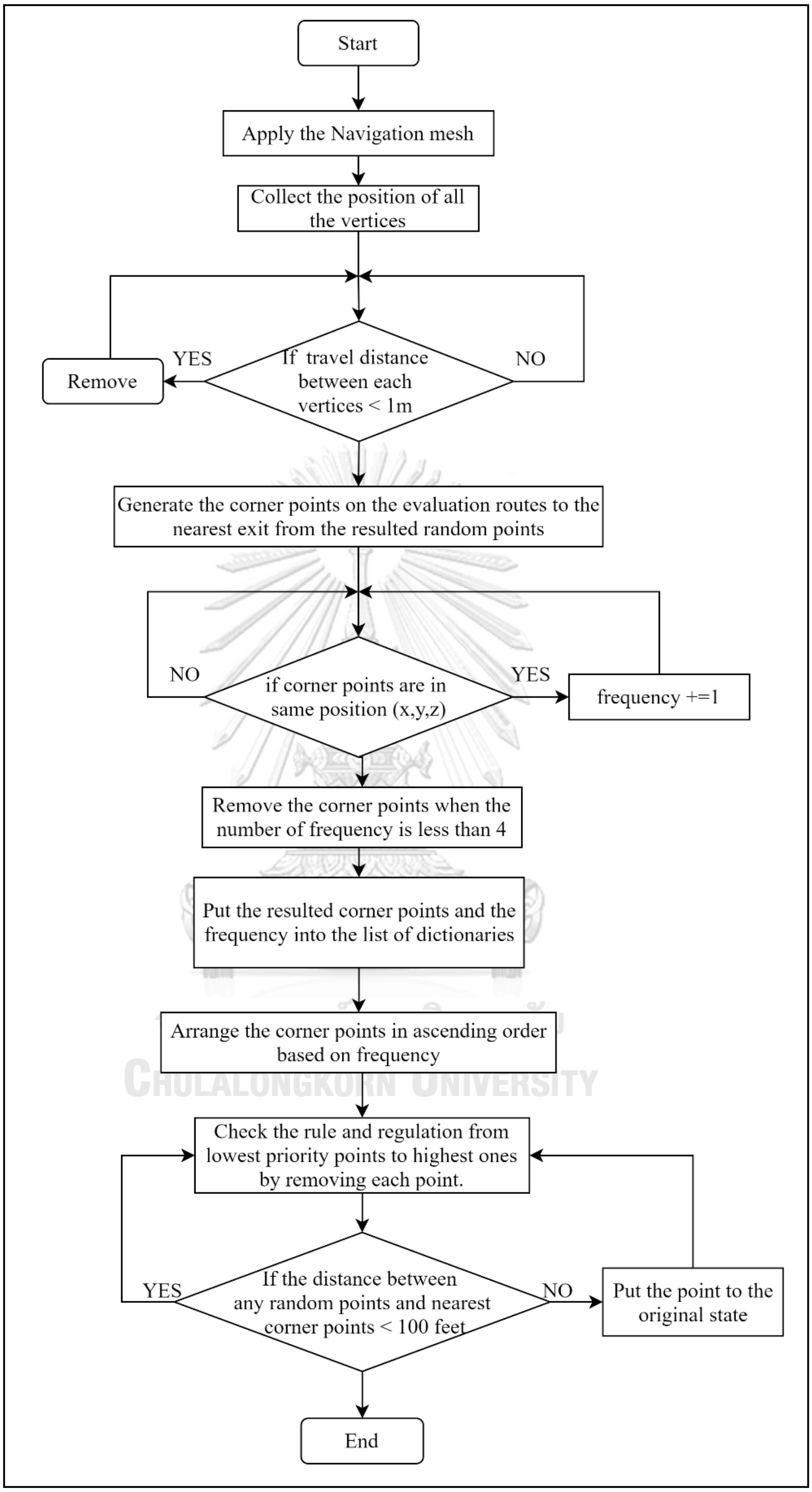



*Figure 4.19 The flow chart of the algorithm for fire extinguisher installation plan*

According to the fire safety rules and regulations, the distance between any point and fire extinguishers should not be exceeded 100 feet. In order to develop this statement, points or random points are needed to create and place in construction buildings. The navigation mesh is applied and the location of vertices are collected. The NavMesh vertices are shown in Figure (4.20). Following this, all of the vertex positions are put into the array and arranged in ascending order based on the X-axis. The random points are created at these vertex points. The number of random points is reduced to lessen the running time. To perform this task, A star algorithm is used, and the random points are removed when the distance between reference random points and the other random points is less than one meter. The random points are taken as the reference random points in terms of vertices array. The concept of this task is explained in Figure (4.21). In this example, A point is taken as the reference point (red point) and the travel distance is measured to other points. B and C points are within one meter of A point; hence, these two points are removed. Then, A point is put into the resulting random points, while D point is taken as the reference point and the above process is followed.

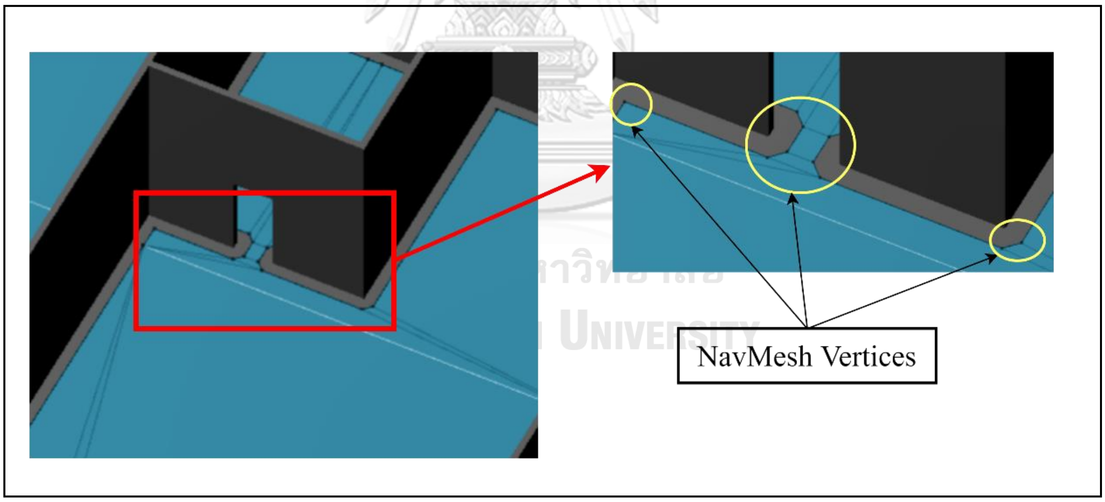



*Figure 4.20 Vertices of NavMesh*

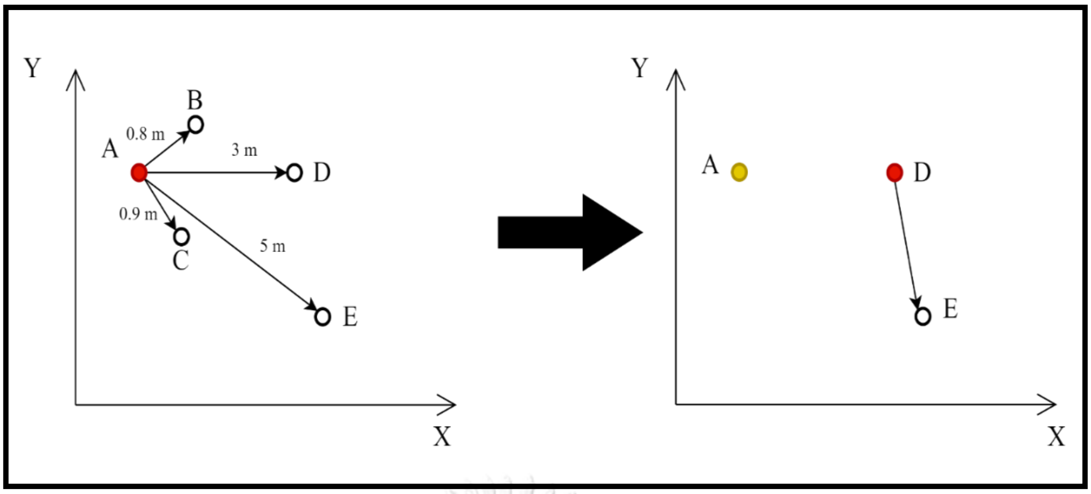



*Figure 4.21 Reducing the random points*

In order to get the temporary position of fire extinguishers, A star algorithm is applied to generate the corner points on the evaluation routes to the nearest exit from the resulting random points. In Figure (4.22), the green lines are the evacuation routes from the random points, and the yellow spheres represent the temporary locations of the fire extinguishers or the corner points. All of the locations of the corner points are put into the array.

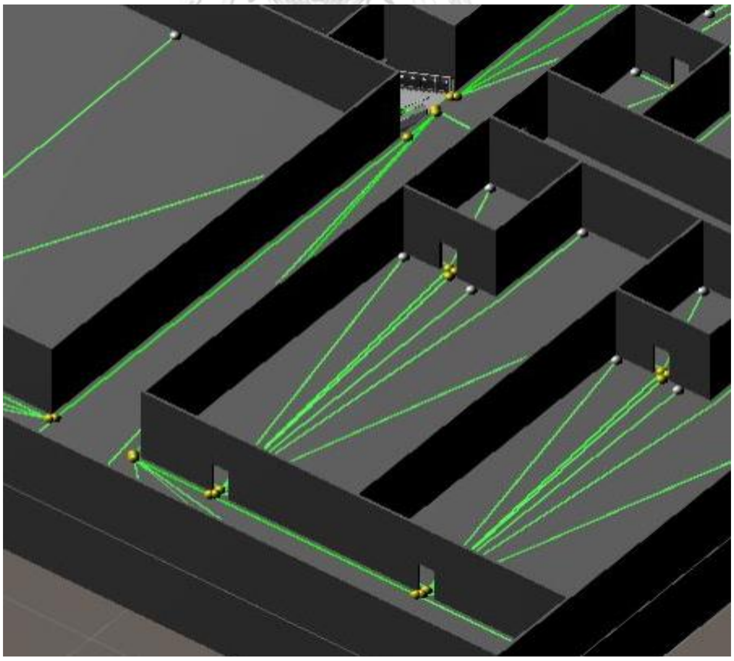


*Figure 4.22 Corner points on the evacuation routes*

Afterward, the system finds the duplicate positions in terms of the vector3 (x, y, z) and counts the number of duplicate positions or the frequency. The corner points are removed when the frequency is less than four. The corner points are arranged in ascending order based on the frequency. The Figure (4.23) demonstrates that the determination of the level of priority of the corner points is in terms of frequency (e.g., the level of priority of the corner points near the main stair is higher than the one that is near the room, and these corner points have a higher chance to be placed as the fire extinguisher location).

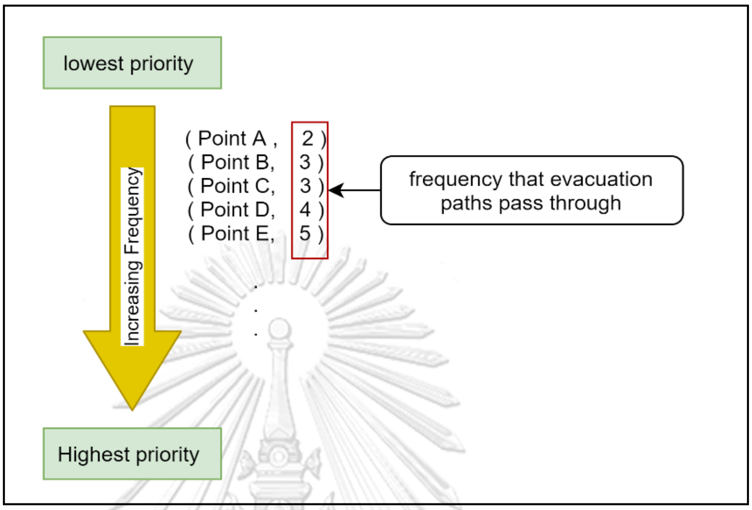



*Figure 4.23 Determining the priority with frequency*

To develop the final fire extinguisher installation plan, the corner points from the lowest priority level are removed, and the fire rules and regulations are checked (i.e., the fact that the distance between any random point and nearest corner point, or temporary fire extinguisher should not exceed 100 feet). If the rest of the location of the temporary fire extinguisher comply with the rules and regulations, the removed point is discarded permanently. If not, the removed corner point is added to the original state. After these processes have been done in every corner point, the final locations of the fire extinguishers appear on the 3D building model (Figure 4.24). For another rule and regulation (i.e., 10B fire extinguishers shall be provided within 50 feet of wherever more than 5 gallons of flammable or combustible liquids or 5 pounds of flammable gas are existed), the 10B fire extinguishers are placed near the flammable gas.

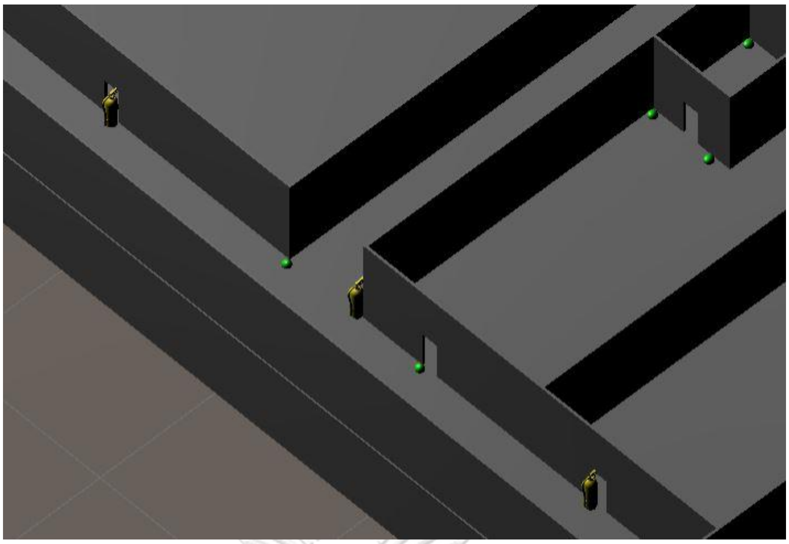


*Figure 4.24 The final fire extinguisher installation plan*

4.4.2 The algorithm of fire extinguisher installation plan for Thailand rules and regulations

According to Thailand rules and regulations, fire extinguishers must be placed every 1000 $m^2$ and the distance between fire extinguishers and any location in a construction building must not be greater than 45 m. To calculate the required number of fire extinguishers (2A), the floor area is measured based on the area of floor or slab from the BIM and divided by 1000 $m^2$. In order to develop these statements, the algorithm from Figure (4.25) is created. The early procedures are the same as the OSHA algorithm, while the procedures from yellow box are different.

After arranging the corner points in ascending order based on frequent, the corner points from the lowest priority level are removed, and the Thailand fire safety rules and regulations are checked (i.e., the fact that the distance between any random point and nearest corner point, or temporary fire extinguisher should not exceed 45 meters). After this step, the temporary fire extinguisher locations or locations which have potential to put fire extinguishers are produced. If the number of temporary fire extinguisher location is less than the required number of fire extinguisher, the distance between any random point and nearest corner point, or temporary fire extinguisher is reduced by 1 meter in order to increase the number of temporary fire extinguisher location and this statement is looped until the number of temporary fire extinguisher location equal with the required number of fire extinguisher. If the number of temporary fire extinguisher locations is equal or greater than the required number of fire extinguishers, the fire extinguishers are placed at temporary fire extinguisher location.

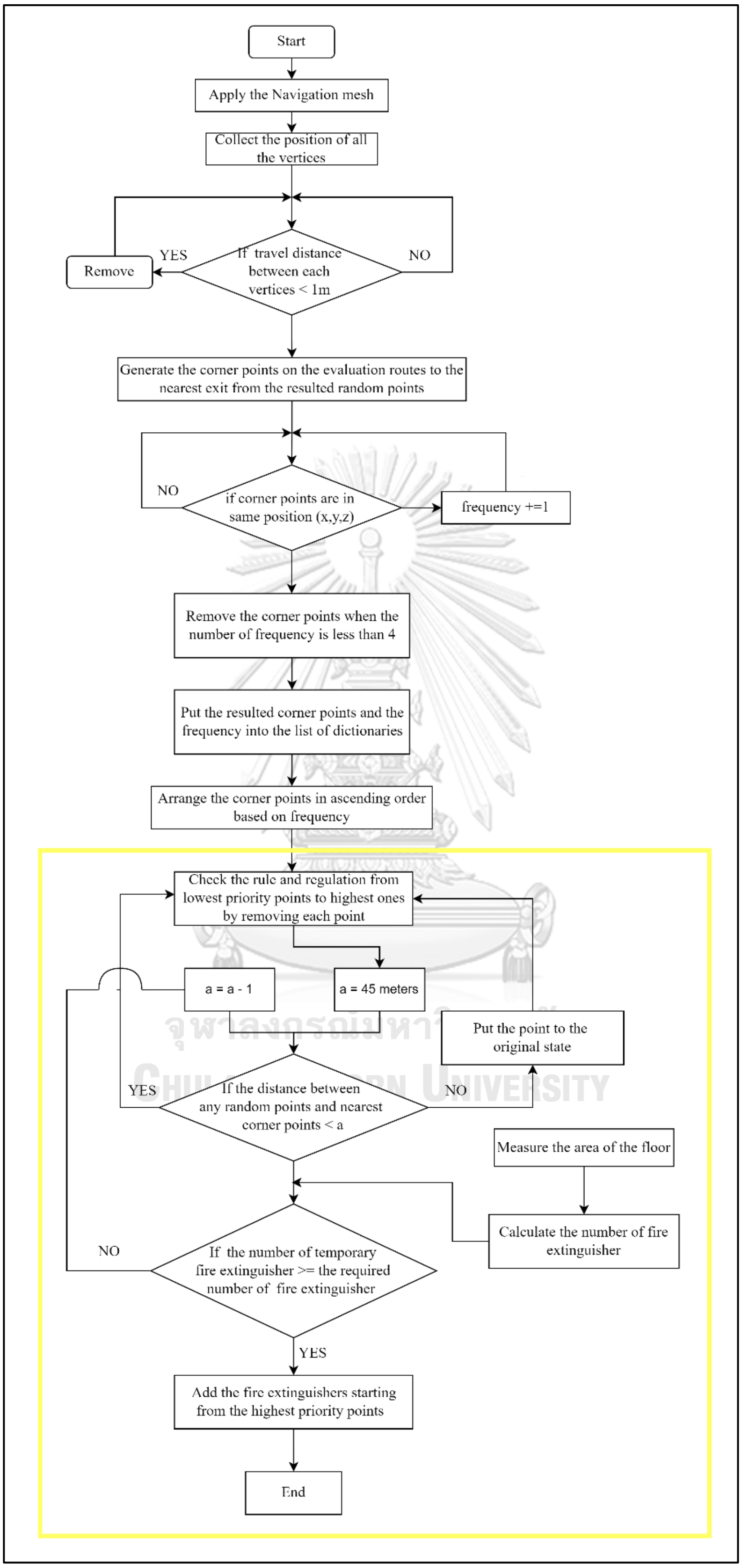



*Figure 4.25 The flow chart of the algorithm for fire extinguisher installation plan*

4.4.3 The algorithm for selecting the evacuation route

In this proposed system, producing the sub-optimal evacuation route is one of the common human errors in the constructions. The sub-optimal route is produced by in-charge personnel due to the nature of the terrains and amount of information that is needed to be considered. To rid the production of sub-optimal routes, the speed on different terrains is one of the major factors in the construction site. The flow chart of the algorithm is as shown in Figure (4.25).

At first, the system creates the starting point or area at the middle of the room according to the room information from BIM. The fastest evacuation route from the starting point is produced by applying the A star algorithm and collecting all of the corner points along the evacuation route (Figure 4.26). After that, the system measures the distance between each corner point along the way from starting point to endpoint. In order to calculate the total travel time of the evacuation route, the distance between each corner point is needed to be divided by “n” ratio (approximately 1 centimeter), using the equation in Figure (4.27). The distance between each corner point is rounded to the nearest integer since they will be divided proportionally.

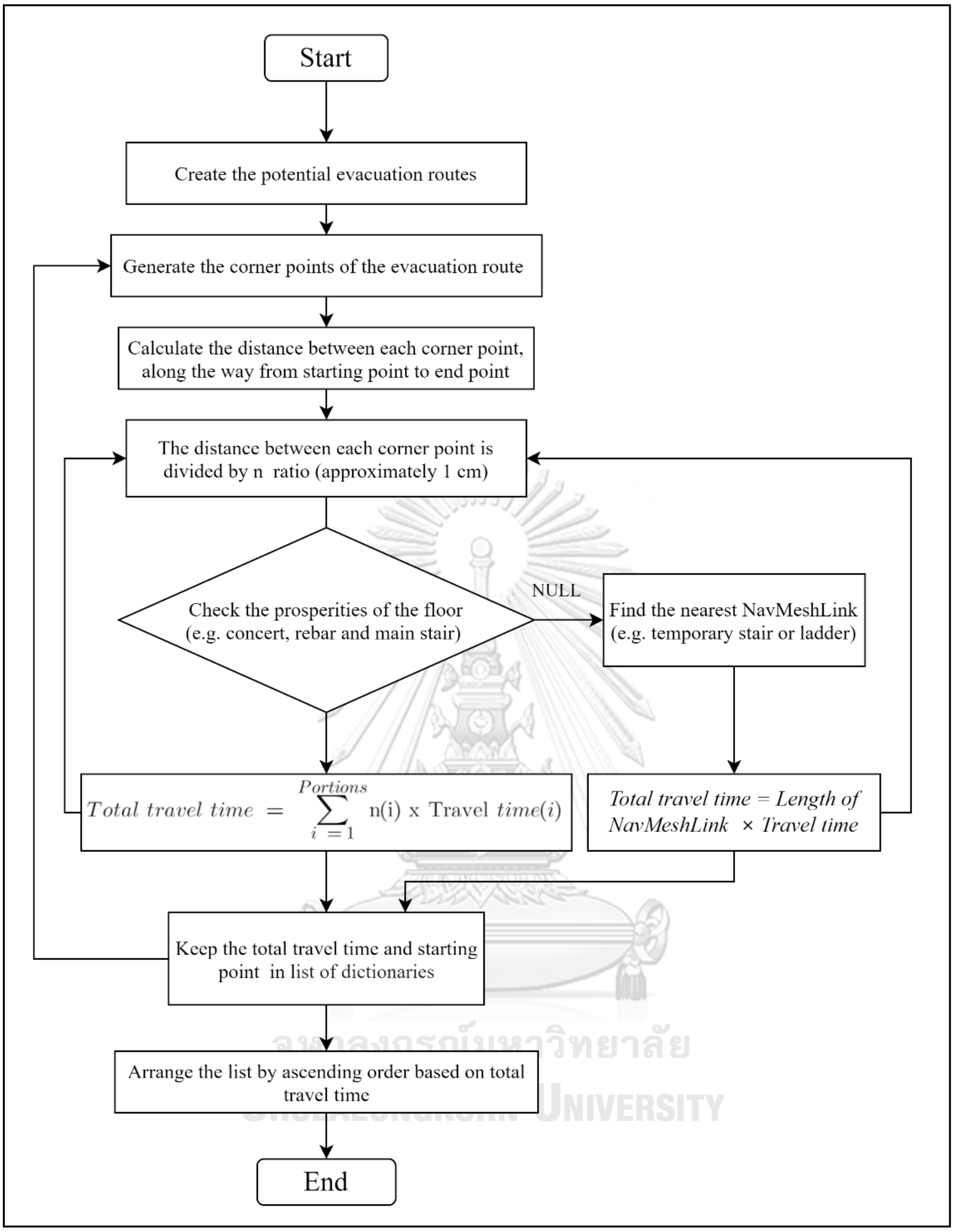



*Figure 4.26 Flow chart of the algorithm for selecting the evacuation route*

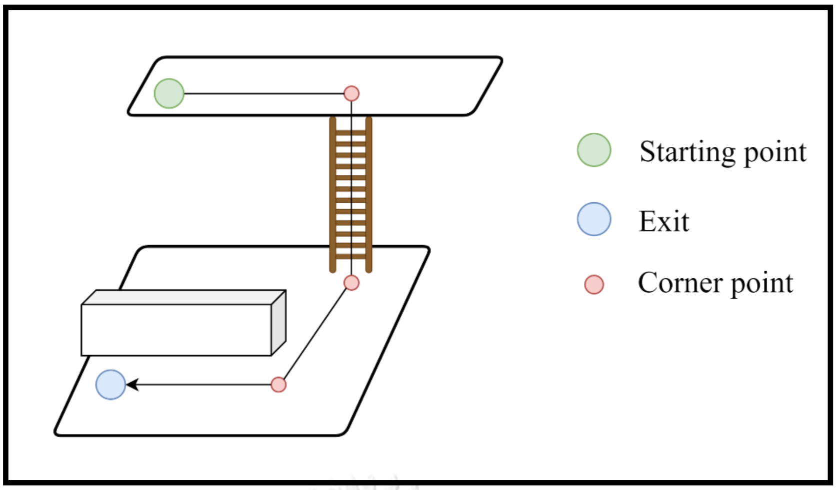



*Figure 4.27 The corner points on the evacuation route*

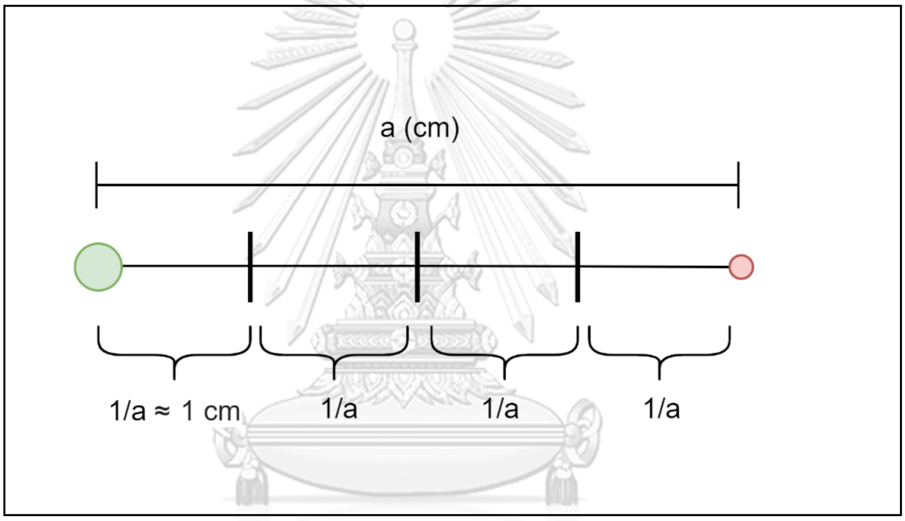



*Figure 4.28 The divided portions between the two corner points*

$$n = \frac{\textit{The distance between two corner points}}{\textit{The distance between two corner point that rounded to nearest integer}} \quad (4)$$

where, n = the length of the portion.

Following this, the endpoints of every portion are defined by using the API called vector3.lerp. The type of NavMesh at the endpoint of every portion is checked by using SamplePoint API and the values of area cost are mentioned in Table. But, the SamplePoint API can only check the NavMesh types and it produces "null" as the result at the NavmeshLink (e.g., temporary stair or ladder). Therefore, two types of equations are used to calculate the travel time between two corner points and the example of checking the prosperities of floor and link are shown in Figure (4.28).

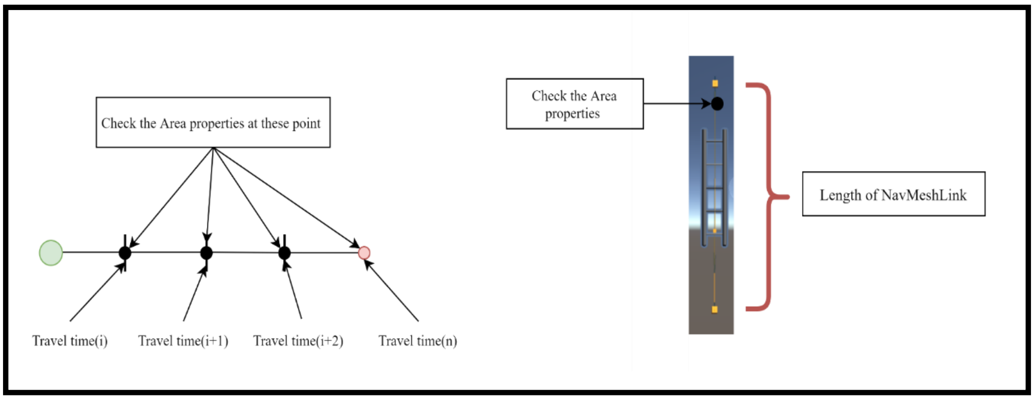



*Figure 4.29 Checking the properties of area and devices*

$$Total\ travel\ time = \sum_{i=1}^{Portions} n(i)\ x\ Travel\ time(i) \tag{5}$$

$$Cost = length\ of\ NavMeshLink\ x\ Travel\ time \tag{6}$$

where, n = the length of the portion

i = 1,2,3, ......, n.

The procedures are carried out for the rest of the corner points and calculate the total cost by combining all of the costs. Then, the total cost and exit are saved in the list of dictionaries. The rest of the evacuation routes follow the same procedure, and all of the total cost is saved in the list. The list of dictionaries is arranged in descending order based on the total cost, and the lowest total cost is selected as the optimal evacuation route.

# CHAPTER 5

## Case Study and System Validation

5.1 Introduction

In this chapter, the proposed system, which is developed to support not only safety engineers and construction personnel in producing the fire extinguisher installation plan and evacuation path plan, but also workers in evacuation process during emergency cases, will be tested to prove its precision and efficiency. Due to the Covid-19, the proposed system cannot be tested in real construction sites. Therefore, different scenarios are created on the sample building model and real construction building to perform as the case studies. After the process, this system is validated by the safety engineers and construction personnel.

5.2 Case study

At first, the architectural model from the Revit was exported into the NWC file in order to open the model on Navisworks. After that, the FBX file was exported from Navisworks and input the model to the Unity game engine. In Unity, the doors and windows from the model need to be deleted.

Users need to use the user inputs in order to create the real construction conditions in Unity software. First, building element status defines the structural design and surface condition in terms of current construction progress (e.g., the wall is finished or not). Second, the location of materials, temporary stairs and ladder, fire extinguishers and exits should be defined from the construction site. Figure 3 shows how to assign the user input that simulates the desired construction site conditions. To identify the finished components and unfinished components, users need to click the building object in Unity's scene (green box) and change the properties by using the layers (yellow box). The other user inputs such as the location of materials, temporary stairs and ladder, and exits can be input by dragging the model from the prefab file (red box) into the scene and then place to desired locations.

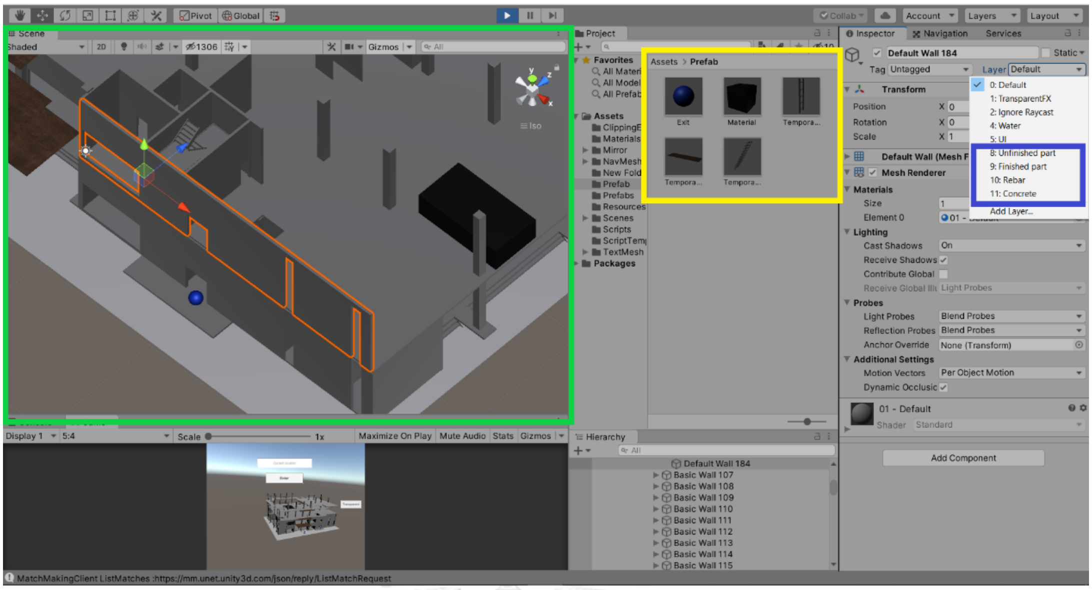


*Figure 5.1 User interface for inputting the user input*

There are many functions that are developed in the proposed system, such as generating and assessing fire extinguisher installation plans (OSHA and Thailand fire safety rule), illustrating the unsafe work areas, and presenting virtual objects regarding safety. The functions that are mentioned will be tested in this section. As described in the literature review, some of the factors have affected the rules and regulations for the fire extinguisher installation plan and evacuation paths. Therefore, the functions are tested according to the changing factors such as flammable substances, exits, finished and unfinished components, material locations, temporary stair and ladder, fire extinguishers and properties of floor to verify their accuracy on sample building and real construction building.



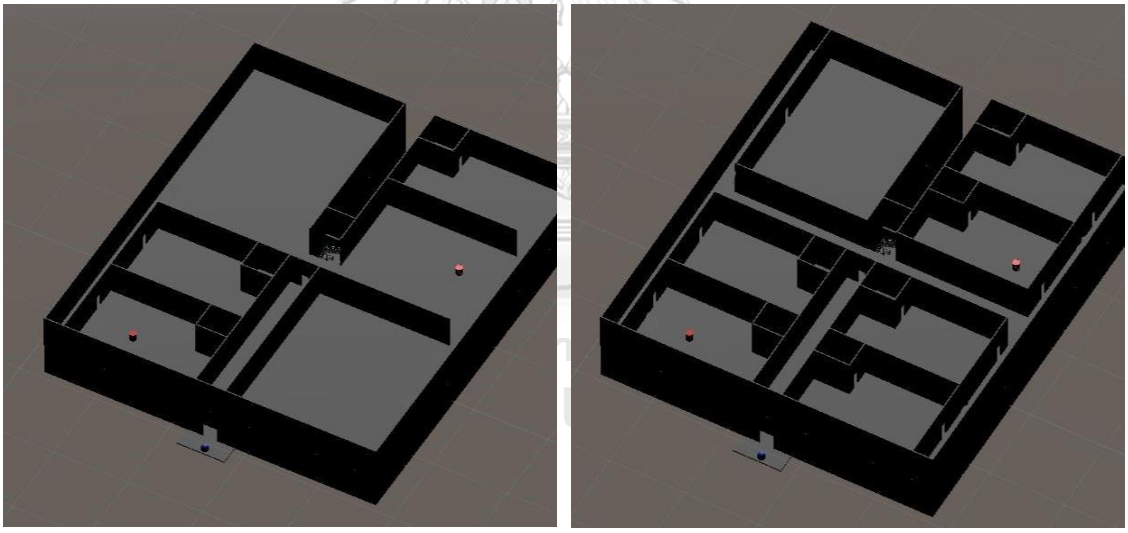
5.2.1 Generation of the fire extinguishers installation plan

In order to assess the function for developing a fire extinguisher installation plan, sample building model (C) and real construction building model (D) are set. Sample model has two floors and the second floor is taken as a representative to test the proposed system. Real construction building model is the 17-story building and the system will be tested on the 1$^{st}$, 2$^{nd}$, 3$^{rd}$ and 4$^{th}$ floors. In these two models, different scenarios (1C, 2C, 1D and 2D) that have different site conditions will be created. In this case study, two sections are divided as the functions that follow (1) fire safety rule of OSHA and (2) fire safety rule of Thailand. The main purpose is to validate the fact that the proposed system is able to generate the locations of fire extinguishers according to the rules and regulations of OSHA and Thailand, and can also handle different factors that have effect on the fire extinguisher installation plans.

5.2.1.1 Generation of the fire extinguishers installation plan which follow the fire safety of OSHA

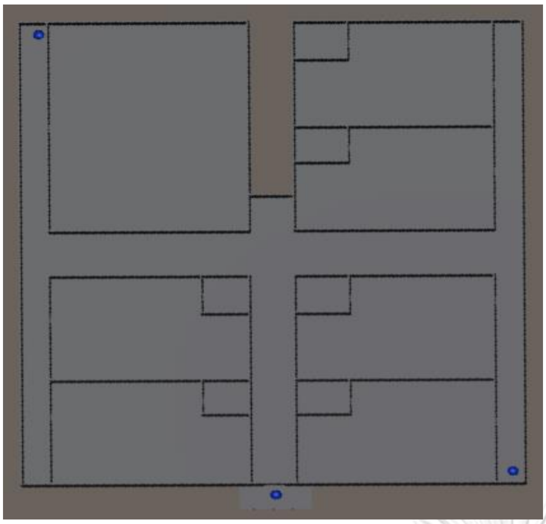
**<u>Testing on scenarios 1C and 2C in sample building</u>**

Firstly, the function is tested on the sample building (C). Two scenarios (1C and 2C) are created by using the user inputs such as finished and unfinished components, flammable substances and exits. Scenario model 1C shows that some walls from the second floor are not finished and Scenario model 2C simulates all models of the structure, and architectural works are completed (see Figure 5.2 (b)). The flammable substances are placed in the same location in both scenarios. In this system, the blue sphere and red slender represent the exit and flammable substance, respectively.

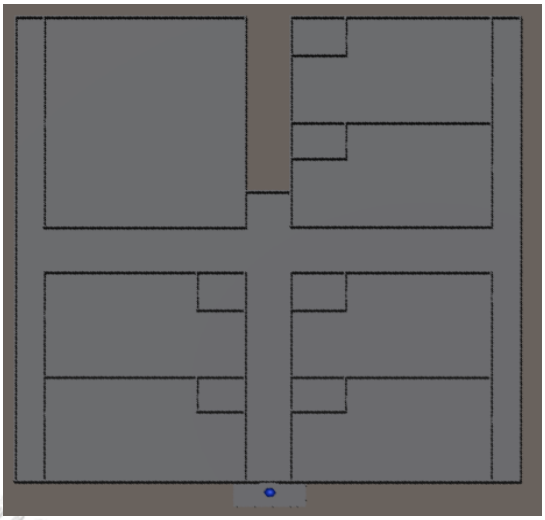


(a) Scenario 1C (b) Scenario 2C

*Figure 5.2 3D view of scenario 1C and 2C on sample building*



(a) Top view of 1st floor of scenario 1C



(b) Top view of 1st floor of scenario 2C

*Figure 5.3 Top View of 1st floor of two scenario on sample building*

In Figure (5.3), the 1st floor of each scenario is presented. The completed walls or structure are the same but the locations of exit are different in each scenario. In scenario 1C, three exits are placed while only one exit is added in scenario 2C. The main purpose of adding a different number of exits is to check the fact that the system can generate the fire extinguishers installation plan according to the common locations or corridors.

The generated fire extinguisher installation plans for two scenarios are shown in Figure (5.4). The results show that some locations of fire extinguishers are different but the number of fire extinguishers is still the same in these given scenarios. The location of the fire extinguisher in the yellow box is not the same due to the difference in evacuation paths from room R1. In 2C, there is only one exit (E1) and the system chooses the route to the E1 as the evacuation path from room R1. So, the corner becomes the common location and the system places the fire extinguisher at this corner. While, in 1A, the door corner becomes the common location because the evacuation paths from room R1 choose the second exit (E2), and the door corner becomes the point where several evacuation paths pass through. The location of the fire extinguisher from the green box is different in both scenarios because the system prioritizes the exit more than the common location, during the placement of fire extinguishers.


(a) FEIP for 1st floor of scenario 1C (b) FEIP for 1st floor of scenario 2C

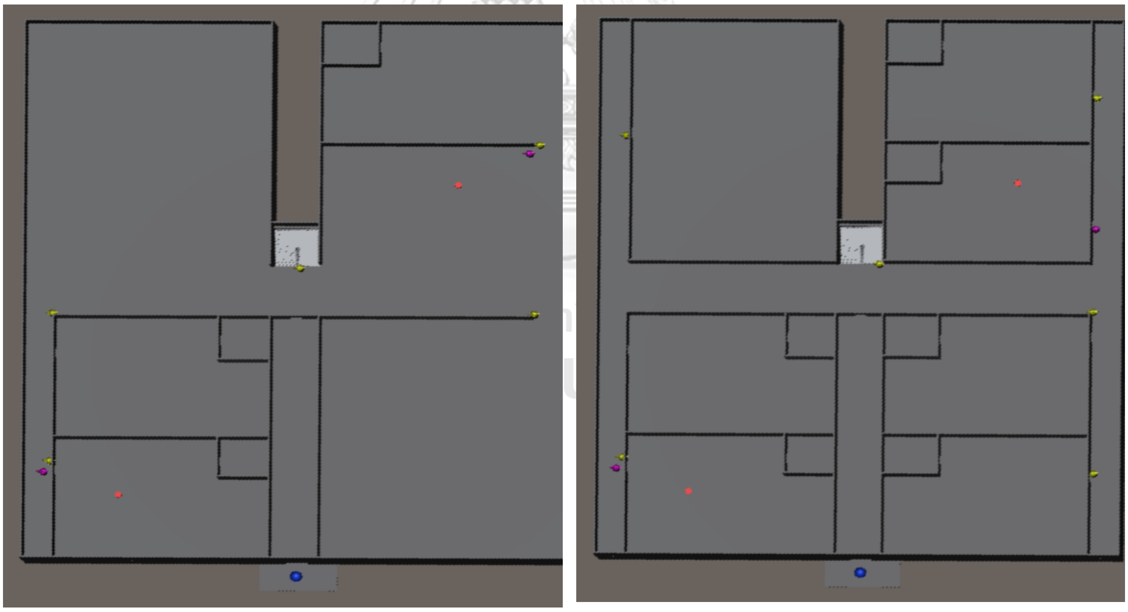
*Figure 5.4 Fire extinguisher installation plan (FEIP) for 1st floor of two scenarios on sample building*

(a) Top view of 2nd floor of scenario 1C (b) Top view of 2nd floor of scenario 2C

*Figure 5.5 Top View of the 2nd floor of two scenario on sample building*

Figure (5.5) demonstrates the building structure of the 2nd floor of scenario 1C and 2C. The locations of flammable substances are the same in both scenarios, however, the completed and uncompleted walls are different. In 1C, some of the walls are uncompleted while all of the walls are finished in 2C. From these two scenarios, it will be tested whether the system can produce the fire extinguishers installation plan according to the building structure based on the construction progress.

After running the system, the results present the fire extinguishers installation plan, containing two different types of fire extinguisher, 2A and 10B (see Figure 5.6). The number of fire extinguishers (2A) is also different in both cases. The system allocates four fire extinguishers (2A) in 1C, while five fire extinguishers (2A) are added in 2C. The site condition of the 2$^{nd}$ floor of 2C scenario is more complex than that of 1C, because all the walls are finished. This results in a longer travel distance when it is measured from random points to fire extinguishers. Moreover, the locations of fire extinguishers are not the same in both scenarios due to the fact that the system generates the plan based on the construction site conditions. The system also places 10B fire extinguishers on 1C and 2C since both scenarios have flammable substances. Hence, it can be noted that the system can handle the difference in construction site conditions when it is used to generate the fire extinguishers installation plans.

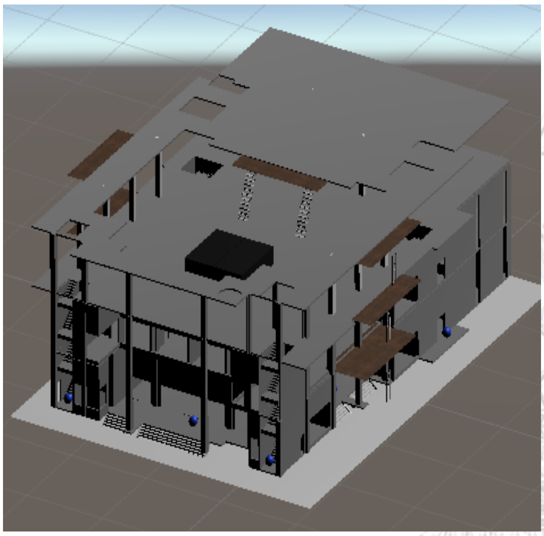


(a) FEIP for 2$^{nd}$ floor of scenario 1A (b) FEIP for 2$^{nd}$ floor of scenario 1A

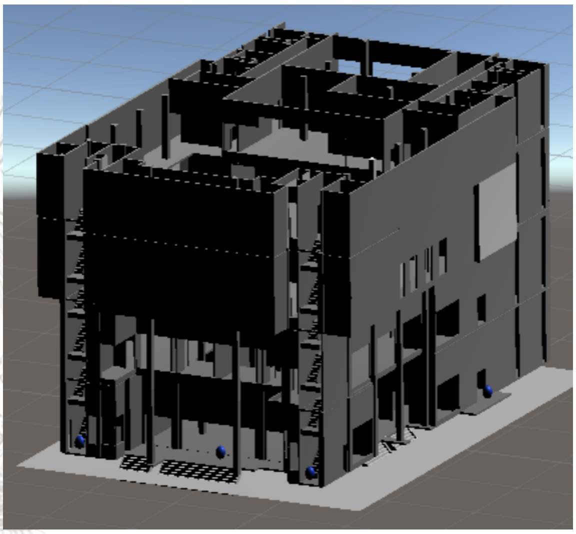
*Figure 5.6 Fire extinguisher installation plan (FEIP) for 2$^{nd}$ floor of two scenarios on sample building*

**Testing on scenarios 1D and 2D in real construction project**

The function for the fire extinguisher installation plan is tested on the real construction building (D). In this building design, two scenarios are created, noting as 1D and 2D. Scenario 1D is created as the construction phase while 2D is created as a finishing phase. The locations of exits are placed at the same location in both scenarios but that of flammable substances are different. Temporary stairs and ladders are used in 1D.



(a) 3D view of scenario 1D



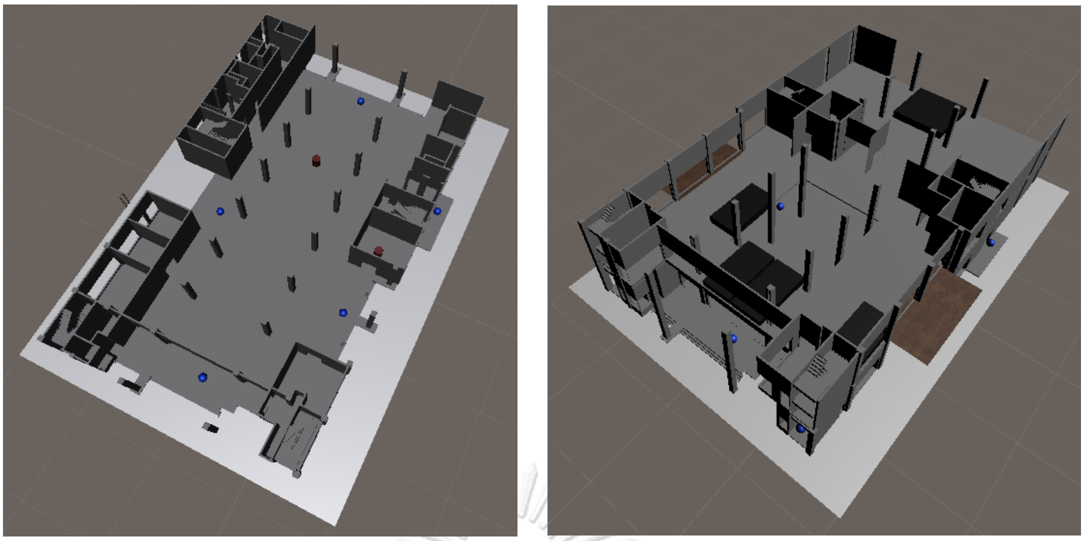
(b) 3D view of scenario 2D

*Figure 5.7 3D view of scenario 1D and 2D on real building*



Scenarios 1D

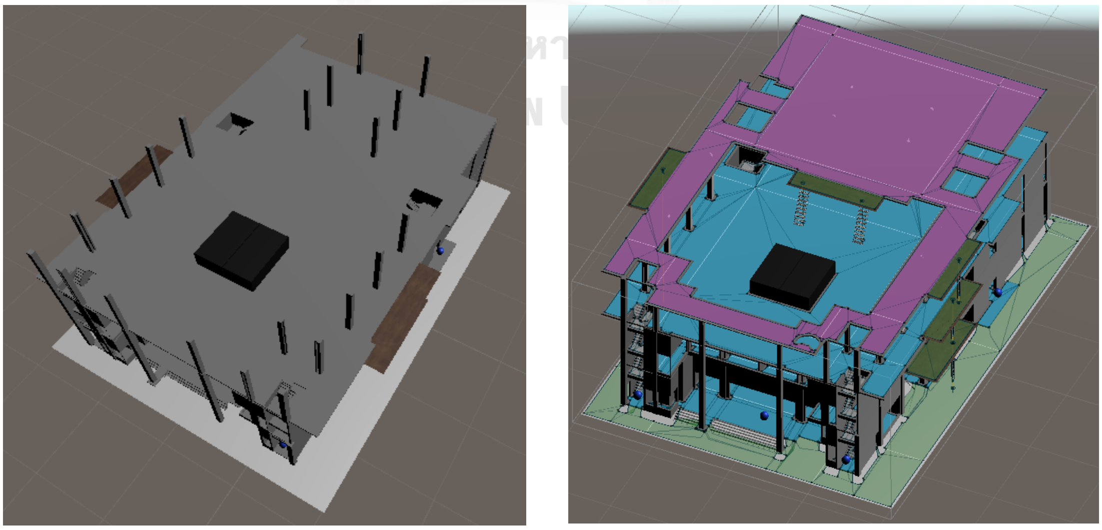
Figure 5.8 (a) demonstrates that the 1st floor and walls are unfinished in the building. Two flammable substances (red slender) are placed in a room and hall, and seven exits (blue spheres) are placed. On second floors, construction materials (black box) are positioned and temporary ladders from 1st floor to 2nd floor are added on both sides of the building.



(a) 3D view of 1st floor of scenario 1D (b) 3D view of 2nd floor of scenario 1D

*Figure 5.8 3D view of 1st and 2nd floors of scenario 1D*

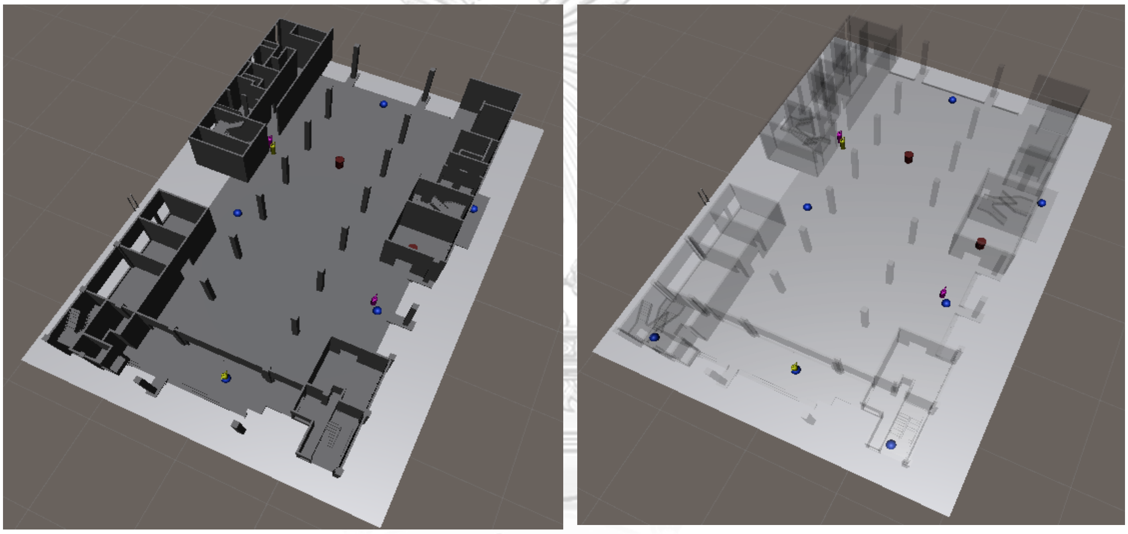
The structural design of 3rd and 4th floors of 1D can be seen in Figure (5.9). On the 3rd floor, the walls are not finished and the materials are placed. Two temporary ladders from 2nd floor to 3rd floor are placed on both sides of the building. The temporary stairs from 3rd floor to 4th floor are placed in the middle of the 4th floor, and temporary ladders are placed on both sides of the building. The floor of the 4th is in rebar condition (red surface).



(a) 3D view of 3rd floor of scenario 1D (b) 3D view of 4th floor of scenario 1D

*Figure 5.9 3D view of 3rd and 4th floors of scenario 1D*

The fire extinguisher installation plans for $1^{st}$, $2^{nd}$ and $3^{rd}$ floors of 1D are shown in Figure (5.10), Figure (5.11) and Figure (5.12), respectively. Three (2A) and two (10B) fire extinguishers are placed for the $1^{st}$ floor's FEIP. In the $2^{nd}$ floor's FEIP, three (2A) fire extinguishers are needed according to the rules and regulations, and two fire extinguishers are placed at the stairs. There is not a single (10B) fire extinguisher in the $2^{nd}$ floor since flammable substances are not positioned there (see Figure 5.11). In Figure (5.12), the FEIP of the $3^{rd}$ floor is presented and it can be witnessed that four (2A) fire extinguishers are placed at four stairs, while 10B fire extinguishers are not considered necessary for the $3^{rd}$ floor. For the $4^{th}$ floor, there is no FEIP because fire extinguishers should not be placed in rebar condition.

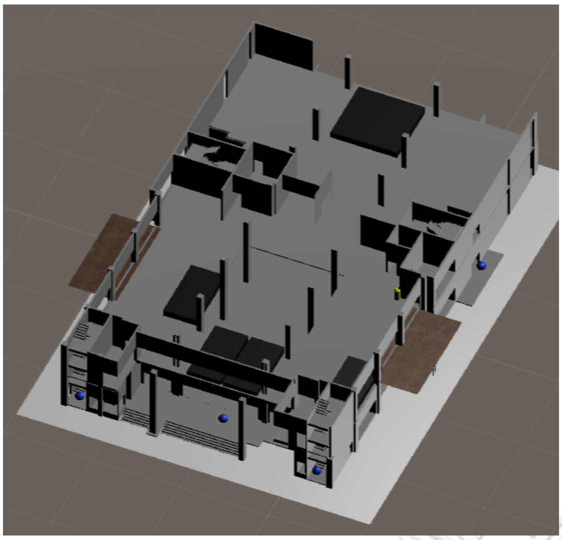


(a) FEIP for $1^{st}$ floor of scenario 1D

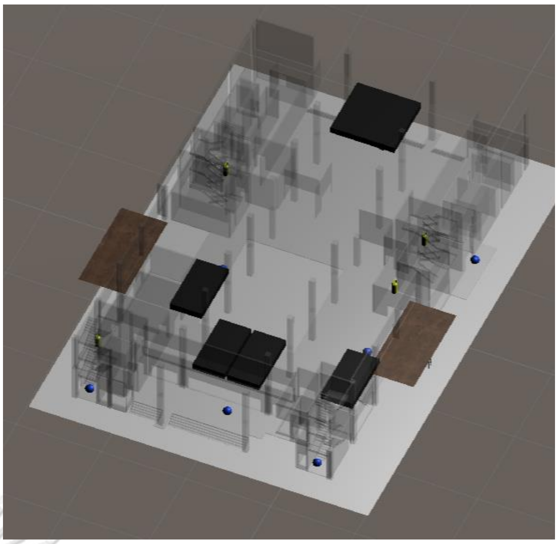
(b) FEIP for $1^{st}$ floor of scenario 1D (Transparent view)



*Figure 5.10 Fire extinguisher installation plan for $1^{st}$ floor of scenario 1D*



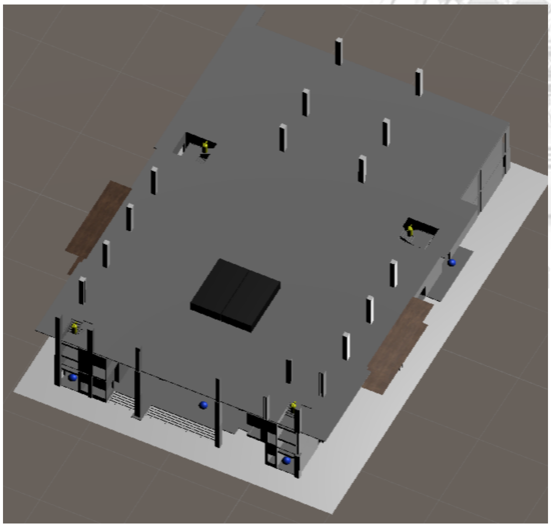
(a) FEIP for 2nd floor of scenario 1D



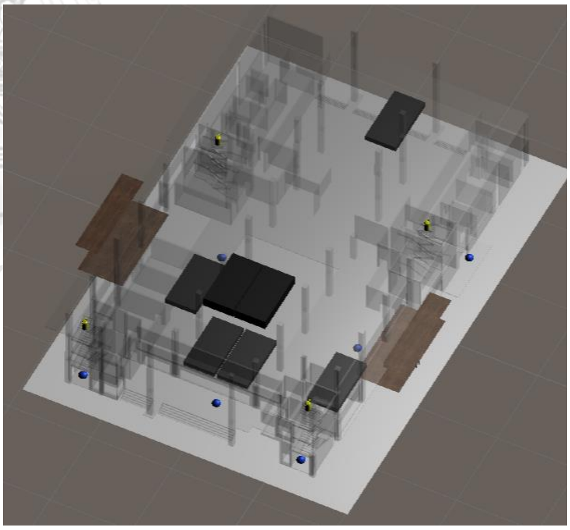
(b) FEIP for 2nd floor of scenario 1D

(Transparent view)

*Figure 5.11 Fire extinguisher installation plan for 2nd floor of scenario 1D*



(a) FEIP for 3rd floor of scenario 1D



(b) FEIP for 3rd floor of scenario 1D

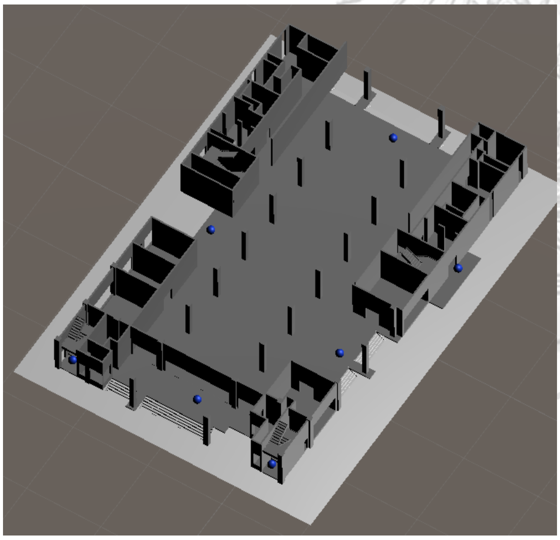
(Transparent view)

*Figure 5.12 Fire extinguisher installation plan for 3rd floor of scenario 1D*

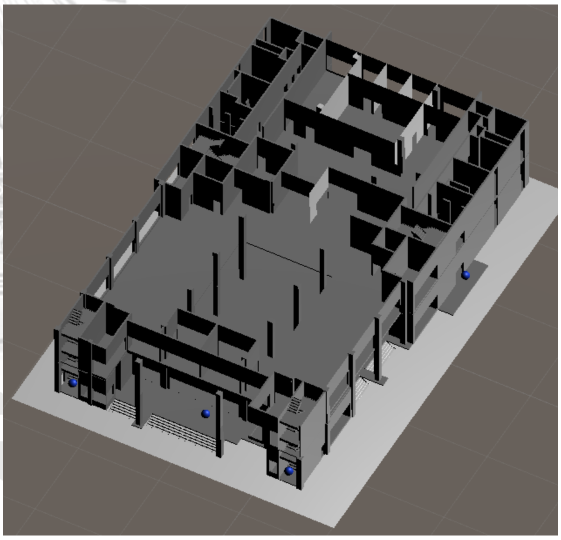
Scenario 2D

In scenario 2D, it is considered that all structural walls of the building are completed. Figure (5.13) and Figure (5.14) illustrate the 3D view of the scenario 2D. In this scenario, a flammable substance is placed on the 3rd floor (see Figure 5.14 (a)).

The fire extinguisher installation plan of the 1st, 2nd, 3rd and 4th floors are shown as transparent views in Figure (5.15) and Figure (5.16), respectively. In Figure (5.15), three (2A) fire extinguishers are placed on both 1st and 2nd floors, while the chosen location is the exits in 1st floor and stairs in 2nd floor. Figure 5.16 (a) shows that two types of fire extinguishers are placed on the 3rd floor. Four (2A) fire extinguishers are placed at the stairs and one (10B) fire extinguisher is added at the corner of the room which is near the flammable substance. For the 4th floor, only four (2A) fire extinguishers are needed based on rules and regulations.

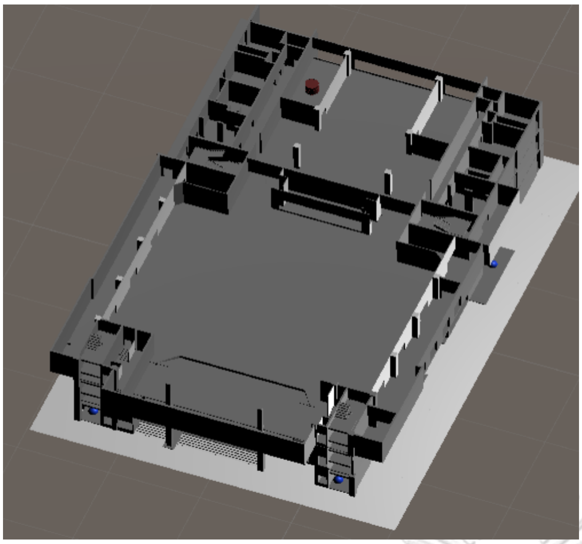


(a) 3D view of 1st floor of scenario 2D

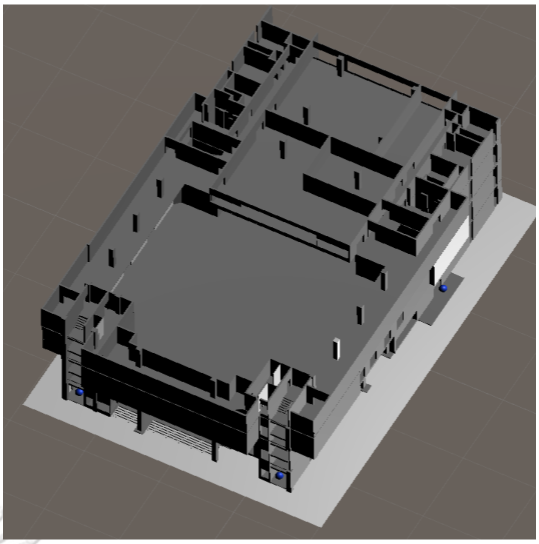


(b) 3D view of 2nd floor of scenario 2D

*Figure 5.13 3D view of 1st and 2nd floors of scenario 2D*

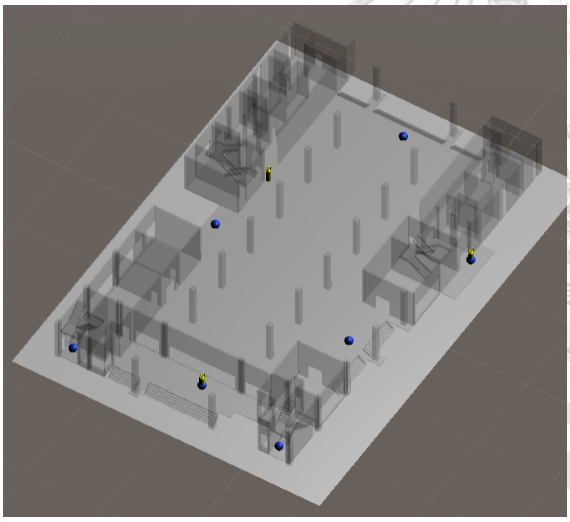


(a) 3D view of 3rd floor of scenario 2D



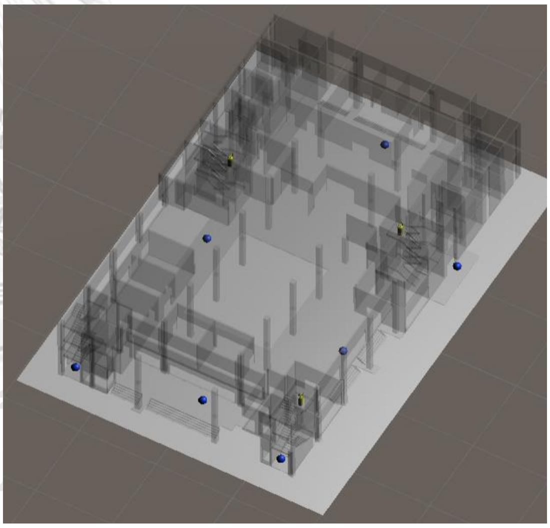
(b) 3D view of 4th floor of scenario 2D

*Figure 5.14* 3D view of 3rd and 4th floors of scenario 2D



(a) FEIP for 1st floor of scenario 2D

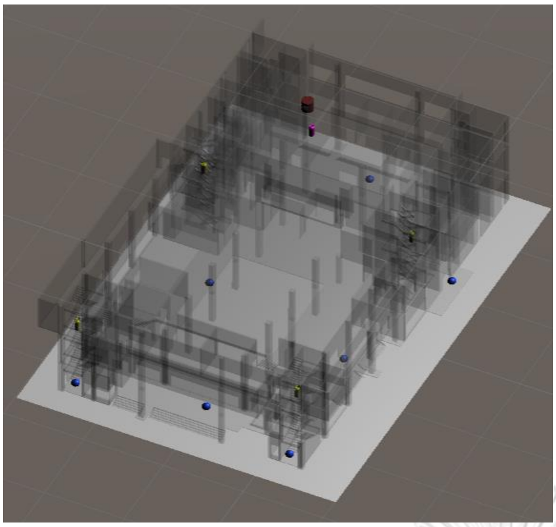
(Transparent view)

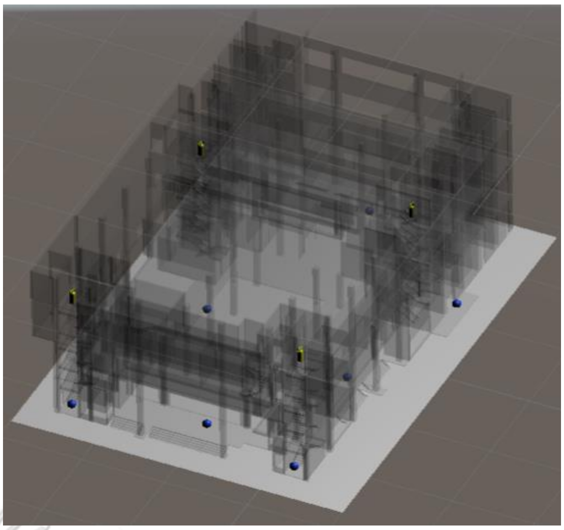


(b) FEIP for 2nd floor of scenario 2D

(Transparent view)

*Figure 5.15* Fire extinguisher installation plan for 1st and 2nd floors of scenario 2D





(a) FEIP for 3rd floor of scenario 1D (Transparent view)

(b) FEIP for 4th floor of scenario 1D (Transparent view)

*Figure 5.16* Fire extinguisher installation plan for 3rd and 4th floors of scenario 1D

**Running time in scenario 1C, 2C, 1D and 2D**

The running time of each scenario in generating the fire extinguisher installation plan is displayed in Table 5.1. In scenario 1C, there are 3 exits on the 1st floor, and this has led to more corner points compared to the situation having only one exit. Therefore, the running time of the 1st floor of 1C is a little higher than that of 2C. The running time of the 2nd floor of 1C, and the 1st and the 2nd floors of 2C are the same.

For the 1st floor of scenario 1D, two flammable substances are placed, hence, it takes more time than the other. The 2nd and 3rd floors of 1D take seven seconds and six seconds running time, respectively. Since the completed structure of 2D is more complex than that of 1D, running time of 2nd and 3rd floors of 1D is higher than that of 2D. Nevertheless, the running time of the 1st floor of 2D is lower than the 1st floor of 1D because there is no flammable substance in 2D, where the system does not need to consider (10B) fire extinguishers. It can be determined that all the running times are within the acceptable range for implementing in real life scenarios.

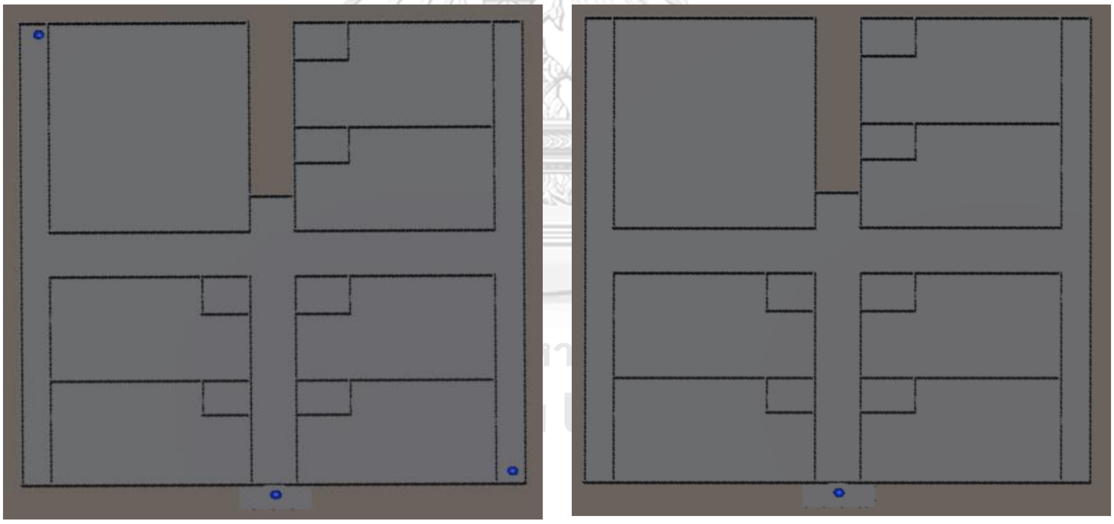
*Table 5.1 System running time of four scenarios*

| Scenario | 1C | | 2C | | 1D | | | 2D | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Floor number | 1st floor | 2nd floor | 1st floor | 2nd floor | 1st floor | 2nd floor | 3rd floor | 1st floor | 2nd floor | 3rd floor | 4th floor |
| Running time (s) | 8 | 6 | 6 | 6 | 36 | 7 | 6 | 14 | 17 | 56 | 33 |

5.2.1.2 Generation of the fire extinguishers installation plan which follow the fire safety rules of Thailand

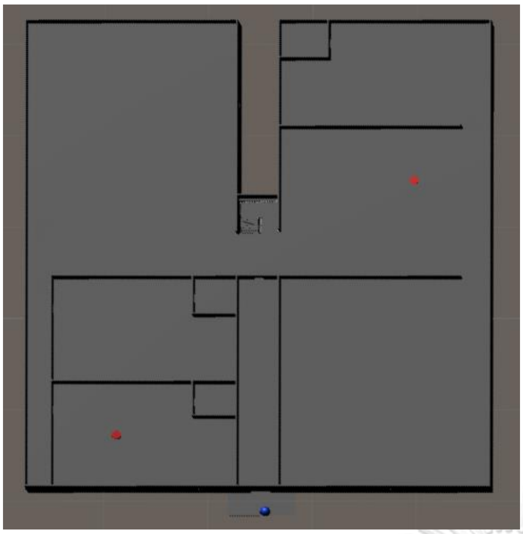
**<u>Testing on scenarios 1C and 2C in sample building</u>**

Figure (5.17) and Figure (5.18) show the 1st and 2nd floors of the scenarios 1C and 2C. The structure design of the scenarios and locations of the exits and flammable are the same as the previous testing (5.2.1.2).

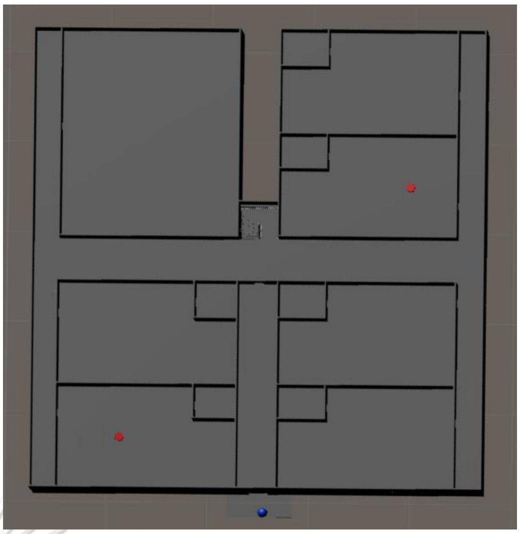


(a) Top view of 1st floor of scenario 1C (b) Top view of 1st floor of scenario 2C

*Figure 5.17 Top View of 1st floor of two scenario on sample building*



(a) Top view of 2nd floor of scenario 1C



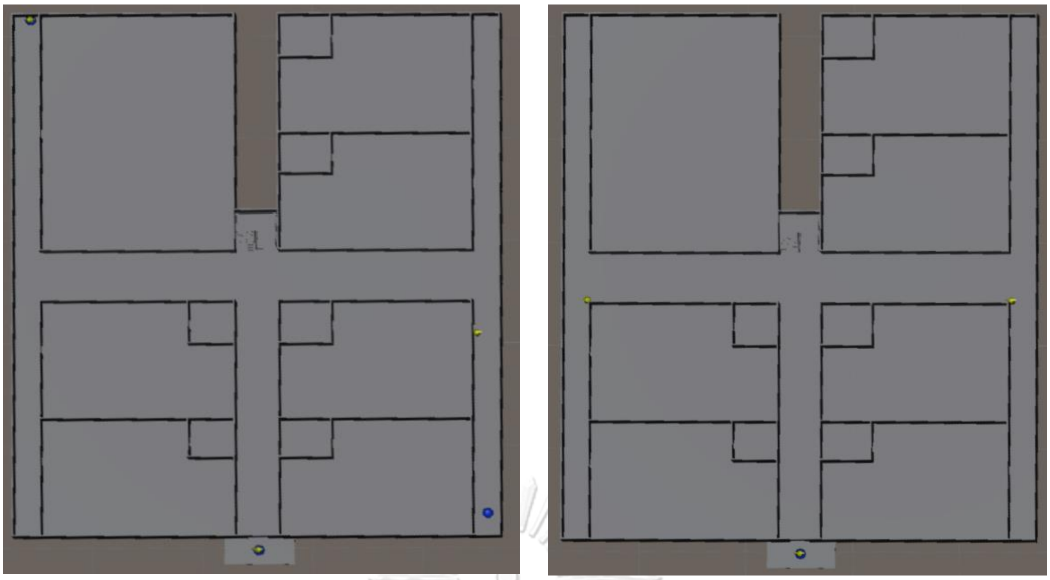
(b) Top view of 2nd floor of scenario 2C

*Figure 5.18 Top View of the 2nd floor of two scenario on sample building*

The generated fire extinguisher installation plans for the 1st and 2nd floors of two scenarios are shown in Figure (5.19) and Figure (5.20), respectively. The area of each floor of these scenarios is around 2200 square meters. Therefore, the results show that some locations of fire extinguishers are different but the number of fire extinguishers is still the same in these given scenarios.

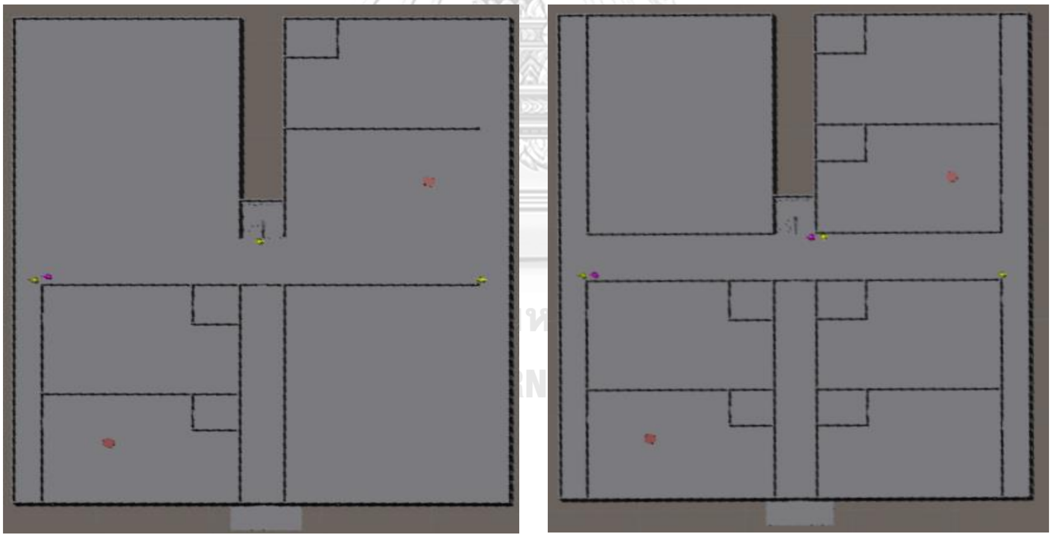
In Figure (5.19(a)), the two fire extinguishers are placed at two exits and another one fire extinguisher is at the room corner. The result of the 1st floor of scenario 2C shows that two fire extinguishers are placed at the room corner and one fire extinguisher is put at the exit. The locations of two 2A fire extinguishers are different in both scenarios because the system prioritizes the exit more than the common location, during the placement of fire extinguishers.

The system generated fire extinguisher installation plan of the 2nd floor of these scenarios are shown in Figure (5.20). The results show that the number and locations of fire extinguishers are the same in both scenarios. In Figure 5.20 (a), two 2A fire extinguishers and 10B fire extinguishers are at the corners and one fire extinguisher is near the stair. Two 10B fire extinguishers and three 2A fire extinguishers are required for the second floor (Figure 5.20 (b)).



(a) FEIP for 1st floor of scenario 1C (b) FEIP for 1st floor of scenario 2C

*Figure 5.19 Fire extinguisher installation plan (FEIP) for 1st floor of two scenarios on sample building*



(a) Top view of 2nd floor of scenario 1C (b) Top view of 2nd floor of scenario 2C

*Figure 5.20 Top View of the 2nd floor of two scenario on sample building*

**<u>Testing on scenarios 1D and 2D in real construction project</u>**

The function for the fire extinguisher installation plan is tested on the real construction building (D). The locations of exit, flammable substance and the building design of the scenarios 1D and 2D are the same as the previous testing (see Figure (5.7)). The area of each floor from these two scenarios are around 1400 square meters.

The fire extinguisher installation plans for 1st, 2nd and 3rd floors of 1D are shown in Figure (5.21), Figure (5.22) and Figure (5.23), respectively. The fire extinguisher installation plans show that two 2A fire extinguishers are placed in each floor because Thailand rule and regulations mentioned that there must be one fire extinguisher in every 1000 square meters. According to Figure 5.21, two 2A fire extinguishers are placed at exit and one 10B fire extinguisher is added because of the flammable substances. Two 2A fire extinguishers are placed at two staircases in Figure (5.22) and Figure (5.23).

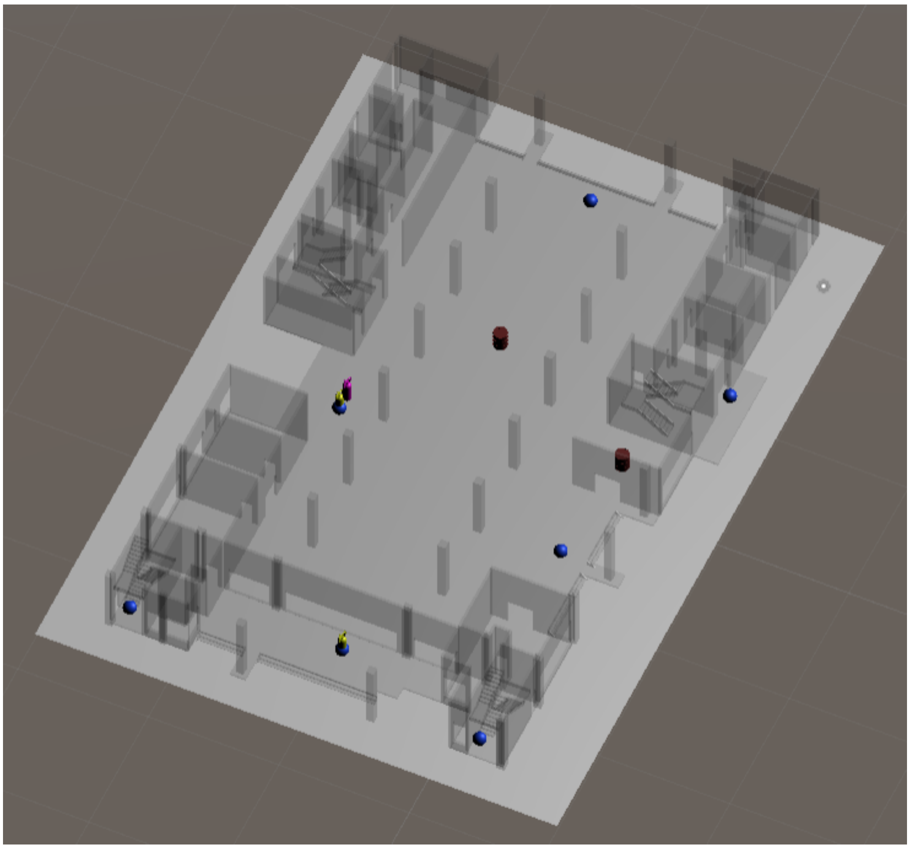


*Figure 5.21 Fire extinguisher installation plan for 1st floor of scenario 1D*

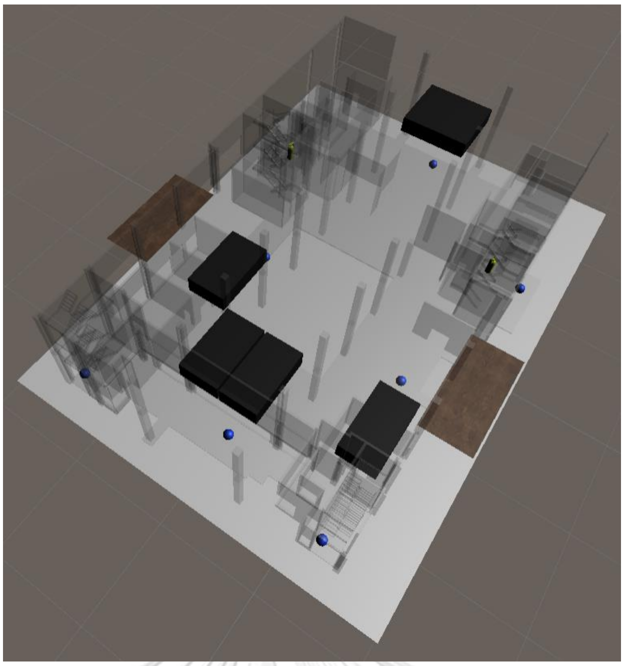


*Figure 5.22 Fire extinguisher installation plan for $2^{nd}$ floor of scenario 1D*

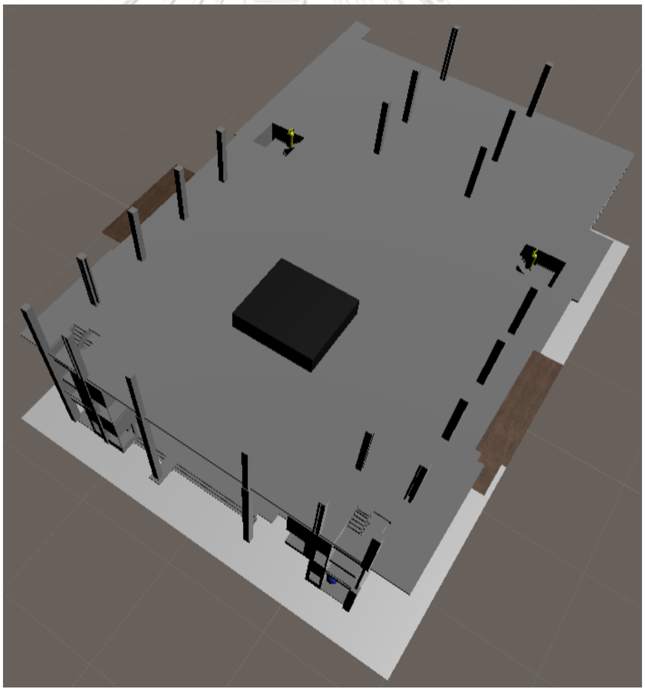


*Figure 5.23 Fire extinguisher installation plan for $3^{rd}$ floor of scenario 1D*

Scenario 2D

In scenario 2D, it is considered that all structural walls of the building are completed. In this scenario, flammable substances are placed on the 3rd floor.

The fire extinguisher installation plan of the 1st, 2nd, 3rd and 4th floors are shown as a transparent view in Figure (5.24), Figure (5.25), Figure (5.26) and Figure (5.27), respectively. In Figure 5.24, two (2A) fire extinguishers are placed at two exits on the 1st floor. Two 2A fire extinguishers are placed at two staircases on the 2nd, 3rd and 4th floors while one 10B fire extinguisher is placed on the 3rd.

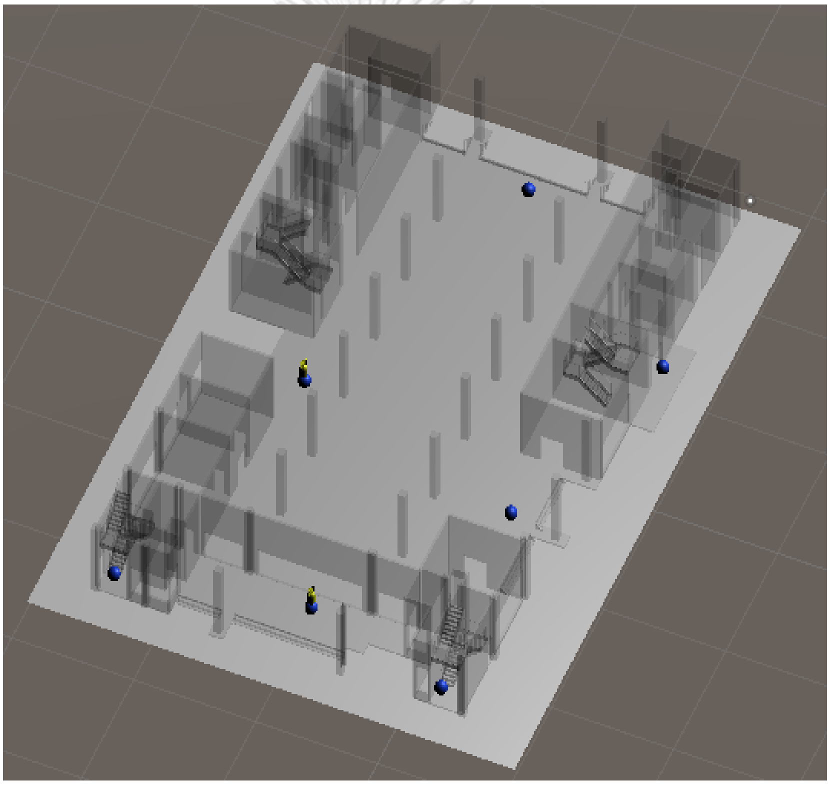


*Figure 5.24* Fire extinguisher installation plan for 1st floor of scenario 2D

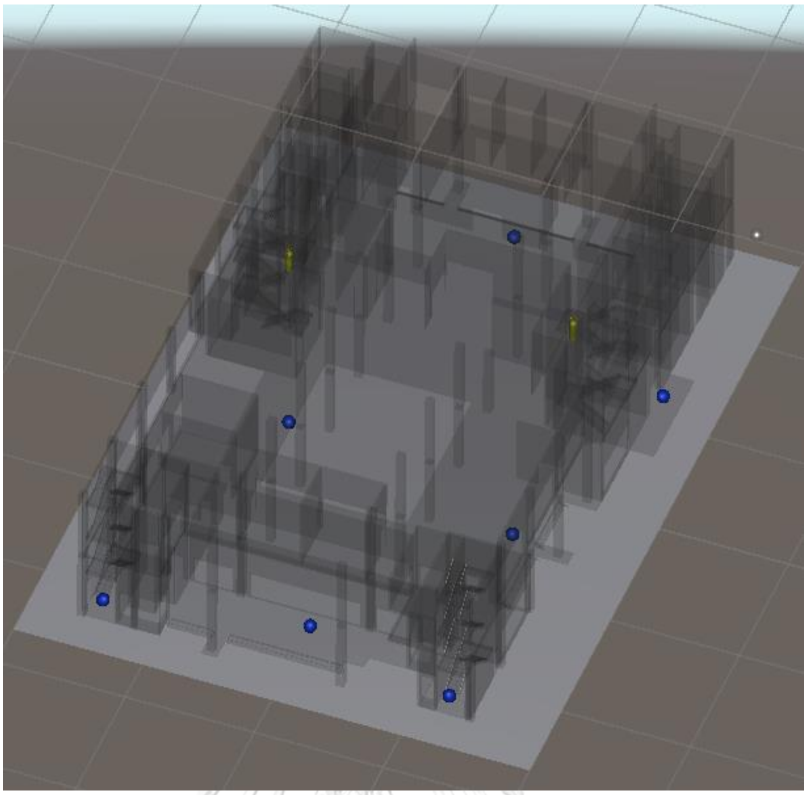


*Figure 5.25* Fire extinguisher installation plan for 1st and 2nd floors of scenario 2D

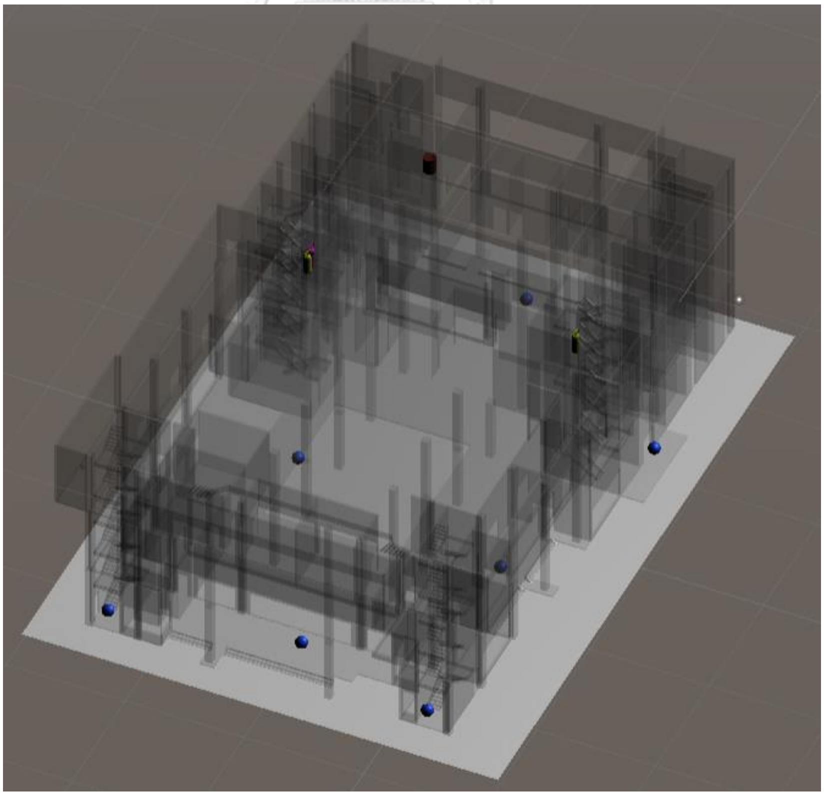


*Figure 5.26* Fire extinguisher installation plan for 3rd floor of scenario 1D

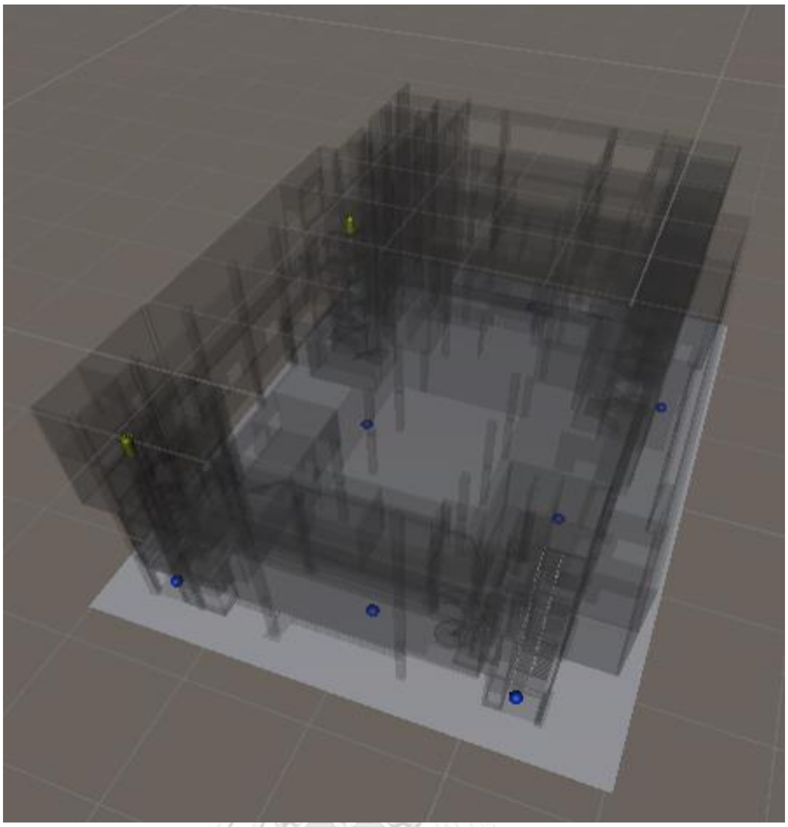


*Figure 5.27* Fire extinguisher installation plan for 4th floor of scenario 1D

**Running time in scenario 1C, 2C, 1D and 2D**

The running time of each scenario in generating the fire extinguisher installation plan which follows Thailand fire safety rules is displayed in Table 5.2. In scenario 1C, there are 3 exits on the 1st floor, and this has led to more corner points compared to the situation having only one exit. Therefore, the running time of the 1st floor of 1C is a little higher than that of 2C. The running time of the 2nd floor of 1C, and 1st and 2nd floors of 2C are the same.

For the 1st floor of scenario 1D, two flammable substances are placed, hence, it takes more time than the other. The 2nd and 3rd floors of 1D take seven seconds and six seconds running time, respectively. Since the completed structure of 2D is more complex than that of 1D, running time of 2nd and 3rd floors of 1D is higher than that of 2D. Nevertheless, the running time of the 1st floor of 2D is lower than the 1st floor of 1D because there is no flammable substance in 2D, where the system does not need to consider (10B) fire extinguishers. It can be determined that all the running times are within the acceptable range for implementing in real life scenarios.

*Table 5.2 System running time of four scenarios*

| Scenario | 1C | | 2C | | 1D | | | 2D | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Floor number | 1st floor | 2nd floor | 1st floor | 2nd floor | 1st floor | 2nd floor | 3rd floor | 1st floor | 2nd floor | 3rd floor | 4th floor |
| Running time (s) | 7 | 7 | 8 | 7 | 6 | 7 | 6 | 28 | 18 | 43 | 47 |

5.2.2 Assessment of fire extinguisher installation plan

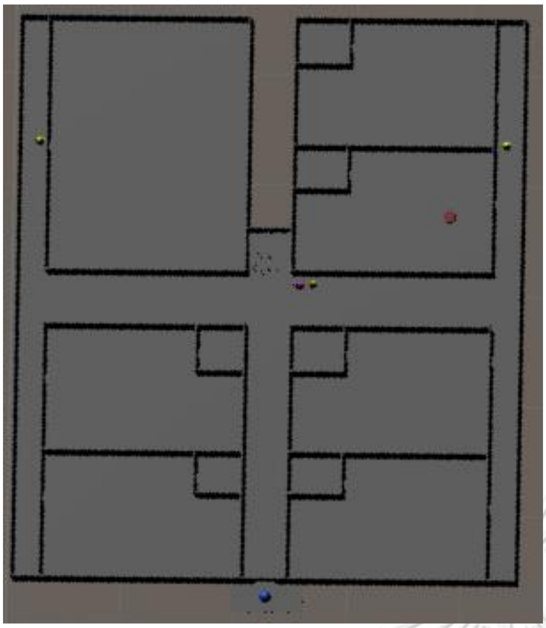
To verify the function, two scenarios are created on sample building (3C) and real construction project (3D). Both scenarios include two types of fire extinguisher and flammable substances. In the first scenario (3C), 1st and 2nd floors of the building are produced and tested. For 3D scenarios, 1st, 2nd and 3rd floors are created and applied for assessment. This testing can be divided into two sections such as (1) assessment according to OSHA rules and regulations and (2) assessment according to Thailand safety rules. The main purpose of testing on different scenarios with different locations of fire extinguishers and flammable substances is to validate the fact that the system can check if any fire extinguisher installation plans are complying with the rules and regulations. In this system, the unsafe area is shown as the red sphere and the safe area is as the green sphere. If the flammable substance locations don't comply with rule and regulation, the large red sphere will appear.

5.2.2.1 Assessment of fire extinguisher installation plan Based on OSHA fire safety rules

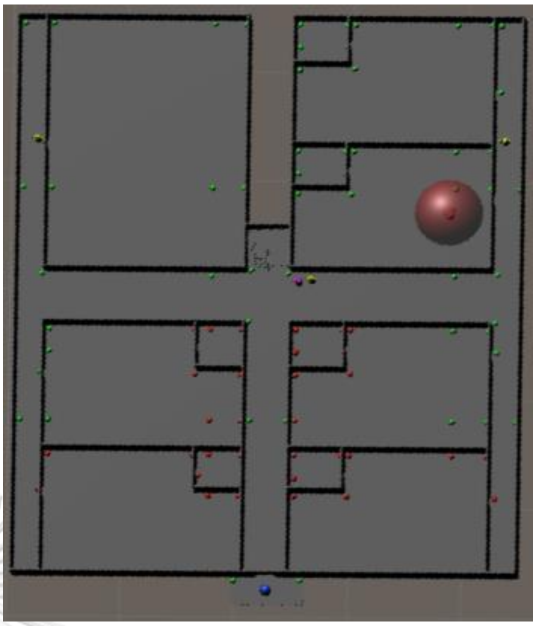


**Testing on Scenario 3C**

In Figure 5.28 (a), the architectural structure and the locations of fire extinguishers and flammable substances on the 1st floor of scenario 3C are provided, allocating three (2A) and one (10B) fire extinguishers. Figure 5.28 (b) provides the assessment of FEIP which demonstrates the unsafe area of the 1st floor of scenario 3C as a red sphere. The location of flammable substances is also regarded as the unsafe area because the distance between flammable substances and (10B) fire extinguishers exceeds thirty feet.

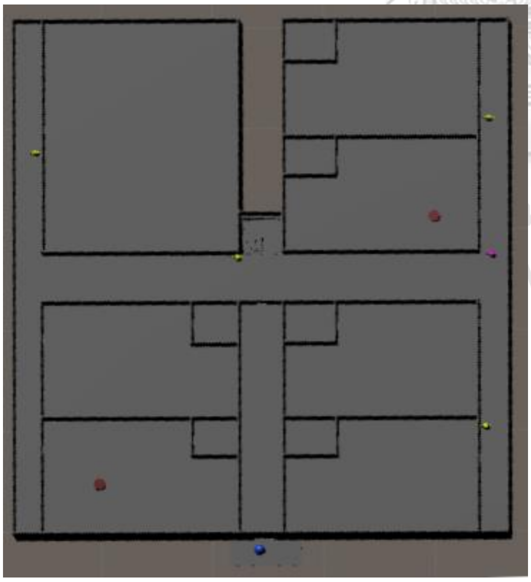


(a) Manually inputted fire extinguishers in the 1st floor of scenario 3C (Before)

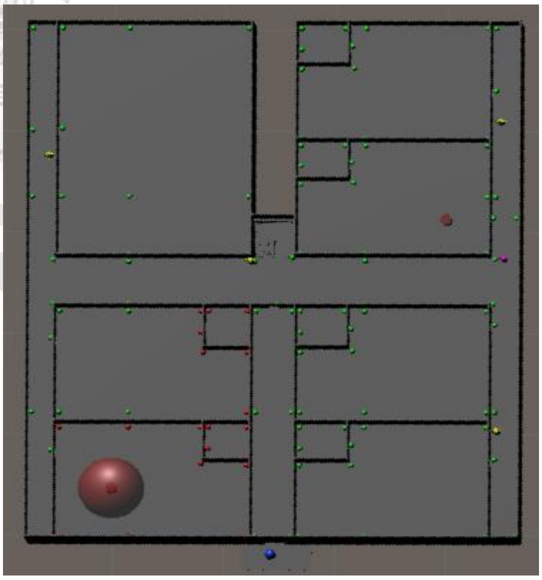


(b) Assessment of FEIP for the 1st floor of scenario 3C (After)

*Figure 5.28 Manually inputted fire extinguishers and assessment of FEIP for the 1st floor of scenario 3C*



(a) Manually inputted fire extinguishers of the 2nd floor of scenario 3C (Before)



(b) Assessment of FEIP for the 2nd floor of the scenario 3C (After)

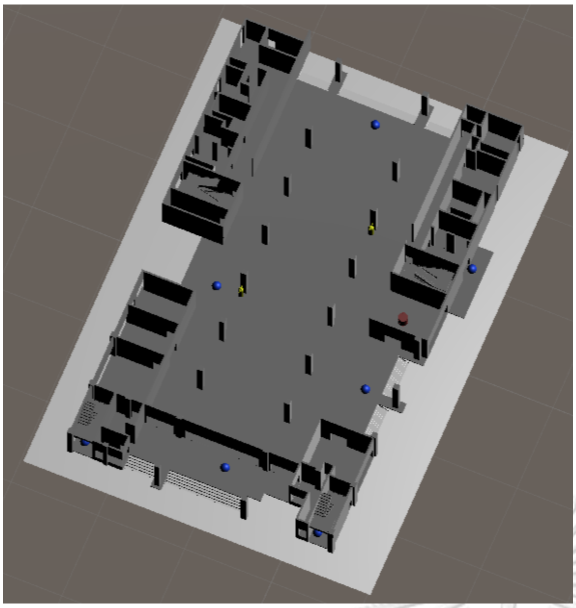
*Figure 5.29 Manually imputed fire extinguishers and assessment of FEIP for the 2nd floor of scenario 3C*

The 2nd floor of scenario 3C with the placement of four (2A) and one (10B) fire extinguishers are shown in Figure 5.29(a). It can be realized that one of the flammable substances complies with the rules and regulations, while the others clearly do not meet the requirement. To conclude, some of the areas on the 2nd floor are identified as the unsafe ones but the amount is less than that of the 1st floor.

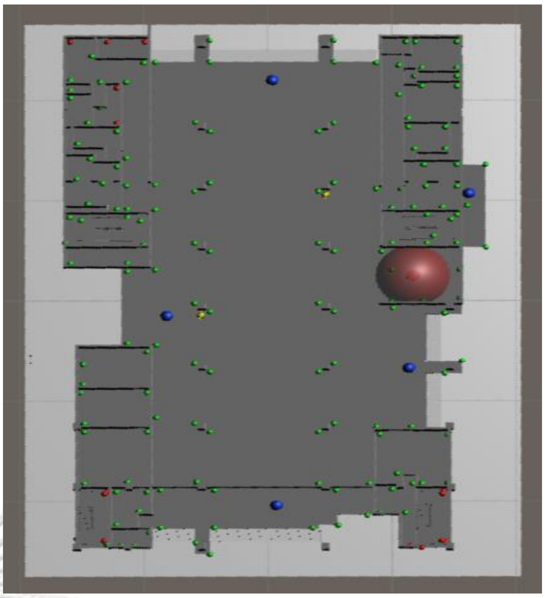
**Testing on Scenario 3D**

There are two (10A) fire extinguishers and one flammable substance on the 1st floor of scenario 3D (see Figure 5.30 (a)). According to Figure 5.30 (b), the locations of two fire extinguishers are considered inappropriate or need more fire extinguishers because an unsafe area appears on the result. Moreover, flammable substances are also noted as unsafe locations because there are no (10B) fire extinguishers.

Figure 5.31 (a) represents the 3D view of the 2nd floor of scenario 3D which has three (2A) fire extinguishers and two flammable substances. The assessment of FEIP shows that one (10B) fire extinguisher is needed for one flammable substance while three (2A) fire extinguishers are enough to comply with the necessity (see Figure 5.31 (b)). In the 3rd floor of the 3D scenario, only two (2A) fire extinguishers are placed. Regarding the assessment of FEIP, two (2A) fire extinguishers are at the correct position and the plan follows the required rules and regulations (see Figure 5.32 (b)).

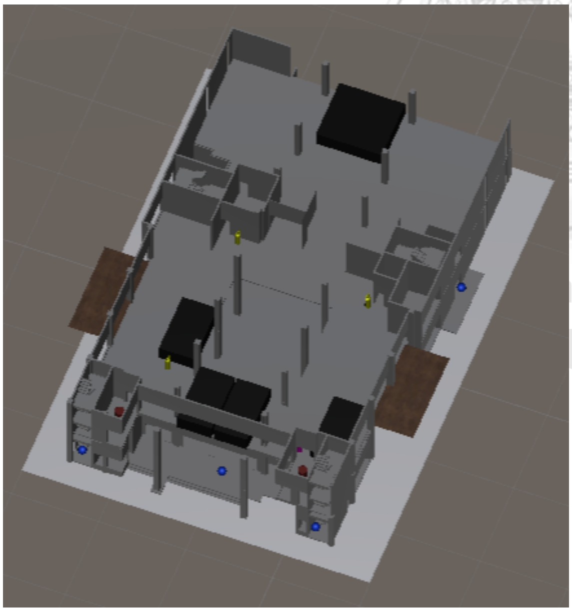


(a) Manually inputted fire extinguishers on $1^{st}$ floor of scenario 3D (Before)

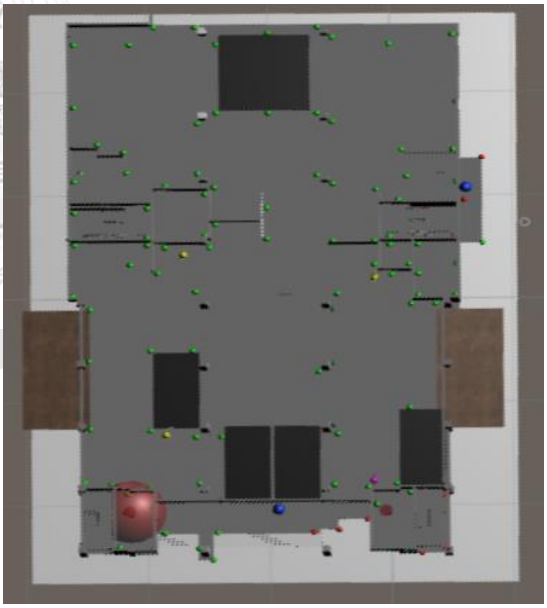


(b) Assessment of FEIP for $1^{st}$ floor of scenario 3D (After)

*Figure 5.30 Manually inputted fire extinguishers and assessment of FEIP for $1^{st}$ floor of* 3D

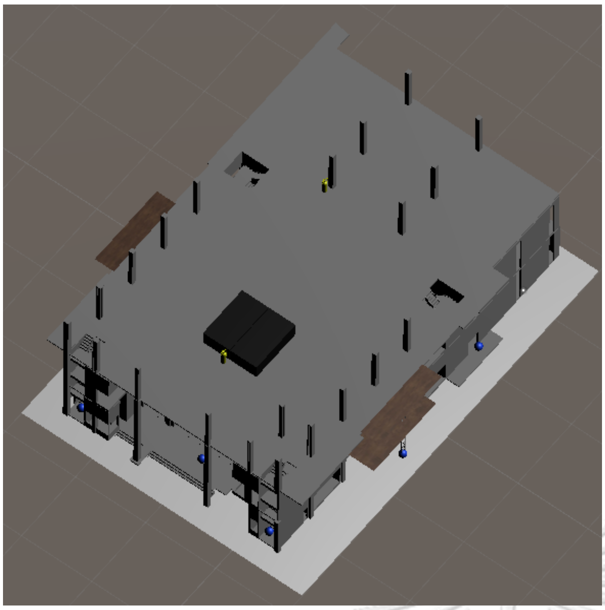


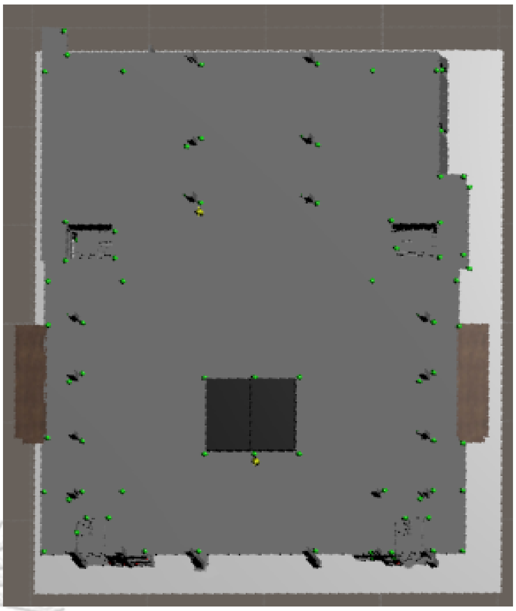
(a) Manually inputted fire extinguishers of $2^{nd}$ floor of scenario 3D (Before)



(b) Assessment of FEIP for $2^{nd}$ floor of scenario 3D (After)

*Figure 5.31 Manually inputted fire extinguishers and assessment of FEIP for $2^{nd}$ floor of 3D*





(a) Manually inputted fire extinguishers of 3rd floor of scenario 3D (Before)

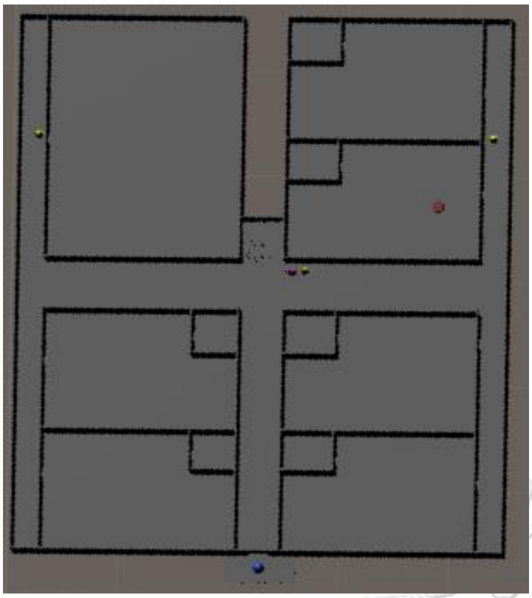
(b) Assessment of FEIP for 3rd floor of scenario 3D (After)

*Figure 5.32 Manually inputted fire extinguishers and assessment of FEIP for 3rd floor of 3D*

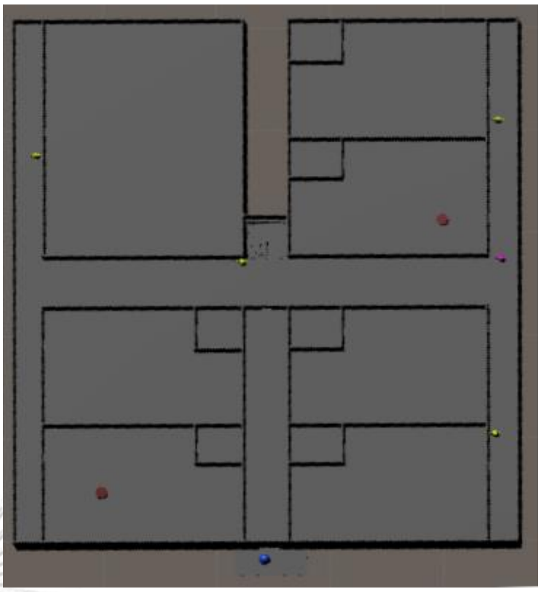
5.2.2.2 Assessment of fire extinguisher installation plan Based on Thailand fire safety rules

**Testing on Scenario 3C**

In Figure 5.33, the architectural structure and the locations of fire extinguishers and flammable substances on the 1st and 2nd floors of scenario 3C are shown. The number of required 2A fire extinguishers which are calculated based on the floor area and the number of actual (or) manually inputted 2A fire extinguishers are shown in blue box (Figure 5.34).



(a) Manually inputted fire extinguishers in the 1st floor of scenario 3C



(b) Manually inputted fire extinguishers in the 2nd floor of scenario 3C

Figure 5.33 Manually inputted fire extinguishers on the 1st and 2nd floors of scenario 3C

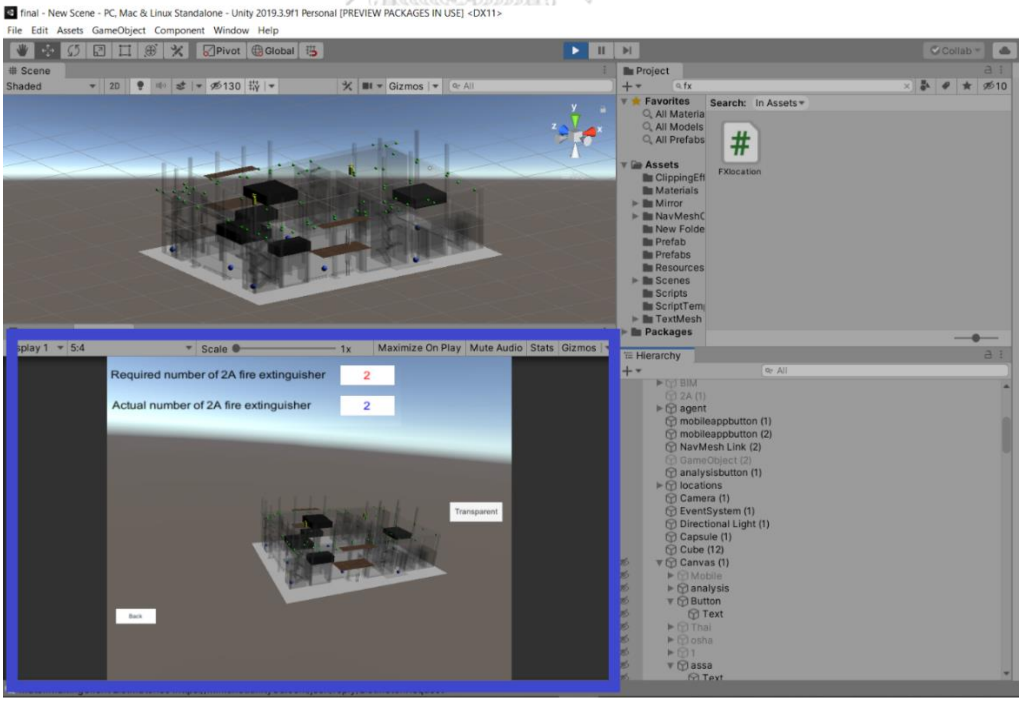
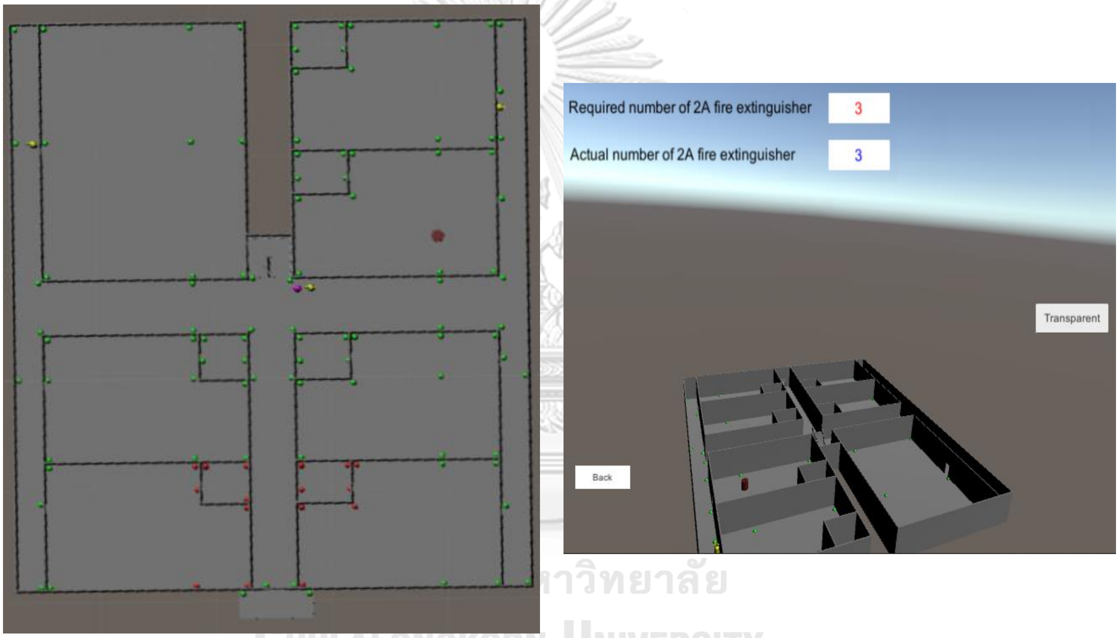



*Figure 5.34 User interface for the assessment of fire extinguisher installation plan*

Regarding the Figure (5.35), three 2A fire extinguishers and one 10B fire extinguisher are enough for the 1st floor but the results show that the locations of fire extinguishers are not at the correct positions. Therefore, some unsafe areas (red sphere) appear in this assessment.

In Figure (5.36), the number of manually added fire extinguishers is more than the required number of fire extinguishers because the floor area is around 2200 square meters. But, the result shows that the locations of 2A fire extinguishers are not at the inappropriate positions and there are some unsafe areas in this assessment. One flammable substance is not complied with rules and regulations.

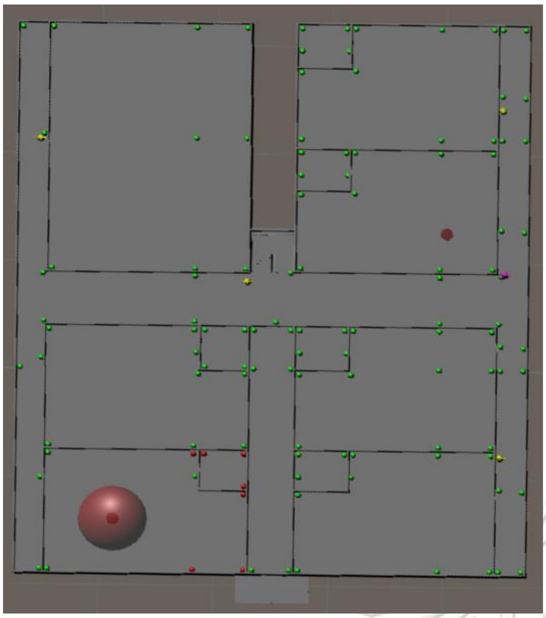


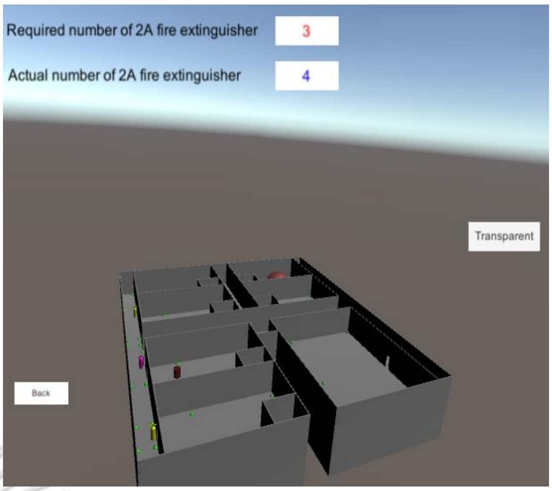



(a) Assessment of FEIP for the 1st floor of the scenario 3C

(b) Required and actual number of 2A fire extinguisher for the 1st floor of the scenario 3C

*Figure 5.35 Assessment of FEIP for the 1st floor of scenario 3C*






(a) Assessment of FEIP for the 2nd floor of the scenario 3C

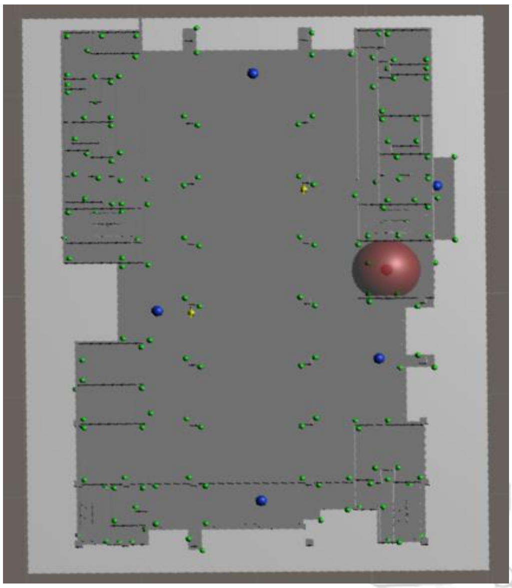
(b) Required and actual number of 2A fire extinguisher for the 2nd floor of the scenario 3C

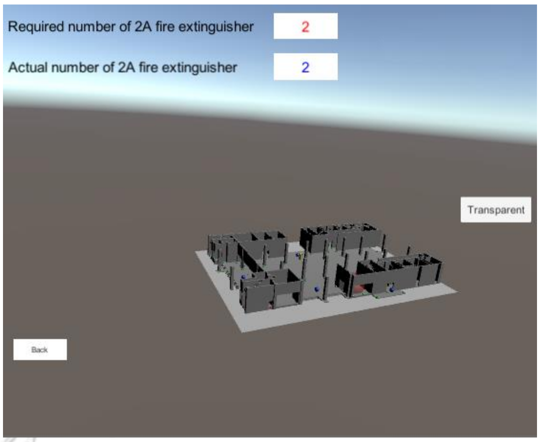
*Figure 5.36 Assessment of FEIP for the 2nd floor of scenario 3C*

**Testing on Scenario 3D**

There are two 10A fire extinguishers and one flammable substance on the 1st floor of scenario 3D. According to Figure 5.37 (a), the locations of two fire extinguishers are considered appropriate because there is no unsafe area on the result. Moreover, flammable substances are also noted as unsafe locations because there are no 10B fire extinguishers. Figure 5.37 (b) shows that the number of manually inputted fire extinguishers is enough for this floor.

Figure 5.38 (a) represents the 3D view of the 2nd floor of scenario 3D which has three 2A fire extinguishers, three 10B fire extinguishers and two flammable substances. The assessment of FEIP shows that one 10B fire extinguisher is needed for one flammable substance while the locations of three 2A fire extinguishers are complied with the fire safety rules (see Figure 5.37 (a)). According to Figure 5.38(b), the number of 2A fire extinguishers is more than the number of 2A fire extinguishers which are required for this floor. In the 3rd floor of the 3D scenario, only two (2A) fire extinguishers are placed. Regarding the assessment of FEIP, two 2A fire extinguishers are at the correct position and the plan follows the required rules and regulations (see Figure 5.38 (a)).

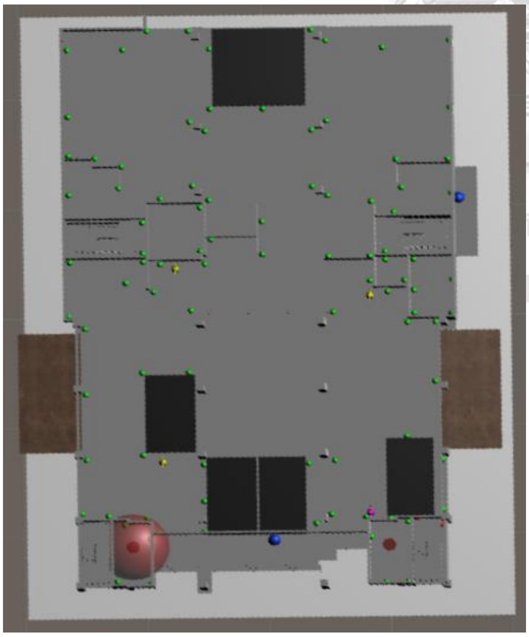


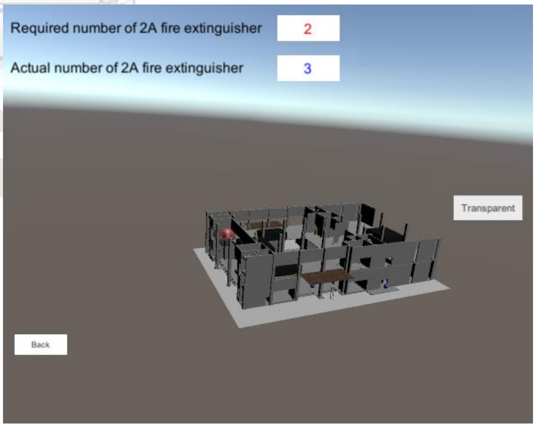



(a) Assessment of FEIP for the 1st floor of the scenario 3D

(b) Required and actual number of 2A fire extinguisher for the 1st floor of the scenario 3D

*Figure 5.37 Assessment of FEIP for 1st floor of scenario 3D*

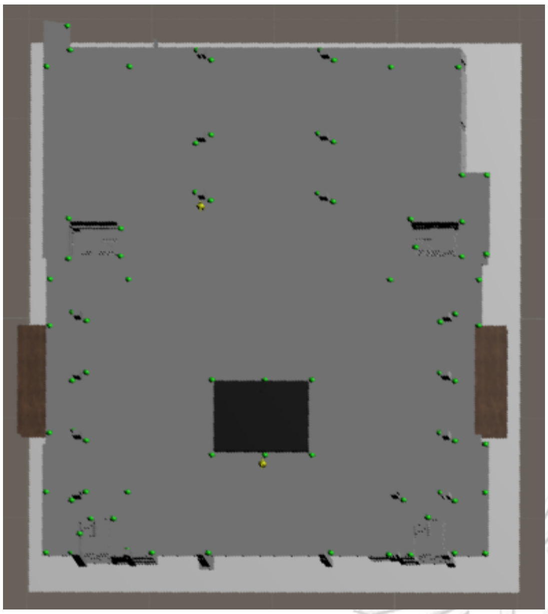




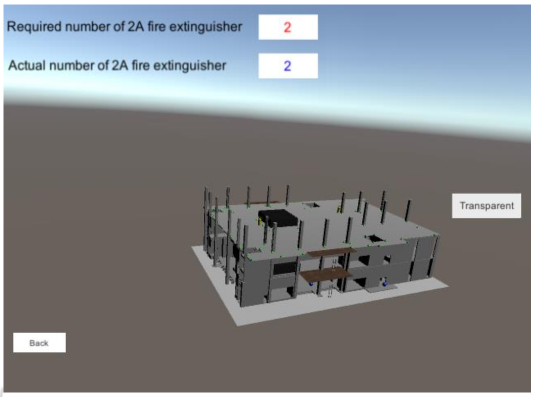

(a) Assessment of FEIP for the 2nd floor of the scenario 3D

(b) Required and actual number of 2A fire extinguisher for the 2nd floor of the scenario 3D

*Figure 5.38 Assessment of FEIP for 2nd floor of scenario 3D*



(a) Assessment of FEIP for the 3rd floor of the scenario 3D




(b) Required and actual number of fire extinguisher for the 3rd floor of the scenario 3D

*Figure 5.39* Assessment of FEIP for 3rd floor of scenario 3D

5.2.3 Generation of evacuation route plan

To test the function for evacuation route plan, 4D and 5D scenarios are created and chosen as the case study. The structural design of scenario 4D and 5D are the same as that of 1D from the previous case study, although two more material's locations are placed in 5D. In this testing, three data are collected; the position of corner points, the distance between each corner points, and the travel time to reach the goal. The main purpose of collecting the location of corner points and the distance between each corner point are to make the hand calculation for comparison of the manual calculation of travel time with the one generated from the system. The conditions of the floor on the evacuation route are determined by eyesight in manual calculation. The percentage error is also calculated.

5.2.3.1 Testing on the scenario 4D

Nine exits are added in scenarios 4D (see Figure 5.40) and evacuation routes will be generated from three different places (Green star). The fire location is on the 2nd floor at Room number 2042 (see Figure 5.41). Room number 3029 from the 3rd floor is tested as the second location (see Figure 5.42). Figure (5.43) shows the third location as Room number 4031 from the

4th floor. In the system, the room location or starting point will be presented as the green cube (see Figure 5.44). The evacuation routes from those three places are shown in Appendix B, C and D.

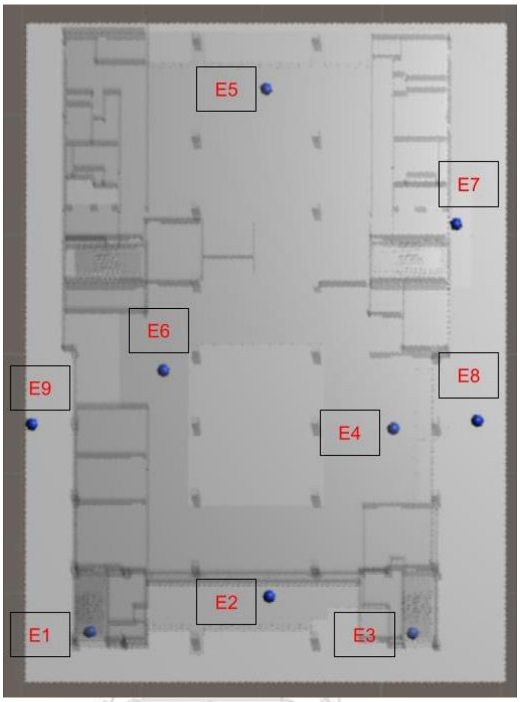



*Figure 5.40* Name of exits in scenario 4D

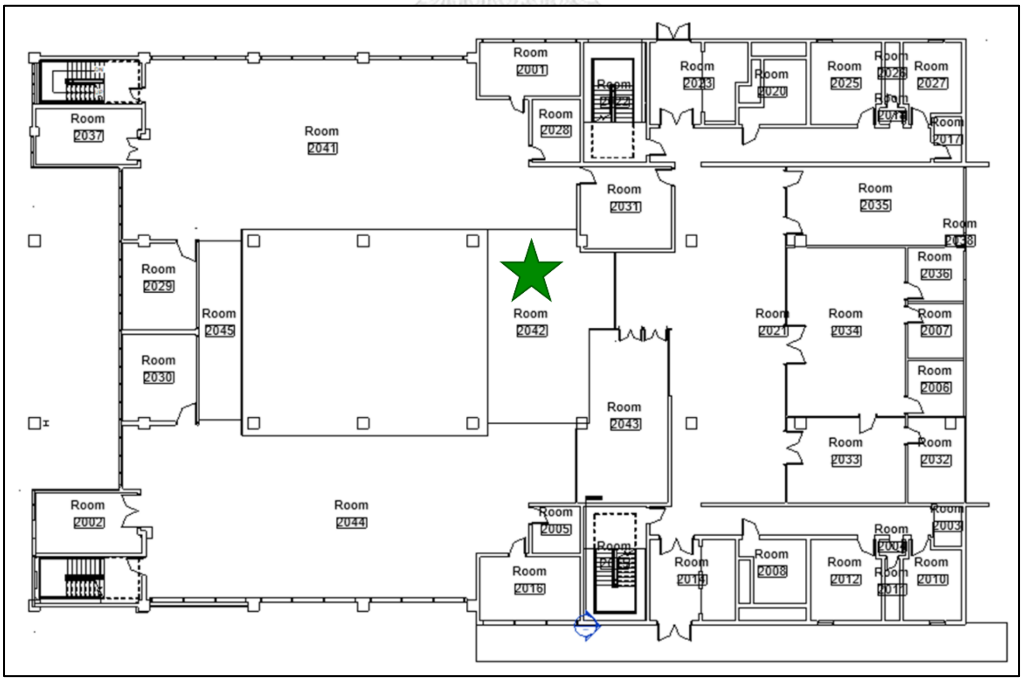



*Figure 5.41* The floor plan of 2nd floor with respective Room numbers

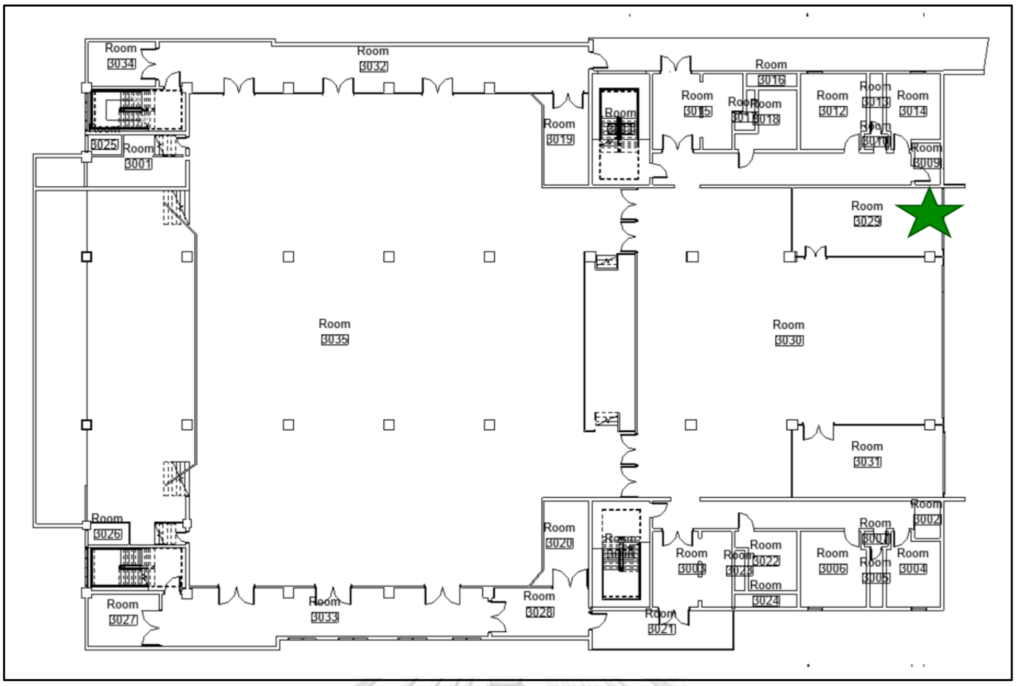



*Figure 5.42* The floor plan of 3$^{rd}$ floor with respective Room numbers

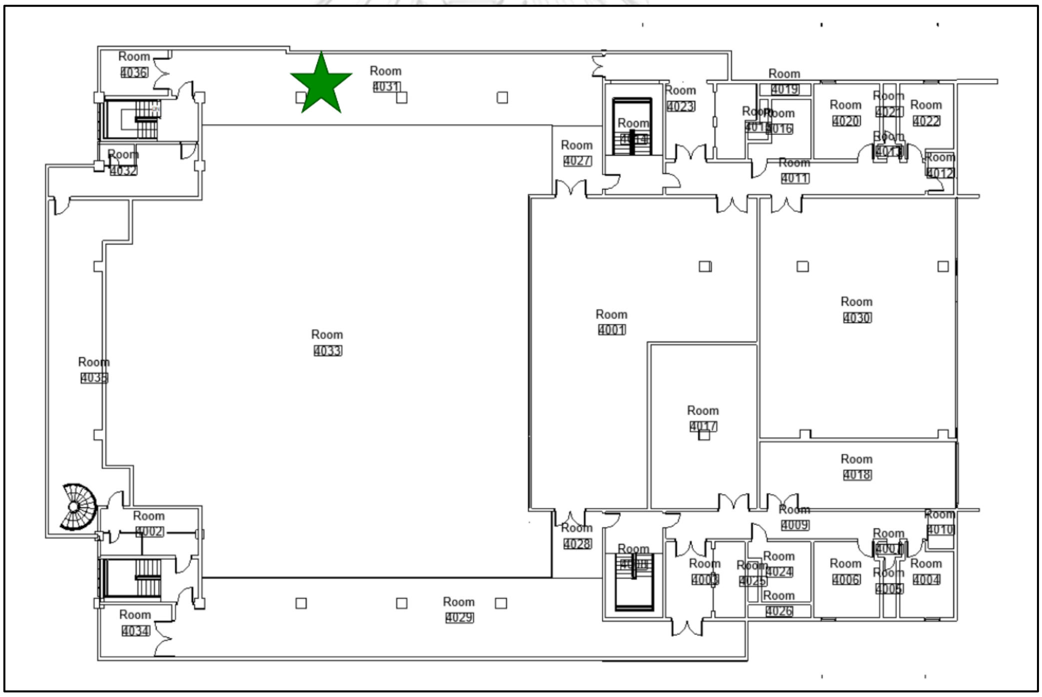



*Figure 5.43* The floor plan of 4$^{th}$ floor with respective room numbers

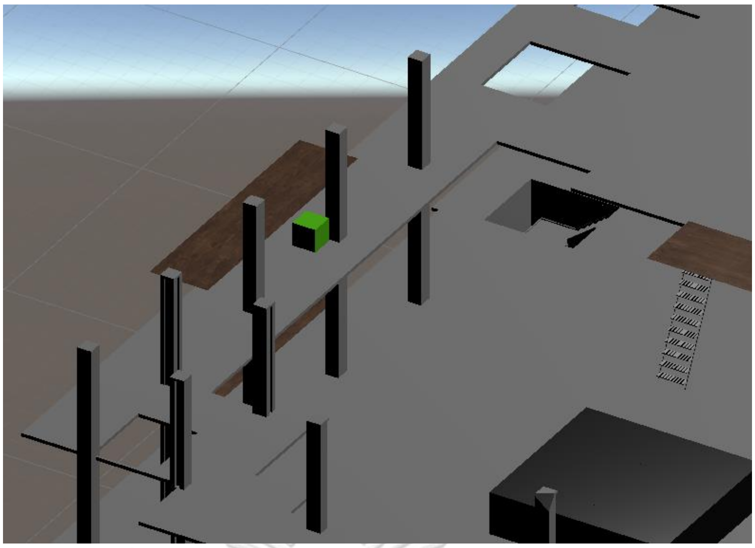


*Figure 5.44* Starting point in Unity

The user interface for the evacuation path plan is illustrated in Figure (5.45). Users have to input the location and the system will generate the fastest evacuation route, the travel distance and the travel time with the acquired information from the user.

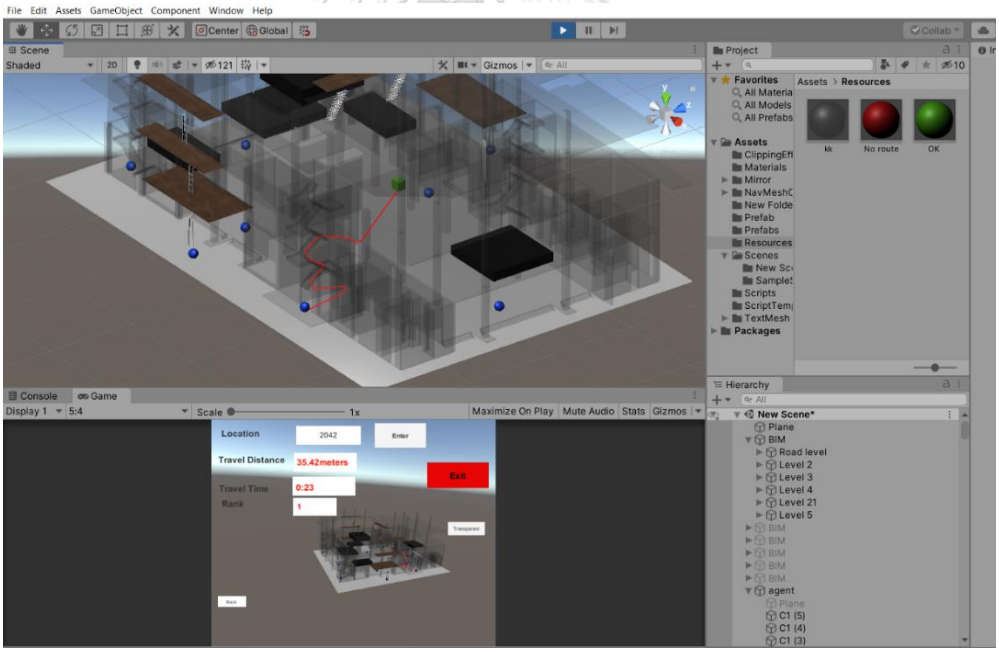



*Figure 5.45* User interface of the system showing evacuation routes

Tables 5.3, 5.4 and 5.5 present the comparison of manual and system calculations of travel time from three different locations in scenario 1E. According to Table 5.3, the percentage of error for the evacuation route from Room 2041 to exit E7 is 1.2% and this is the highest error among the nine exits. Moreover, the evacuation route from Room 3029 to exit E7 also has the highest error percent in nine evacuation routes (see Table 5.4). Table 5.5 concludes that all of the error percentages from nine exits are lower than 0.7%.

*Table 5.3 Comparison of manual and system calculation of travel time from Room 2042 in scenario 1E*

| Exits | E7 | E9 | E8 | E1 | E4 | E5 | E6 | E3 | E2 |
|---|---|---|---|---|---|---|---|---|---|
| Rank | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Travel distance(m) | 35.42 | 27.23 | 27.63 | 40.7 | 34.6 | 48.43 | 38.95 | 46.5 | 54.64 |
| System Calculation(s) | 23.07 | 25.13 | 25.31 | 26.9 | 28.99 | 29.95 | 31.34 | 35.3 | 39.87 |
| Manual Calculation(s) | 23.34 | 25.14 | 25.31 | 26.93 | 28.88 | 29.98 | 31.35 | 35.18 | 39.50 |
| Percentage error | 1.2% | 0.0% | 0.0% | 0.1% | 0.4% | 0.1% | 0.0% | 0.3% | 0.9% |

*Table 5.4 Comparison of manual and system calculation of travel time from Room 3029 in scenario 1E*

| Exit | E6 | E9 | E7 | E5 | E4 | E3 | E1 | E2 | E8 |
|---|---|---|---|---|---|---|---|---|---|
| Rank | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Travel distance(m) | 49.90 | 49.50 | 55.02 | 55.42 | 65.29 | 67.04 | 68.45 | 70.47 | 50.50 |
| System Calculation(s) | 35.91 | 35.93 | 38.24 | 38.81 | 44.05 | 44.71 | 45.97 | 46.8 | 47.11 |
| Manual Calculation(s) | 35.95 | 35.92 | 38.88 | 38.84 | 43.97 | 44.66 | 45.99 | 46.81 | 47.14 |
| Percentage error | 0.1% | 0.0% | 1.7% | 0.1% | 0.2% | 0.1% | 0.0% | 0.0% | 0.1% |

*Table 5.5 Comparison of manual and system calculation of travel time from Room 4031 in scenario 1E*

| Exit | E7 | E9 | E8 | E1 | E4 | E5 | E6 | E3 | E2 |
|---|---|---|---|---|---|---|---|---|---|
| Rank | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Travel distance(m) | 21.74 | 43.34 | 33.55 | 64.07 | 47.28 | 52.36 | 59.25 | 60.19 | 61.93 |
| System Calculation(s) | 42.47 | 48.47 | 48.73 | 53.75 | 56.00 | 58.69 | 62.60 | 62.84 | 63.76 |
| Manual Calculation(s) | 42.51 | 48.54 | 48.6 | 53.79 | 56.11 | 59.10 | 62.82 | 62.84 | 63.79 |
| Percentage error | 0.1% | 0.1% | 0.4% | 0.1% | 0.7% | 0.0% | 0.3% | 0.1% | 0.2% |

5.2.3.2 Testing on the scenario 5D

In scenario 5D, two more material locations are placed on the second floor (Figure 5.46). The materials are placed on the evacuation routes in order to test the fact that the ranks of the evacuation route or the fastest evacuation route are changed by considering the material locations.

The evacuation routes are generated from room 2042 and Table 5.6 shows the difference of evacuation route data between scenario 4D and 5D. In scenario 4D, exit E7 is the fastest evacuation route while E7 is at the fifth place in scenario 5D because one of the materials is placed on the way to the exit E7 (see Appendix B and E).

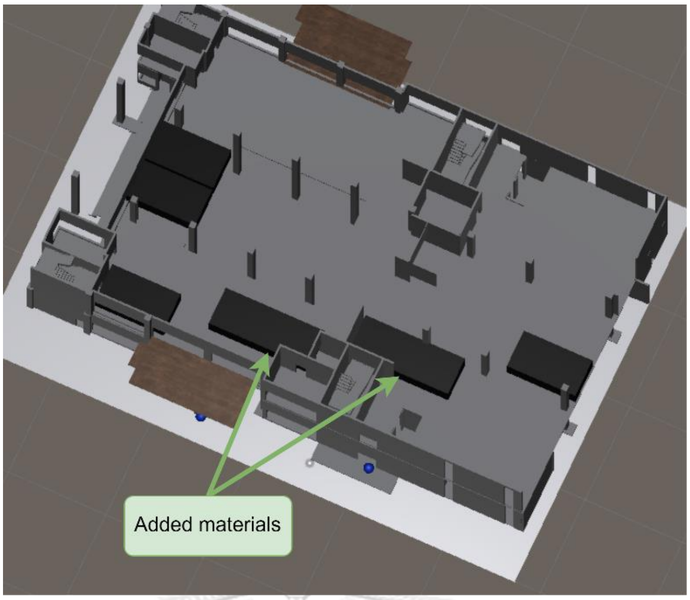



*Figure 5.46* 3D view of 2nd floor of scenario 5D

*Table 5.6 Comparison of 2nd floor of 4D and 5D scenario*

| | Rank | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario 4D | Exit | E7 | E9 | E8 | E1 | E4 | E5 | E6 | E3 | E2 |
| | Travel distance | 35.42 | 27.23 | 27.63 | 40.7 | 34.6 | 48.43 | 38.95 | 46.5 | 51.85 |
| | System Calculations | 23.07 | 25.13 | 25.31 | 26.9 | 28.99 | 29.95 | 31.34 | 35.3 | 38.47 |
| Scenario 5D | Exit | E9 | E1 | E6 | E8 | E7 | E5 | E4 | E3 | E2 |
| | Travel distance | 27.17 | 40.5 | 43.23 | 32.94 | 46.08 | 48,43 | 40.13 | 52 | 52.71 |
| | System Calculations | 25.17 | 26.79 | 27.18 | 28.17 | 28.75 | 29.95 | 31.87 | 38.27 | 38.7 |

5.2.4 Mobile application for evacuation and rescue process

In this section, mobile application in evacuation and rescue process will be tested in scenario 4D with the following five functions:

(a) Function to show the evacuation route and route to fire extinguishers,

(b) Function to send the location of fire to all mobile application users,

(c) Function to notify safe arrival,

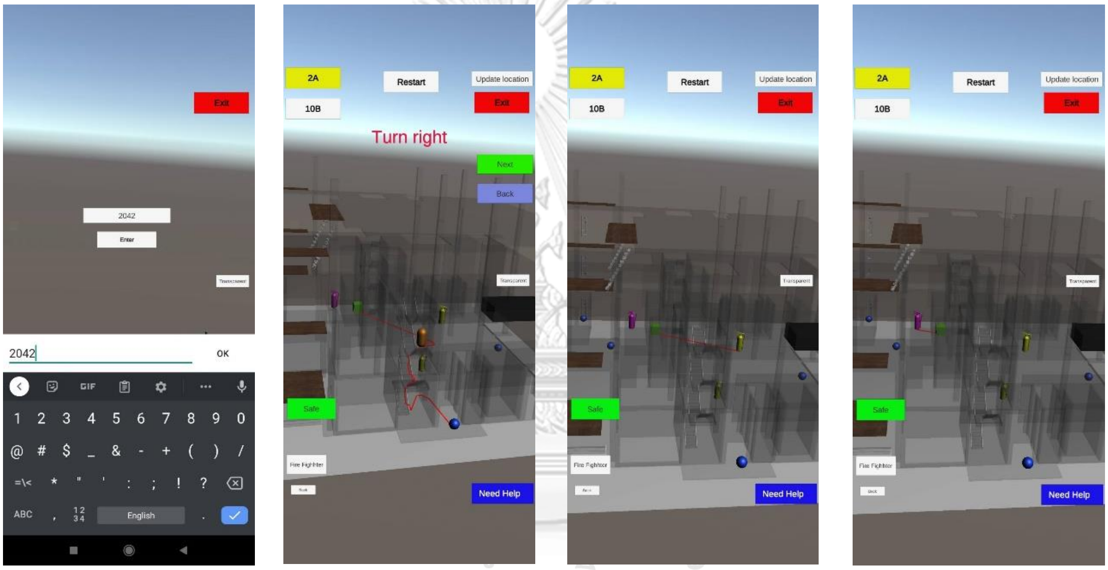
(d) Function to inform the location that evacuee where he or she is stuck,

(e) Function to show the route for firefighters.

5.2.4.1 Function to show the evacuation route and route to fire extinguishers

This function is targeted to workers or evacuees for escaping from construction sites easily and showing the locations of fire extinguishers. Function for the evacuation route not only provides the fastest evacuation route (red line) but also provides the steps-by-steps guidance or directions by pressing a button (next and back). Figure 5.47 also shows that the mobile application also has the capability to show the next waypoint (orange capsule) that workers have to go and also inform the directions with voice and text (such as turn right, turn left, go straight, go down and go up).

The function for fire extinguishers can show two types of fire extinguisher such as 2A and 10B. The users press on the 2A, the mobile application will show the nearest 2A fire extinguisher with the red line. The mobile application will show a 10B fire extinguisher when the user presses on the 10B button.




(a) Input the location (b) The fastest evacuation route (c) The nearest (2A) fire extinguisher (d) The nearest (10B) fire extinguisher

*Figure 5.47 User interface for evacuees or workers for evacuation route and route to fire extinguishers*

5.2.4.2 Function to send the fire location to all mobile applications

At first, the engineer from the office has to create a server with a PC by pressing the “H” button from the keyboard. After that, every mobile user can connect to the server by pressing the green button with WIFI picture. The engineer presses “F” and the fire will appear on the screen and move to the desired location by using a mouse (see Figure 5.48). All users can see the location of fire on the mobile application and the evacuation routes are also updated. But, to get the system to recommend exit, the user needs to press the reset button.

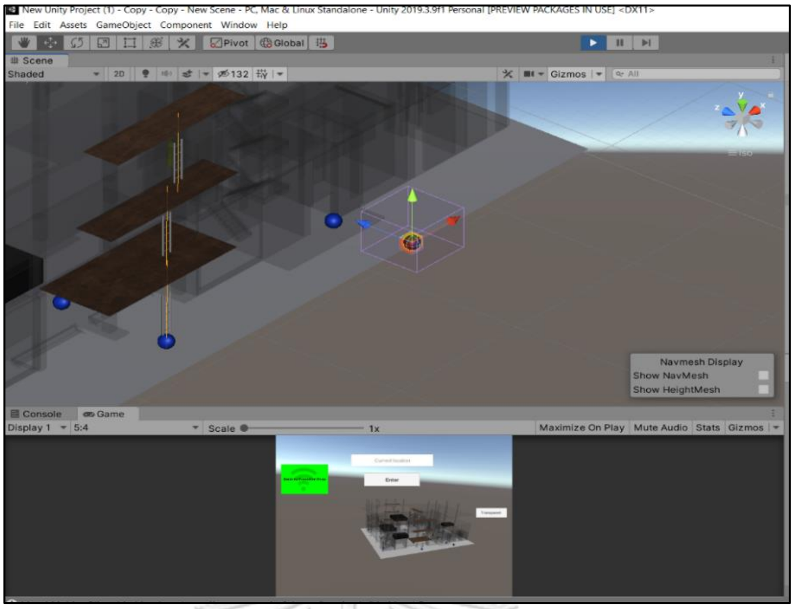
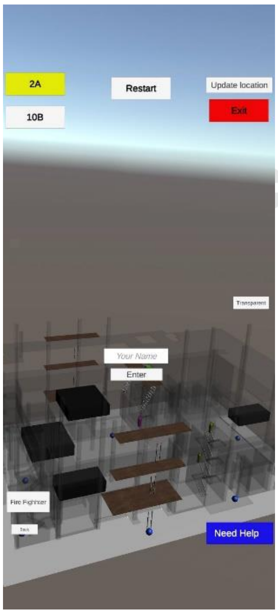
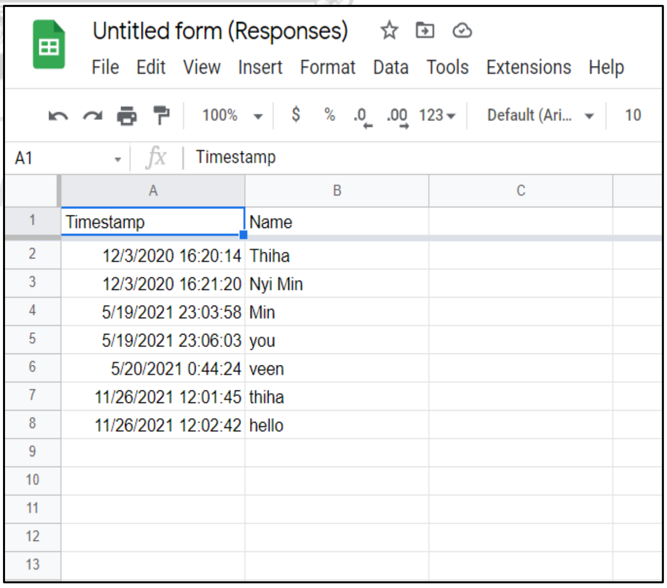



*Figure 5.48 Add fire location from server*

5.2.3.3 Function for safe arrival

To report the safe arrival, the user needs to be online. The user needs to press the green button with safe arrival, and input the name (see Figure 5.49(a)). The name of evacuee will be appeared in the google sheet and safety engineers and construction personnel can easily know how many people are escaped (see Figure 5.49(b))




| | A | B | C |
|---|---|---|---|
| 1 | Timestamp | Name | |
| 2 | 12/3/2020 16:20:14 | Thiha | |
| 3 | 12/3/2020 16:21:20 | Nyi Min | |
| 4 | 5/19/2021 23:03:58 | Min | |
| 5 | 5/19/2021 23:06:03 | you | |
| 6 | 5/20/2021 0:44:24 | veen | |
| 7 | 11/26/2021 12:01:45 | thiha | |
| 8 | 11/26/2021 12:02:42 | hello | |
| 9 | | | |
| 10 | | | |
| 11 | | | |
| 12 | | | |
| 13 | | | |

(a) Report safe arrival from mobile application

(b) Safe arrival list from google sheet

*Figure 5.49 Function for safe arrival*

5.2.4.4 Function to inform the location that evacuee stuck

To send the location to the firefighter or rescue team, the mobile application of evacuee needs to connect with the server. Evacuees need to press the “Need help” and input the location where he/she is stuck. After that, the location and number of people stuck will be shown in fire fighter mode (see Figure (5.50)).

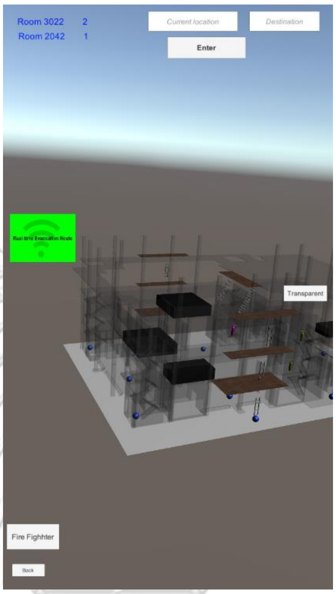



*Figure 5.50 The location of evacuee stuck and total number of evacuees from fire fighter mode*

5.2.3.5 Function to show the route for firefighters

In the firefighter mode, a firefighter or rescuer needs to input the exit name (e.g., E1, E2, ….) and room number or area where they want to go. The mobile application will show the route with a red line and also give the steps-by-steps guidance with voice and text (see Figure 5.51).

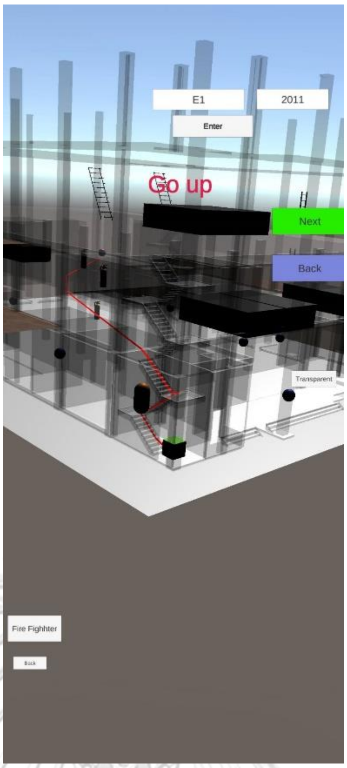



*Figure 5.51 Showing the route from exit E1 to room number 2011.*

5.3 System validation

In order to evaluate the proposed system, questionnaires were designed. The designed questionnaires are aimed at gathering qualitative rather than applying quantitative feedback. The 4 safety engineers and 11 site personnel from Myanmar who have experience in fire safety planning are recruited to answer the questionnaires. Before answering the questionnaires, the videos that show how to use the system and what kinds of functions can be performed will be shown to respondents. The designed questionnaires were divided into two parts, as presented in Appendix A. The first part was used to survey the respondents' demographic and second part was the questions to evaluate the proposed system. The distribution of the questionnaires and the demographic profile of the respondents is presented in Table 5.6. Moreover, the proportion graphs for each variable of the respondents' demographic profile are presented in Figure 5.52 to Figure 5.54.

*Table 5.7 Demographic profile of respondents*

| Variables | Distribution (n=15) |
|---|---|
| Gender | |
| Male | 73% |
| Female | 27% |
| Age(year) | |
| Mean | 32.4 |
| Education level | |
| Bachelor | 67% |
| Master degree | 33% |
| Other | 0% |
| Work experience | |
| 1-5 years | 47% |
| 5-10 years | 33% |
| Over 10 years | 20% |
| Job Position | |
| Safety engineers | 27% |
| Construction personal | 73% |



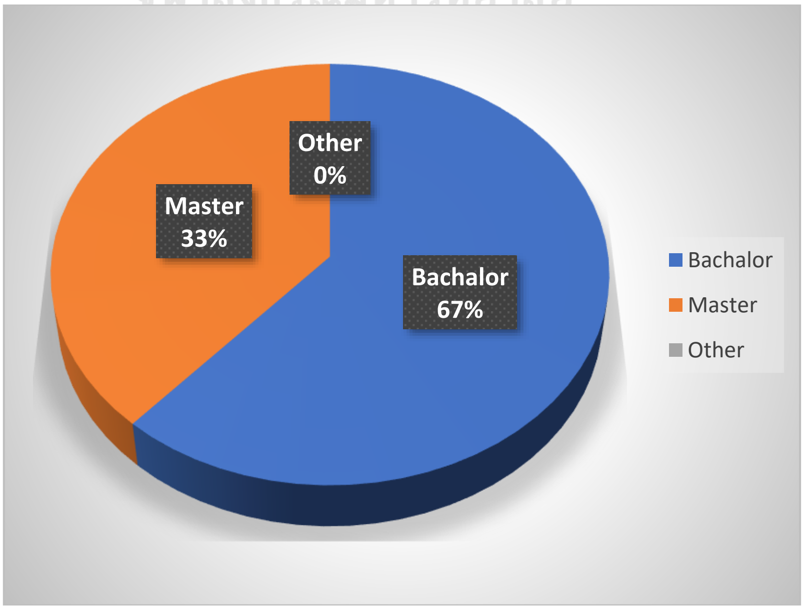



*Figure 5.52 Education level of respondents*

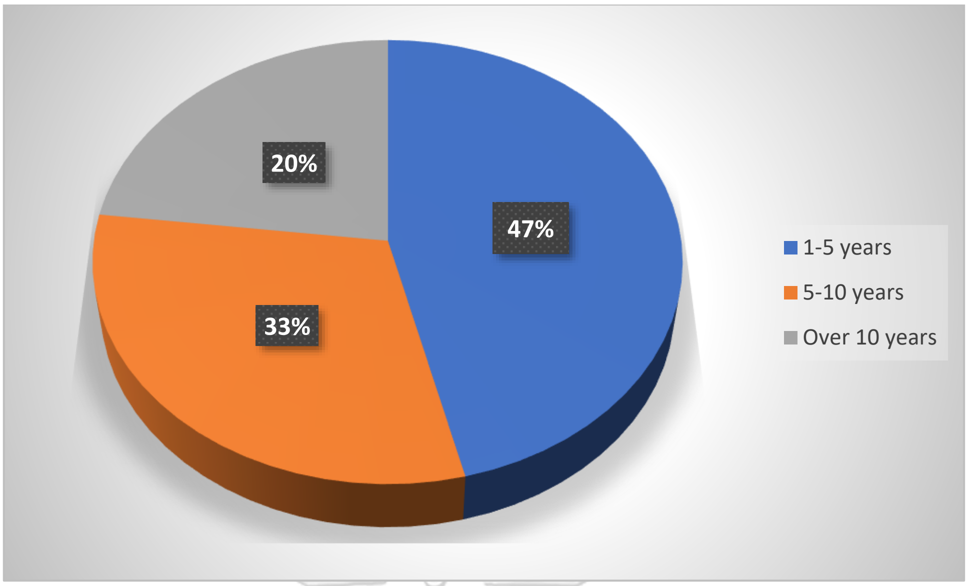



Figure 5.53 Work experience of respondents

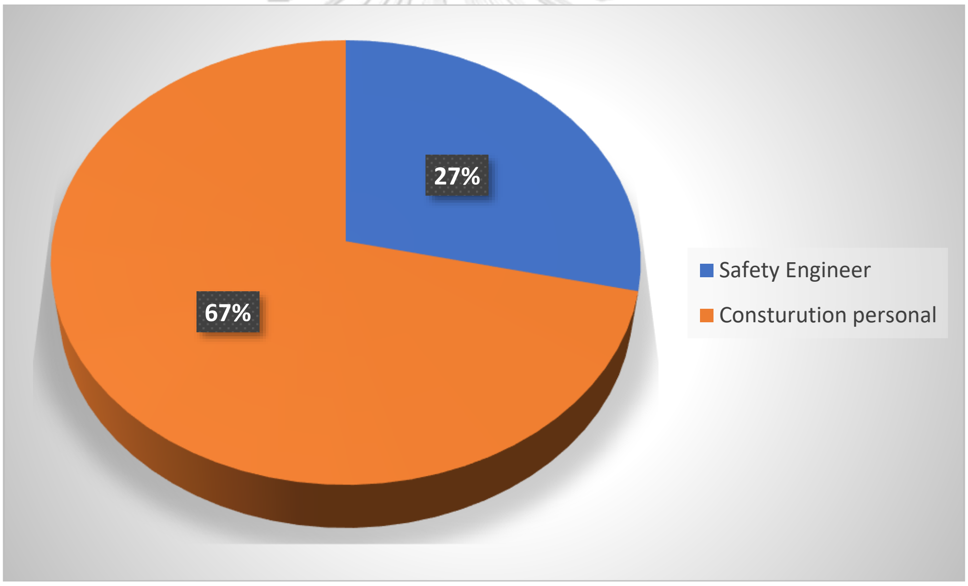



*Figure 5.54 Job position of respondents*

The evaluation results for the proposed system for fire safety plan and mobile application are presented in Table 5.8. Regarding the performance of this system to support the respondents in planning the evacuation route, the score is obtained as 4.07, which means that the proposed system is effective. The results of the proposed system in evacuation route awareness, and setting and adjusting of evacuation route directions are only 3.67 and 3.53, respectively. However, the validation of the performance of the proposed system in developing and assessing the fire extinguisher installation plan results in high scores of 4.33 and 4.07. The mobile application for evacuation and rescue process is the most likable of respondents with the average score of 4.53.

*Table 5.8 Results of the evaluation of the proposed system by the respondents*

| Question no | Content | Average score |
|---|---|---|
| 1 | I felt that the developed system for fire safety aided the evacuation route planning. | 4.07 |
| 2 | I felt that the developed system for the fire safety plan aided in the evacuation route awareness. | 3.67 |
| 3 | I felt that the developed system for the fire safety plan aided in setting up and adjusting the directions of emergency exit signs. | 3.53 |
| 4 | I felt that the developed system for the fire safety plan aided in developing the fire extinguisher installation plan. | 4.33 |
| 5 | I felt that the developed system fire safety plan aided in assessing the existing fire extinguisher installation plan. | 4.07 |
| 6 | I felt that the mobile application aided the evacuation and rescue process in case of emergency. | 4.53 |

## 5.4 Conclusion

The proposed system was tested in sample buildings and real construction buildings to verify the accuracy of the travel time calculations and verify the running time of the development of fire extinguisher installation plans that are within acceptable range or not. Moreover, the results of development and assessment of the fire extinguisher installation plan show that the system can handle the dynamic nature of construction.  The function of the mobile application is also tested and all functions are fully functionable.

For the validation, 4 safety engineers or officers and 11 construction personals which include construction managers, project managers, project engineer and scenario engineers, were chosen to be the subject for testing. The questionnaires were applied to collect information on the respondent’s backgrounds. The functions and capabilities of the proposed system will be explained before evaluating the system. The overall evaluation results indicated that the proposed system for fire safety plan supports the safety engineers and construction personnel, and mobile application also assists the firefighters and people who are involved in construction in the evacuation process.

# CHAPTER 6

## Research Conclusion and Recommendations

The objective of this chapter is to summarize the overall research and the research results which are the new system for developing the fire safety plan and new mobile application to help workers, safety engineers and construction personnel and fire fighters during evacuation process. And this chapter mentions the summary of the research, research aim, objectives, contribution and limitations. Moreover, recommendations for future works are also presented.

6.1 Conclusion of overall research

Fires in under-construction threaten worker safety and have a lot of negative impacts on many aspects of construction that were reported the past few years. Many constructions do not possess the permanent fire protection system, and only rely on the fire extinguisher or water tank to extinguish the fire. Moreover, a construction site has numerous features that make its uncommon and unanticipated structure. In a construction environment, changing is one of the characteristics that make it unique compared to others. Due to the dynamic nature of construction, the fire safety plan in construction needed to be reviewed and updated according to construction progress. The conventional approach or manual process to develop the fire safety plan for a construction project can be a time-consuming and enormous labor-intensive task. Furthermore, some of the emergency signs are unclear due to the nature of construction and some are not showing the correct evacuation route because of the structural design change based on the construction progress.



Therefore, an innovative and proactive approach for supporting safety engineers and construction personnel that they can create a fire safety plan and helping the workers during evacuation process so that they can easily escape from the building. The presentation style is the 3D view so that they can easily understand the building design. Therefore, this proposed approach can provide a virtual fire safety plan and evacuation route that can adapt the dynamic nature of construction.

For system design, the concept of the system design will be chosen from the related literature, technological reviews and interview. The limitations of the previous research (e.g., the dynamic changing of building structure, temporary facilities and different types of terrain) and some functions that can make improvements will be noted. The problems of current practices in the evacuation planning process are analyzed and the limitations and advantages of the prototype are examined. The main factors that effect on the fire safety plan and evacuation process was listed and these factors are as follows;

1. Dynamic changing of the construction site that can impact on searching the paths,
2. Exits that allow working crews to escape from a construction structure and a job site,
3. Surface conditions that have impacts on the walking speed (e.g., the rebar surface condition is not an ideal pathway),
4. Objects that can block the escape route of workers,
5. Temporary structures such as temporary stairs and temporary ladders.
6. Fire locations.
7. Flammable gas (more than 5 pounds) or liquid (more than 5 gallons).

The development of the system needs various types of software such as Autodesk Revit, Navisworks, Unity (Game Engine), Visual studio and google form. Autodesk Revit and Navisworks are used for creating and exporting the model to Unity. Unity and visual studio are applied for developing the user interface and code that is based on rules and regulations.

In this research, there are three innovations such as a system for fire extinguisher installation plan development and assessment, system for evacuation route plan and mobile application for evacuation process. Moreover, this research introduced two new algorithms such as algorithm for the development of fire extinguisher installation plan based on rule and regulation and algorithm for decision making in choosing the fastest evacuation route. First algorithm is applied in the function for developing the fire extinguisher installation plan and the second algorithm is used in the system for evacuation route plan and mobile application.



Due to the Covid19, the prototype hadn't chance to test in the real construction sites. So, the building designs from real construction projects are created. Two different timelines are created by using sample building and real construction building. First timeline is the time that most of the walls are not finished and the second timeline is the time for internal work (e.g., decorations). In order to test those three systems, many scenarios are also created based on two different timelines by adding material location, flammable substances, fire extinguisher and exits.

For the system validation, 4 safety engineers and 11 construction personnel who have knowledge in fire safety are chosen to be the respondents. The backgrounds of respondents are collected. The results and functions of the proposed system will be explained to the respondent before conducting the survey questions in order to evaluate the system. According to the results of evaluation, the proposed system assists the safety engineer, construction personnel, firefighters and workers in the fire safety planning and evaluation process.

6.2 Benefit of the proposed system

The proposed System can support safety engineers and construction personnel in developing the fire safety of construction projects, and assist firefighters and people that are involved in construction in escaping from the construction building. This system can handle the dynamic nature of construction. The user can easily understand by looking at virtual objects or 3D models representing fire extinguishers, unsafe areas, evacuation route and structural design of the building based on construction progress. The following fourteen applications were developed:

1. Development and assessment of fire extinguisher installation plan
    1.1. Developing the fire extinguisher installation plan
    1.2. Assessing the fire extinguisher installation plan
2. Planning for the evacuation route
    2.1. Planning for the evacuation route that is the fastest route.
3. Mobile application for evacuation process
    3.1. Showing the evacuation route and route to fire extinguishers
    3.2. Sending the fire location to all mobile application user's
    3.3. Reporting safe arrival.
    3.4. Informing the location that evacuee stuck
    3.5. Show the route for firefighters

6.3 Research outcomes

1. The product of this research is a prototype system that can help in developing the fire safety for safety engineers and construction personnel, and assist firefighters and people who are involved in construction in the rescue and evacuation process.

2. Two new algorithms based on rule and regulation and velocity of different terrain are to support the fire safety in developing the fire extinguisher installation plan and in making the evacuation route plan.

## 6.4 Research contributions

1. The main contribution of this research consisted in an innovative and proactive approach to improving the current practices of fire safety in construction. Clear visualization associated with structural design of construction and evacuation routes provide the understanding and perception of safety engineers, construction personnel and workers.
2. The product of this research is a prototype system that can help in developing the fire safety for safety engineers and construction personnel, and assist firefighters and people who are involved in construction in the rescue and evacuation process. Moreover, this prototype can also apply in other construction in fire safety plans.

## 6.5 Recommendation and limitation

1. The system for developing fire extinguisher installation plans focus on fire extinguisher rule and regulation and does not consider optimizing the number of fire extinguishers.
2. Some of the rules are taken as assumptions in the generating and assessing fire extinguisher plan which follows the Thailand fire safety rules.
3. The mobile application also needs to update on a daily basis.
4. Other factors which may cause or influence evacuation processes, such as fire growth or radiation, were excluded from this research.
5. There is no system that can track the location of a mobile application's user in real time.

## 6.6 Future works



1. An advanced device or sensor that is suitable for construction should be integrated with the mobile application to get the real time location of users. Moreover, the size of the fire should be grown or moved according to the wind flow.
2. In this study, the pathing finding system is only focused on the travel time and the system does not consider the reliability of the evacuation route. Therefore, more related factors should be explored based on the project, and a heuristic function should be applied in choosing the evacuation route.
3. The system for updating the construction progress or material location and adding the fire location should be done via the mobile application.

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