BIM AND SMOKE SIMULATION-BASED ASSESSMENT OF OCCUPANT BEHAVIOR DURING FIRE EVACUATION IN HIGH-RISE RESIDENTIAL BUILDINGS

BY

ABDULLAH EHTESHAM AKBAR

A Thesis Presented to the

DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ARCHITECTURAL ENGINEERING

May 2023

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Abdullah Ehtesham Akbar** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ARCHITECTURAL ENGINEERING.**

M. Hassanain

Dr. **Mohammad Hassanain**
(Advisor)

Hadidi

Dr. Laith Awni Al-Hadidi
Department Chairman

Dr. **Ahmed Abdelfattah**
(Member)

Dr. Suliman Saleh Al-Homidan
Dean of Graduate Studies

Djamel Ouis

Dr. **Djamel Ouis**
(Member)

15/11/2023
Date

كلية الدراسات العليا والتخصصات البينية
COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES

Dedicated to my loving parents and family members

ACKNOWLEDGMENTS

First of all, I would like to thank Allah the almighty for blessing me with good health and ability in order to purse my master’s degree. I would also like to thank King Fahd University of Petroleum and Minerals for providing me with this opportunity and assisting me throughout my study.

I am immensely grateful to my thesis supervisor, Dr. Mohammad Hassanain, for his guidance, encouragement, and support throughout my research journey. I would also like to thank the committee members, Dr. Ahmed Abdelfattah, Dr. Djamel Ouis and Dr. Daeung Kim for their expertise. Their feedback, and constructive criticism have been instrumental in improving the quality of this thesis, and I could not have completed it without their support.

I am grateful to my family, especially my parents Mrs. and Mr. Mohammad Ehtesham for their unwavering support and encouragement throughout my academic journey. Their love and encouragement have kept me motivated and focused, even during the most challenging times.

Finally, I would like to thank the faculty members of Architectural engineering department as well as the Construction engineering department for sharing their valuable knowledge and supporting me throughout my study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Full Name : Abdullah Ehtesham Akbar

Thesis Title : BIM and smoke simulation-based assessment of occupant behavior during fire evacuation in high-rise residential buildings

Major Field : Architectural Engineering

Date of Degree : May,2023

Fire safety design is a critical process when designing high-rise residential buildings, owing to the various demographics of the occupants. Design professionals must ensure that their designs will reduce the occupant evacuation time, as a risk mitigation strategy against loss of life. Observations from local Architectural/ Engineering (A/E) practices indicated that occupant behavior and evacuation during fire emergencies have not been considered when designing buildings. This gap has prompted the need for investigating the variables effecting the occupant behavior and evacuation time in high-rise residential buildings. Simulation tools such as Pathfinder and PyroSim provide effective means for identifying and visualizing the challenges effecting the occupant behavior and evacuation time during fire emergencies. The first objective of this research is to investigate passive and active fire protection measures that can affect occupants evacuation time. The second objective is to select and study a case study building to assess fire evacuation scenarios. Lastly, multiple scenarios were simulated to see the most efficient design layout for the occupant's evacuation time. Width of the exit doors as well as the staircase width were modified to see their impact on the overall evacuation. After investigating several scenarios of the building layout and design of egress, suggestions and recommendations for future work were provided. The outputs of the simulation tools helped in improving the occupant evacuation efficiency by 10%, hence minimizing injuries and fatalities.

ملخص الرسالة

الاسم الكامل: عبدالله احتشام اكبر

عنوان الرسالة: تقييم قائم على BIM ومحاكاة الدخان لسلوك الركاب أثناء الإخلاء بسبب الحريق في المباني السكنية الشاهقة

التخصص:الهندسة المعمارية

تاريخ الدرجة العلمية: مايو 2023

يعد تصميم السلامة من الحرائق عملية حاسمة عند تصميم المباني السكنية الشاهقة، نظرًا للتركيبة السكانية المختلفة لشاغليها. يجب أن يتأكد محترفو التصميم من أن تصميماتهم ستقلل من وقت إخلاء المستخدمين، كإستراتيجية لتخفيف المخاطر ضد الخسائر في الأرواح. أشارت الملاحظات من الممارسات المعمارية / الهندسية المحلية (A / E) إلى أن سلوك المستخدمين والإخلاء أثناء حالات الطوارئ الناجمة عن الحريق لم يؤخذ في الاعتبار عند تصميم المباني. وقد دفعت هذه الفجوة إلى الحاجة إلى التحقق من المتغيرات التي تؤثر على سلوك المستخدمين ووقت الإخلاء في المباني السكنية الشاهقة. توفر أدوات المحاكاة مثل Pathfinder وPyroSim التي وسائل فعالة لتحديد وتصور التحديات التي تؤثر على سلوك المستخدمين ووقت الإخلاء أثناء حالات طوارئ الحريق. الهدف الأول من هذا البحث هو التحقيق في تدابير الحماية من الحرائق السلبية والفعالة التي يمكن أن تؤثر على وقت إخلاء المستخدمين. الهدف الثاني هو تطوير مبنى دراسة الحالة يتوافق مع كود البناء السعودي لتقييم سيناريوهات الإخلاء من الحريق. أخيرًا، تمت محاكاة سيناريوهات متعددة لرؤية تخطيط التصميم الأكثر كفاءة لوقت إخلاء المستخدمين. تم تعديل عرض أبواب الخروج وكذلك عرض الدرج لرؤية تأثيرها على الإخلاء الكلي. بعد التحقق من عدة سيناريوهات لتخطيط المبنى وتصميم الخروج، تم تقديم اقتراحات وتوصيات للعمل المستقبلي. ساعدت مخرجات أدوات المحاكاة في تحسين كفاءة إخلاء المستخدمين بنسبة 10٪، وبالتالي تقليل الإصابات والوفيات.

CHAPTER 1

INTRODUCTION

1.1 Background

With the improvement in technology and the development of modern cities with a growing population and population density and a limited amount of area, the best solution is high-rise buildings. Many high-rise buildings are being built in the modern days. NFPA defines the high-rise building as “buildings greater than 75 feet or 23 meters approximately where the height is measures from the lowest level of the fire department access to the floor of the highest possible occupiable story”.

According to a study done by (Qu, Wang and Du, 2021) around 53 high-rise buildings over 200m were constructed in 2019 across the world, and the number will only increase in the future. High-rise buildings can be of many different categories for different functions such as, residential buildings, hotels, offices, apartment buildings and retail. Each category presents its own set of characteristics and challenges from the point of emergency evacuation. Thus, the analysis of the selected building is critical in identifying the human behavior and to check for proper implementation of fire safety code. The occupants’ physical ability and movement speed will also impact the evacuation time. This study will focus specifically on high-rise residential buildings.

It is important to study the evacuation in tall residential buildings because they are usually occupied by a large number of people of different demographics. There have been many deaths before which occur in high-rise building from not being able to evacuate the building properly, one reason is sprinkler systems are not present in the building or were not activated (Oven and Cakici, 2009).

There have been simulations done before since the inception of computers, if not by computers they were done by doing live fire drills and observing the evacuation process (Proulx, 1995). In recent years advances simulation software are being used to assist in understanding the fire evacuation process and the human interaction with the surroundings.

The simulation tools which will be used in this research are Pathfinder and Pyrosim, these are the latest simulation tools available which have much more realistic and optimized engine to simulate the fire and smoke as real as possible. PyrsoSim is used to simulate fire and smoke inside a building, it will be used to analyze fire control and smoke dissipation in the high-rise building for fire protection and safety.

Similarly, Pathfinder simulates the evacuation of the occupants which will help in understanding the building users egress time, pattern, and congestion hazards. By using these two simulation tools, data will be analyzed and assessed to see the impact of the building design, smoke propagation and occupant behavior during fire evacuation scenarios. All buildings are different and each of them will present new scenarios which might not have been identified by the designers or the fire safety team. Using 3D visualization, it will help the stakeholders to avoid any randomness, make them prepared for emergencies and reduce casualties.

1.2 Statement of the problem

Fire safety design is a critical process when designing high-rise residential buildings, owing to the various demographics of the occupants. Design professionals must ensure that their designs will reduce the occupant evacuation time, as a risk mitigation strategy against loss of life. Observations from local Architectural/ Engineering (A/E) practices indicated that occupant behavior and evacuation during fire emergencies have not been considered when designing buildings.

Reducing the evacuation time is critical and will save lives along with reducing the number of injuries. Human behavior is volatile, and their behavior varies from one building to another. How they interact with the building and surroundings also plays a major role in the evacuation efficiency and time. The type of egress system present in the building, the presence of fire wardens, latest firefighting systems, voice communication channels and frequent fire training all will greatly affect the evacuation (Akashah *et al.*, 2020) . There are other key factors which this study will look into, such as the impact of the width of the door, staircase and corridors on the evacuation efficiency and time. This can help identify improvements which can be made in the Saudi Building Code (SBC).

This gap has prompted the need to investigate the variables affecting human behavior and evacuation time in high-rise residential buildings. Simulation tools provide effective means for identifying and visualizing the challenges affecting the occupants' behavior and evacuation time during a fire emergency. The outputs of the simulation tools will be used to improve the occupant evacuation efficiency, hence minimizing injuries and fatalities.

1.3 Research Goal

This research aims to utilize BIM, and fire and smoke simulation tools to assess the behavior of occupants during emergency evacuation in high-rise residential buildings and develop measures, in accordance with the Saudi Building code, for enhancing the evacuation time.

1.4 Research Objectives

These are the following objectives of the thesis:

1. To investigate the passive and active fire protection measures that affect occupant's evacuation duration in high-rise residential buildings.
2. To develop a case study to simulate the evacuation time of the occupants from the high-rise building in the case of fire emergency.
3. To investigate different design layout scenarios which can improve the occupants' evacuation time which will be based on the output of the simulation.

1.5 Methodology

The methodology set to achieve the objectives of the thesis are:

1. To carry out Literature review to identify passive and active fire protection measures and evacuation challenges in high-rise residential buildings. A review was carried out on BIM and occupant behavior during fire emergency evacuations in high-rise buildings. The key

search terms for the literature review included: “Building evacuation” “Evacuation in High-rise Buildings” “Occupant behavior in Evacuation” “Simulation for fire evacuation” “Intelligent fire detection”. The search was carried out using mainly Google Scholar, Scopus and ScienceDirect. Over 200 relevant papers were reviewed from 1980 until 2022 out of which 133 were referred for this paper.

2. To select an existing high-rise residential building which comes under the category of residential group R-2 in the Saudi building code 801. This code is assigned to dwellings where occupants are usually permanent in nature. The building will be modelled as a case study using REVIT and ENSCAPE to develop a rendered 3D model of the selected building. This model then will be imported into Pathfinder and PyroSim for simulation.
3. To carry out multiple simulations using (a) PyroSim and for studying the impact of smoke development and propagation in a case study building, (b) Pathfinder for studying the human behavior and movement speed during fire evacuation. The model then will run multiple base case scenarios for different fires for evacuation in the existing building. Probabilistic values will be assumed taking the human movement speed data along with the fire propagation data from the previously published research to get a realistic simulation. The data of the base case results will be compared with the standard data to see the potential danger present inside the building.
4. Analyzing the obtained data out of the two simulation tools (PyroSim, Pathfinder) to identify the values of the key variables affecting the occupants’ evacuation.
5. Verification and Validation of the simulation results from previously stored data of the software programs to ensure the software implements the model correctly as well as reviewing previously published literature to see deviations.

6. Developing measures/solutions for reducing the occupant egress time based on the output of the simulation tools and improving the evacuation efficiency.
7. Developing Conclusions, recommendations, and areas for future research.

The main research questions that will be answered in this research are:

RQ1. What are the key factors pertaining to emergency evacuation in high-rise residential buildings?

RQ2. How do the occupants in different facilities behave during emergency evacuations?

RQ3. What are the inherent limitations in BIM-based simulation for occupant evacuation?

RQ4. What are the future research directions for utilizing smart fire detection and evacuation methods and systems in buildings?

Figure 1 illustrates the research methodology.

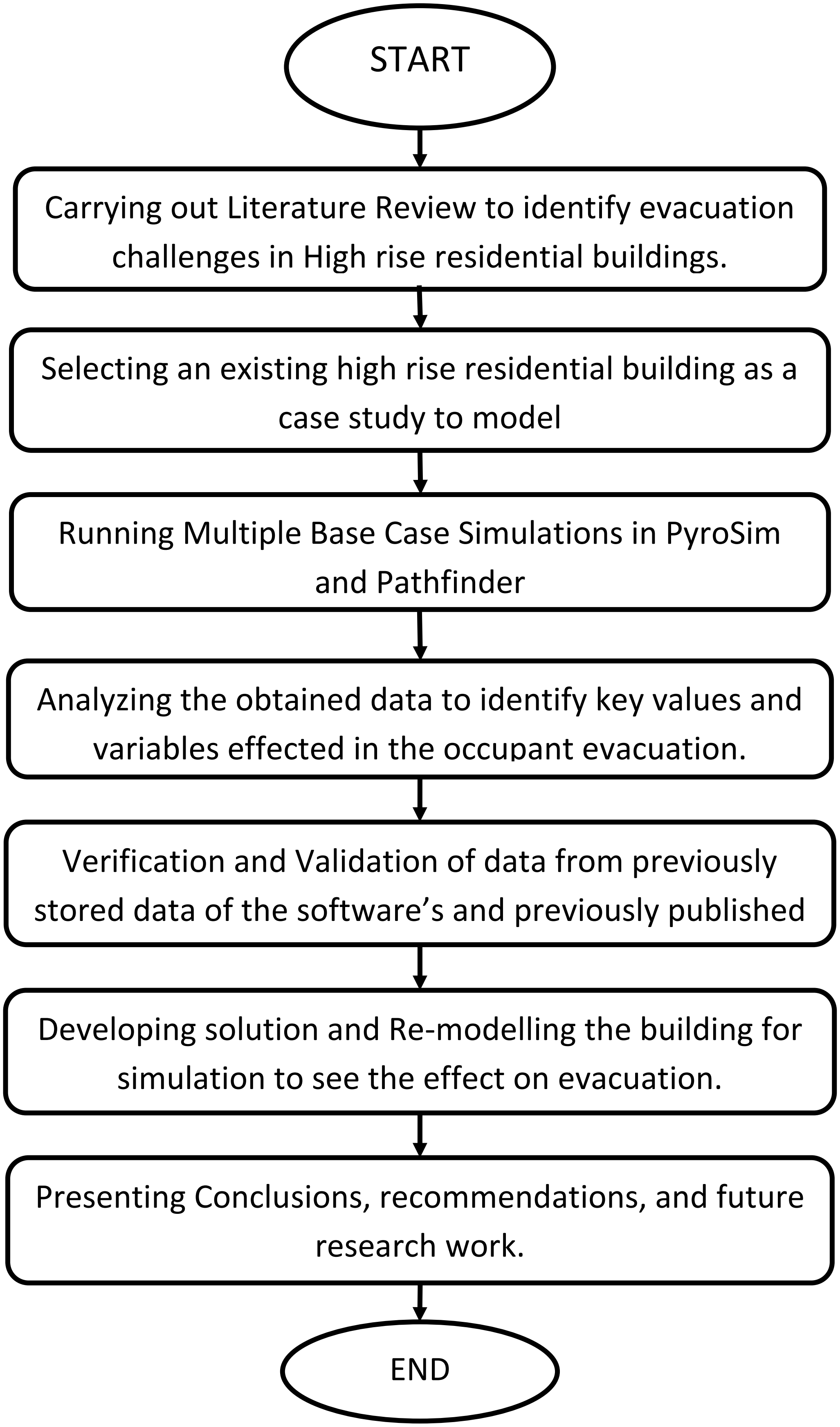


Figure 1 Research methodology

1.6 Research Significance

Fire emergency evacuation in high-rise buildings is a critical problem. These buildings are occupied by many occupants and the amount of space is usually limited. This research will be significant in providing value for the followings:

- This study will help in understanding how the occupants behave during fires and how the smoke propagation and fire spread have an affect occupants' during an emergency evacuation since people lives are at risk and the occupant safety is of utmost importance.

- This study will simulate the scenarios of fire evacuation and study the occupant evacuation and behavior using BIM simulation. This will help in minimizing the loss of life and will inform the impact of design on the fire evacuation time for that particular building.

- This study will be beneficial for architects and fire safety engineers who design buildings to further understand the requirements of egress.

- This study will help fire protection engineers to understand how smoke propagates and what are the factors in high-rise buildings which should be looked into and considered.

- The findings of this study will be beneficial for the Architectural/Engineering (A/E) industry in understanding the impact of the design and their choice of layout and firefighting systems on the emergency evacuation in high-rise buildings.

1.7 Scope and Limitations

- The scope of this paper is focused on smoke simulation and occupant behavior in residential high-rise buildings using the available published data and the anticipated smoke and fire growth rates.

- A high-rise building from Saudi Arabia will be selected as case study and its design and layout will be modified to see how it will affect the evacuation time.

- The data for occupants' physical ability and movement speed will be assumed from the international data available.

- This simulation will estimate the occupant behavior during evacuation in a specific residential building existing in Saudi Arabia. So, there is a good chance this simulation result will not mean all residential buildings will have the same results since there are many factors which affect the evacuation in real life.

- The building location, construction material used, the fire protection systems, the spatial design of the buildings and codes of the country, all these play a critical role, and each building will vary so this study will not delve into the all the materials and specifications which can be in other buildings.

1.8 Structure of the research

In this section, the thesis' content and structure are described.

Chapter 1 - Introduction: Providing background of the topic and discussing the statement of problem, identifying the research questions, defining objectives, methodology significance and limitations of the study.

Chapter 2 – Literature Review: Doing a systematic literature review during the last 20 to 40 years covering the main impactful and related topics.

Chapter3 – Evacuation Modelling: Developing the 3D building in a BIM software and carrying out the simulation in the fire simulation model.

Chapter 4 - Results and Discussion: Describing the results and comparing it with previous simulations and real-life data to see its accuracy and findings.

Chapter 5 – Conclusion and Recommendations: The study's conclusion and future directions.

2 CHAPTER 2

LITERATURE REVIEW

2.1 Literature Review

2.2 Evacuation in high-rise buildings

Rapid development and advancement in technology along with the increased need of housing has resulted in erection of numerous high-rise buildings residential buildings in the last decade. With the human population on the rise, the trend of high-rise residential building seems to be on an upward trajectory.

These buildings accommodate a large number of people from different demographics. This presents a difficulty during emergency evacuation. The fire safety code only permits the use of the stairs for egress, which can be a difficult task for people living on the upper floors especially for disabled, young, and old aged people. The buildings are usually occupied by hundreds of people if not more, crowding and collisions can occur at the staircases during emergencies due to a large number of people wanting to exit the building at the same time which will slow down the evacuation time (Zhiming *et al.*, no date).

Old aged people and people with disabilities will not even attempt to evacuate the building since it's not physically possible for them, especially for those who are residing on the upper floors of the building. Even for adults, in some cases it will be difficult to descend for a long time to their physical stamina. These tenants will instead wait for the firefighting team to rescue them. This is why there has been an interest in recent years for code to allow the use of elevators in tall buildings (Minegishi, 2021) .

In high-rise buildings usually the occupants evacuate late even after hearing the fire alarm and this delay could significantly impact their lives. Delays can be in the form of sleeping, using the bathroom or just not being sure whether to start the evacuation or not since many suspect that it could be a false alarm and not actually a fire. Occupants usually try to investigate about the fire before actually beginning their evacuation (Ding *et al.*, 2021).

Delays in evacuation could mean smoke building up and fire spreading inside the building, which will put the occupants in danger and increase the likely hood of casualties. In some cases, the firefighting systems of the building might not get activated which will further put the tenants at risk. It is important for the fire safety staff of the building to be aware of the situations that could occur because of fire, and they should provide adequate training to the residents on a regular time period to keep improve their knowledge and skills (Koo *et al.*, 2013).

Every building is different and has its own sets of challenges and drawbacks. The selection of materials as well as the amount of fuel load present inside the building will directly have an impact on the evacuation time of the occupants. So, one study or simulation results does not mean it will be the same for the other buildings. Therefore, it is a great problem, which needs proper planning and training for both the staff and the occupants in order to minimize the loss of life.

2.3 Occupant behavior in emergency evacuation

Occupants' behavior is something which is extremely hard to predict. There are many factors and variables, which can be present, and the reactions and responses will vary from one person to another as well as their movement and walking speeds (Muhdi, Davis and Blackburn, 2006). This presents a challenge for the fire safety engineers when they design for fire safety. It is critical to understand the human psychology in order to create adequate evacuation plans.

The behavior will vary depending on age, physical factors as well as mental ability. Their knowledge of the surroundings and their prior fire safety training will matter when calculating the estimated evacuation time. The surrounding environment will also have an impact on the occupant behavior and this also will vary from person to person (Gershon *et al.*, 2007).

Studies have shown that occupants take a long time to start their evacuation and this time is known as the "pre-evacuation time" this can be anywhere from two to eight minutes. This time is usually spent investigating the cause of hazard of the fire as well as getting ready and making the decision to evacuate or not. Families having babies or elderly members might also be reluctant to start their evacuation process (Kuligowski, 2013).

Studies have been done previously on human and occupant behavior but in certain circumstances, this does not mean the same will be observed again. Understanding human behavior will help designers in simulations to try and better predict evacuation times. Before the invention of computers, fire safety engineers used to carry out live evacuation drills to study the occupant behavior in different scenarios. With the advancement in technology and availability of software, simulations were carried out to predict the evacuation time, but the results would vary and were not accurate. This was due to the fact the occupant's behavior comes with uncertainty and it's difficult to simplify the data so most designers make assumptions and simplifications when modelling (Kuligowski, 2013).

There has been more data published in recent years which tries to make a realistic assumption by factoring in different human behaviors but there still remains uncertainty and no one car guarantee the replication of simulation to real life results (Lin *et al.*, 2020). More work still needs be done to better understand human behavior during fire emergencies.

2.4 BIM-based simulation tools for occupant evacuation

Building information modelling (BIM) can be defined as "a digital model of physical orbit environment"(Tien Doan *et al.*, 2019). BIM is useful for architects, engineers and fire safety engineers. When implemented properly BIM can provide valuable information and reduce costs of an organization. BIM is more than just creating 3D drawings, it has data and information stored which can be used in multiple different programs to run experiments and simulations.

Using BIM in occupant evacuation and fire safety design gives insights to both the designers and the client on how the changes have an influence on the complete performance of the design. BIM model can store information pertaining to fire safety, for example, the list of fire extinguishers, smoke detectors, their maintenance dates etc. BIM models can be used to quickly check if the design follows the safety code requirements; it can be used to simulate the occupant evacuation, which gives a rough estimate for long it will take for the occupants to evacuate the building.

BIM model can highlight ideas, which might not have been observed from the 2D drawings. Furthermore, BIM allows professionals in fire safety design and the building occupants to be trained in fire safety, thanks to the new technology advancements in Artificial Intelligence (AR) and Virtual reality (VR) (Lovreglio and Kinateder, 2020). Using VR in safety design also helps designers understand the user experience and their interaction with the surroundings. By studying the occupants behavior for that particular building, the designer can get insights on how the human perceives the environment and can use this knowledge to improve the design (Park *et al.*, 2018).

There has been an interest in using information technology and data monitoring systems to adapt a new concept for evacuation for occupants in buildings. This system can help occupants during their evacuation by guiding them to the nearest exit by scanning the environment of the evacuee and the nearest location of exit. This system is still under testing and needs optimization. Overall BIM tools are really beneficial and in the future it can be expected to be the norm for buildings to have smart systems to guide the building tenants during an evacuation (Fang, Lo and Lo, 2021).

2.5 Smart fire detection and evacuation in buildings

With the advancement in technology and internet of things (IoT), intelligent buildings are increasing in number and are becoming more prominent which use advanced sensors and systems. These smart systems gather data in real time such as the indoor air temperatures, smoke and CO2 levels and raise awareness if there are any faults. This allowed the building management team to always stay alert and up to date with the building issues (Majumder, O'Neil and Kennedy, 2018).

In the early 2000's the main issue with the fire detection systems was there were a lot of false alarms and faults in the systems. This was due to the technology not being that advanced where the smoke detectors could not differentiate between cigarette smoke and a fire smoke. But nowadays the equipment is well designed, and the number of false alarms has significantly decreased (Joshi *et al.*, 2020).

Smart fire detection tries to detect early fires and stop it from propagating once it has ignited. These systems are quite often complex with a lot of information being exchanged and monitored. Smart evacuation is also being developed and tested in many countries to optimize the exit paths for the occupants by guiding them to the nearest exit. Applications are being created where the device will read the surrounding environment conditions and guide the evacuees to the nearest accessible exit by providing information on their personal mobile phones. Other applications of smart technology is by using wireless sensors and radio frequency identification to guide the users in real time by displaying on the exit signages the way to exit the building (Hsu *et al.*, 2014).

One real time smart fire detection system is being developed which can identify the type of fire and its severity and will automatically alert the building users via mobile phones and also the nearest fire station. This will help save the precious time which can make a difference of life and death (Safayet, Rahman and Anam, 2021).

Although there are many advantages of smart fire systems, they are still not easily available to buy commercially and are not fully refined to be implemented en-masse. Over the next, few years it is expected more advanced systems will be implemented which can scale commercially and help save lives (Majumder, O’Neil and Kennedy, 2018).

2.6 Previous studies

2.6.1 Previous studies on Evacuation in high-rise buildings

2.6.1.1 Research output between 1980-1990

By the 1980's, tall buildings, or high-rise buildings, as they are currently referred to, were quite popular. Emergency evacuation in high-rise buildings was a relatively new topic, as three relevant studies were identified during this time period. Two of the reasons for this shortage of studies could be attributed to the lack of articles archiving in digital format, and the limited number of journals on the domain of fire safety. Kendik (1983) studied the movement of occupants in different buildings with varying areas and with different crowdedness densities, to determine the total evacuation time. The study conducted real evacuation tests to analyze the crowd's movement and motion during an emergency evacuation, by staircases. A mathematical model was developed to consider the different factors which impact upon the evacuation, such as the density in each building and the crowd movement speed. The study concluded with developing a formula that can estimate the total evacuation time.

Jones and Hewitt (1986) studied the social context and organizational characteristics of the occupants, which affect their decisions during the emergency evacuations of high-rise office buildings. In depth interviews with 40 evacuees and 10 firefighters were conducted. The interviews heighted that the occupants usually follow their supervisors. Thus, it is highly recommended that the supervisors have adequate training on fire safety, to better guide the occupants during emergency fire evacuations. The study concluded with emphasizing on the importance of fire safety training and awareness by organizations.

Pauls (1987) reviewed previous methods to calculate evacuation times in tall buildings. Mathematical models were developed to calculate evacuation times. However, the study noted that although these models can predict the minimum time required for evacuation, it is merely an assumption, which can be wrong and might not be realistic. The inaccuracies could be attributed to several factors, including the design of the building, flow, speed and occupants' density. Further, the study concluded that human behavior, which is a very uncertain factor, has a significant impact on the calculation of the evacuation time.

2.6.1.2 Research output from 1991 to 2000

During this time period, seven studies were identified, as the demand for high-rise buildings increased, and simulation tools started to emerge to determine evacuation times during fire emergencies. Fahy (1994) investigated the use of an evacuation model (Exit 89), developed to track each occupant individually. The model facilitates predicting the movement of occupants during the fire emergency evacuation. The study observed the occupants' behavior during the evacuation process, corresponding to the surrounding environment along with the development of fire and smoke propagation. Nevertheless, the developed model did not consider occupants' behavior during the emergency evacuation and recommended that this aspect could be investigated in future research. Similarly, Poon (1994) used (EvacSim), a building evacuation model to simulate a variety of complex human behaviors during evacuations. This model was limited through focusing only on the development of fire, without taking into consideration smoke propagation, for a better understanding of the occupants' behavior. Furthermore, Thompson and Marchant (1995) utilized (Simulex), a model to simulate the occupants' escape movement from large complex building structures, through the use of different algorithms. Yet, as in the previous simulations, the individual behavior of an occupant, along with the psychological aspects of fire evacuation, could not be considered, since they vary from one person to another.

Proulx (1995) conducted an experiment to observe the evacuation time and the occupants' movement during a fire emergency. The experiment involved an evacuation drill in 4 different apartment buildings, where all buildings occupied with the maximum number of occupants, who were from different demographics. The results showed that the elderly and disabled people did not have an impact on the evacuation time, since they waited inside their rooms for help to reach them. The results also indicated that some occupants had a delayed reaction, since they could not hear the fire alarm properly. The experiment provided insight that knowing the whereabouts of the building is very important since in one of the four buildings used for the experiment, the occupants were not aware of the building's surrounding environment, and this caused them to panic. While the occupants of the three other apartment buildings knew their buildings well and they all went straight to the main staircase for exit. Overall, the study concluded that the evacuation time did not vary among the evacuees, and that the "starting time to evacuate" was the most important factor in reducing the evacuation time.

Owen et al. (1996) used (Exodus), to simulate the evacuation of a large number of people from a building. The simulation model tracks the trajectory of all occupants, as they evacuate. The evacuation performance was measured by observing the exit flow rates and the average evacuation time per occupant. The model demonstrated that varied individual speed and response times impact upon on the overall evacuation performance.

Promoted by an incident where six building occupants were killed, and over 1,000 injuries, Fahy and Proulx (1997) studied the occupants' behavior during the evacuation of a high-rise building. The study involved surveying the occupants of the building who evacuated from the building. The findings indicated that the floor wardens needed to be available at their assigned posts, and well equipped with the building information to make safe decisions, in the absence of electrical power. The findings also indicated that training should have been provided to all occupants, rather than to only the fire safety team. Further, some occupants complained about the extended time for fire fighters to reach them. However, occupants of high-rise buildings need to know that the higher up they are in a building, the more time it will take the firefighting team to reach them, which was also confirmed from the study done by (Lateef and Anantharaman, 1998).

2.6.1.3 Research output from 2001 to 2011

During this period, high-rise buildings were quite common across the globe. Fifteen studies were identified during this period, aiming to better understand various aspects affecting emergency evacuation and human behavior during egress. As more simulation studies were performed, collection of data on human behavior was necessary to develop accurate outcomes. Fahy and Proulx (2001) developed and published a database including the various characteristics of occupants, along with their different walking speeds, in different types of buildings.

Many evacuation models and simulations were developed using different strategies and software tools (Tong et al., 2001; Pelechano and Malkawi, 2008; Oven and Cakici, 2009). These studies emphasized that although the simulation models can generate evacuation times, the actual results may vary due to human behavior and occupants' interaction with the physical environment. In addition, the actual results may also vary depending on the speed of fire and smoke propagation, which also affects the simulation results, and hence present a challenge in accurately estimating the evacuation time.

Hakonen (2002) simulated the occupants' evacuation time through stairs and elevators. The study concluded that if both stairs and elevators are utilized for evacuation in high-rise buildings, the overall evacuation time would be significantly decreased. However, in low-rise residential buildings, the use of stairs would be more efficient, as the elevators are typically small, with low capacity. The study also noted that in super high-rise buildings, the use of elevators during an evacuation could decrease the evacuation time significantly, down to 15-30 minutes, instead of 2-3 hours.

Sano et al. (2004) conducted an experiment using an evacuation chair. The study concluded that wheelchair users could be easily and quickly evacuated by using this type of specially designed chair. Additionally, Sekizawa et al. (2004) investigated the feasibility of using elevators during fire evacuation. The study highlighted that various occupants', mainly the older aged people, will experience difficulty in using the stairs for evacuation. The study also highlighted that if the building occupants' are assigned to different types of emergency exits to use during an evacuation, the evacuation will be more effective. For example, if a small number of people are assigned elevators during evacuation, while the rest were assigned to use the stairs, the evacuation will be faster. Further, Williamson and Demirbilek (2010) studied the use of elevators during evacuation and emphasized that only buildings where elevators are approved by architects, for evacuation should be used. Furthermore, Chen et al., (2011) in their study discussed the switch of transportation elevators to evacuation elevators in high-rise buildings, to speed up the evacuation.

Lay (2007) discussed other alternative evacuation strategies for high-rise buildings, such as helicopter rescue, rapid slide system and zip wires to neighboring buildings. Yet, these evacuation solutions are unlikely to have a major impact on the time and the efficiency of the evacuation. The study concluded that elevators and stairs are the best solution for emergency evacuations.

Gershon et al., (2007) identified the factors associated with high-rise building evacuation. The key factors included occupants' training on evacuation, degree of familiarity with the building, occupants' physical condition, health status, and footwear. The study also considered occupants' individual behavior to be a significant factor, which is variable, just like fire and smoke.

Helsloot et al. (2008) discussed the vital role of stairs in the efficiency of evacuation in high-rise buildings, as they are the safest and fastest way for occupants' evacuation. The study concluded that it is critical to design the stairs in a manner that facilitates the ease of evacuation.

Zmud (2008) conducted a survey to determine the public perceptions about emergency evacuation preparedness of occupants, in high-rise buildings. The study noted that commercial building users had much higher levels of fire training experience, while residential building users had information gaps, or were significantly lacking in training.

Hassanain (2009) added that high-rise buildings of different functions will have varying amounts of fuel load. The type of furniture and fittings will vary and their characteristics will impact the rapidity of combustion and smoke propagation. The excessive amounts of fuel load can negatively impact the evacuation, due to the release of toxic gases, and the development of smoke, which hinder occupants' evacuation.

2.6.1.4 Research output from 2012 to 2022

During the last ten years, fire Safety concerns have become a priority for all users and stakeholders of high-rise buildings. Several studies pertaining to evacuation in high-rise buildings have been published. Ma and Guo (2012) suggested improvements in the fire safety design codes for high-rise buildings, as the current codes and standards do not accommodate all the variable design conditions for all buildings.

Numerous studies (Lu et al., 2012; Ma et al., 2012; Ma and Guo, 2012; Ma et al., 2013; Koo et al., 2013; Ronchi and Nilsson, 2014; Ding et al., 2021; Fang et al., 2022) have focused on improving the evacuation strategies in high-rise buildings. These studies investigated the utilization of elevators as a means of evacuation, and acknowledged their effectiveness, as they significantly decrease the occupants' evacuation time in high-rise buildings.

Much like the previous years, more simulation tools were used to study the occupants' behavior during evacuation and investigated their movement and evacuation time (Lu et al., 2012; Koo et al., 2012; Yang et al., 2012). Simulations were carried out to simulate the smoke propagation and occupants' behavior during egress. The results from these simulations can assist fire safety engineers and architects to understand the conditions of each building, and hence select the proper evacuation strategy to improve the evacuation efficiency.

On another front, (Sun et al., 2013) indicated that as high-rise buildings increased in height, the selection of appropriate building material and façades becomes critical, as they can significantly increase or decrease the spread of fire and the propagation of toxic gasses which can affect the occupants' movement speed. This would potentially affect the efficiency of the occupants' emergency evacuation.

Choi et al. (2014) investigated case studies of BIM-based evacuation regulation checking procedure for high-rise buildings. The study aimed to create an automated system that allows fire safety engineers, architects, and owners to evaluate the BIM data's adherence to evacuation regulations. An automated evacuation regulation checking system was developed, called InSightBIM-Evacuation. The study highlighted the importance of automated regulation checking of code compliance due to the frequent changes of design during the pre-construction phase. The study concluded that fire safety engineers and architects are able to evaluate design quality according to the standardized method when a change in design occurs.

Wang and Weng (2014) conducted a study on occupants' evacuation characteristics in a high-rise building. The study utilized an evacuation simulation model, which is based on a social force model. The model can simulate the occupants' behavior under different psychological and physiological factors. The study focused on the influence of the design of stairs on evacuation efficiency. Simulations were performed to observe the evacuation process through the stairs. The study concluded by providing a suitable range of the slope gradient of stairs and illustrated the effect on the total evacuation time, with the change in the slope gradient of the stairs.

Lavender et al. (2015) investigated the use of descent equipment for stairs, which can be utilized to evacuate disabled people during an emergency evacuation in high-rise buildings. A pilot study was conducted with a small group of users, with mobility impairments. Three separate designs were presented to the test group. The group were introduced to the equipment and its utilization, along with presenting videos, demonstrating the equipment in use. Each group member was interviewed to provide their feedback and initial impressions. The study concluded that the group were generally accepting the equipment used for evacuation, although more studies need to be conducted with a larger sample size to verify the results. Similarly, Egodage et al. (2020), investigated the emergency evacuation procedures in use for people with mobility impairments. The study revealed that the priority given to the disabled people depended on the type of high-rise building. Hospitals and hotels emphasized the importance of emergency evacuation procedures to their occupants, in comparison to office and residential buildings' occupants. Additionally, the study highlighted the lack of emergency evacuation procedures available for the disabled people throughout all building types.

Xueling (2015) developed a simulation model to study the occupants' group behavior during emergency evacuation from high-rise buildings. The study highlighted several characteristics of high-rise buildings, which present difficulty for occupants' to evacuate. The factors included the height of the building, complexity of the layout, occupants' density inside the building, evacuation distance, and the chimney effect. A framework for fire evacuation process considering individual and group behavior was developed. The study performed evacuation simulations taking into consideration group behavior and real time fire. The results indicated that group dynamics and the actual course of the fire had a significant impact on the pedestrian evacuation, hence, lengthening the evacuation time. A similar study was conducted by Wei et al. (2019) who investigated the effects of family group dynamics on the evacuation time. The study reported similar results were observed where grouping caused an increase in the overall evacuation time. This was attributed to the fact that family groups move together, occupying a larger space that can hinder the movement of other evacuees who have faster movement.

Aleksandrov et al. (2016) conducted a study aiming to highlight the importance of presenting the evacuation time through elevators to occupants' to assist them in making better decisions. Three evacuation scenarios were provided to occupants during the evacuation process in a high-rise residential building. In the first scenario, the evacuation time was not provided to the occupants. In the second case, the arrival time of elevators was provided. The third scenario involved directing occupants to the elevators for evacuation. The simulations were carried out using the evacuation software "Pathfinder". The study indicated that providing the occupants' with the evacuation time results in redirecting more occupants towards the elevators, which will lower the evacuation time. The study highlighted the shortcomings of the simulation such as the occupant behavior, evacuation delay, and the grouping factor, which can influence the evacuation time. These shortcomings were not considered in the simulation.

Ding et al. 2017a) investigated the behavior of the evacuees, and the variables that affect their behavior. It was discovered that the load time of six seconds is considerably faster than the time required to open and close the doors, which was approximately fifteen seconds. In addition, the volume of evacuees and queuing patterns like the arch and line will affect the time that evacuees need to pass through the elevator doors. Occupants' behavior ranged from pushing, feeling uncertain, re-entering the elevator, preference for stairs, and social bonding. The study recommended considering the width of doors and the layout of elevator lobbies in the simulation, which results in simulating more accurate evacuation time. The study also concluded that elevator evacuation simulations can be calibrated and validated using the experiment's fundamental data.

Ding et al. (2017b) developed a Cellular Automata map to enhance the simulation of pedestrian movement in high-rise stairways, during emergency evacuation. Based on the stair’s structure, the simulated map is segmented into zones, where each zone has a specific set of rules for organizing the movement of the evacuees. A fire drill was staged in two high-rise structures to verify the simulation. The outcomes of the simulation showed that it can anticipate the evacuation time more precisely. This will enable fire safety engineers and architects to evaluate their evacuation plans and strategies based on the new simulation.

Soltanzadeh et al. (2018) conducted a study to evaluate the effectiveness of the emergency evacuation features used in high-rise buildings. The study analyzed the ideal period of emergency egress in a 40-story high-rise office building, using simulation tools. The number of elevators, staircases, and locations and areas of refuge floors are independent variables in the simulation, while the number of survivors in the simulation's standard hour was the dependent variable. The findings from the simulation indicated that placing a refuge floor in the middle of the high-rise building will enable more people to be evacuated. The study recommended reducing the number of intersections in the refuge floor plan, to prevent the formation of long lines for elevator use.

Ding et al. (2019) studied the behavior of evacuees during a high-rise building evacuation, in relation to non-irritating smoke and awareness of the evacuation process. Several experiments and questionnaires with 45 participants were carried out. The findings of the comparison of elevator and stair evacuation times, the number of elevator users, elevator wait times, and re-route behavior were all analyzed. The percentage of participants who preferred to take the elevator compared to those who really did, was significantly different. The study noted that elevator overload, physical exhaustion, and social ties played a major role during the evacuation of occupants. The study recommended utilizing elevators only on refuge floors, rather than on each floor to improve the evacuation efficiency.

Akashah et al. (2020) investigated the evacuation plans used in Malaysia's high-rise buildings. A case study on four high-rise buildings was conducted. The study discovered that total evacuation was the most often used evacuation technique. The study highlighted the most significant elements impacting decision-making in the use of evacuation techniques. These included the reliability of the emergency response system, building characteristics/fire safety features, and evacuation strategies. The study also highlighted that occupants' characteristics had the least significance. The study recommended that facilities managers and fire safety administrators devote more attention to occupants' behavior during evacuation drills. Additionally, the study also recommended providing occupants with additional training and highlighting the importance of fire safety training to increase their awareness and sense of responsibility during a fire evacuation.

Mossberg et al. (2021) conducted unannounced evacuation tests in the middle of a 35-story high-rise hotel building. Eye-tracking glasses were worn by a group of occupants, to collect and analyze data on exit choice and eye fixations. Three scenarios, involving two distinct hotel room placements on the floor, and a different navigation system for one of the rooms, were investigated. The findings of the study revealed that although the occupants' hotel room was closer to the evacuation stairs, guests frequently opted to utilize the elevator for evacuation. Further, occupants did not focus on the evacuation signs during the emergency evacuations. An experiment was conducted, in which green lights were flashed next to evacuation paths during evacuations, which made occupants more observant of the egress path, yet the evacuation time was not influenced significantly. The study concluded that fire safety doors without vision panels, with self-closing mechanism can confuse the evacuees, which can increase the evacuation time.

Fang et al. (2022) investigated the utilization of elevators for emergency evacuations. The study highlighted the necessity of using elevators, as high-rise residential buildings are occupied by elderly people, where evacuation might take longer time for occupants living on the upper floors. The study proposed a simulation program called smart elevator-aided building fire evacuation (SEABFE). The simulation program provides real time guidance to evacuees by determining the safest and most efficient strategy of evacuation. The simulations' results revealed that the evacuation time can be decreased by 38% when utilizing elevators along with stairs. However, the study noted that the frequent stops of elevators on each floor may increase the evacuation time. This can be avoided by providing a refuge floor at different levels, which will make the evacuation more efficient.

Gerges et al.(2022) highlighted the importance of understanding human behavior, to improve the efficiency of emergency evacuation. The study indicated that although previous research has been conducted to understand the human behavior during emergency evacuation, fire safety engineers and architects have not yet utilized such data on occupants' behavior, in evacuation simulations. To further examine the human behavior in high-rise residential buildings, the study examined occupants' behavior, while being provided with evacuation instructions directly on their smart phones. The study demonstrated that utilizing smart phones during emergency evacuation has reduced the overall evacuation time, through guiding the occupants to the fastest egress route.

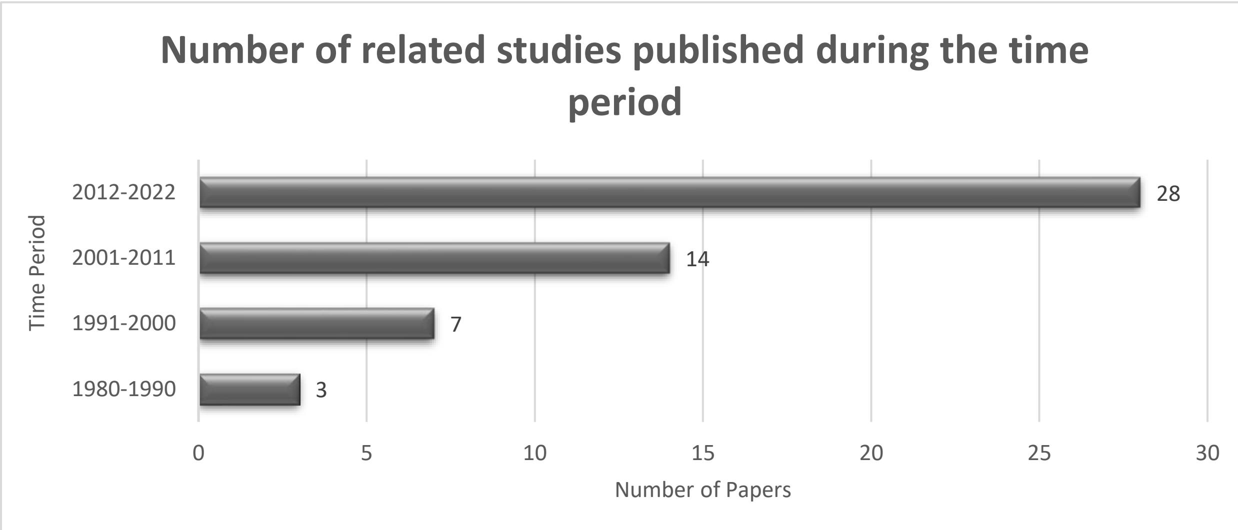


Figure 2 Reviewed literature references on Evacuation in high-rise buildings. Distribution by Time Period

2.6.1.5 Analysis and discussion of the previous studies on evacuation in high-rise buildings

The reviewed literature covered the evacuation in high-rise buildings, in detail. Different strategies and methods were proposed, and numerous factors were identified, which have an impact on the evacuation. Different options were investigated through conducting real-life evacuation drills and computer modelling and simulations. There are several factors which influence the evacuation time, such as the occupants' behavior and demographics. Another factor which can lower the evacuation time significantly in high-rise buildings, is the use of emergency elevators. Utilizing elevators can significantly lower the evacuation time, especially for the people occupying the upper floors of the building. Building occupants having training for fire emergency evacuation was deemed to be very important in lowering the evacuation time.

From the review of the literature, it was also evident that the higher up the occupants are, the longer it will take them to evacuate. Further, as occupants are located higher up, evacuation become more difficult, due to the extended travel distance, which causes fatigue, and consequently reduces the occupants' moving speed. Other factors which affected the evacuation time included the inappropriate location of the fire alarm, resulting in the inability of the occupants to hear the fire alarm. On the other hand, the sound of the fire alarm was too loud. Hence, occupants were not able to communicate with the fire fighters. This presents a challenge for the disabled people, since they cannot move easily. More studies are advocating the use of elevators for emergency evacuation in very tall buildings. This can be attributed to the amount of time that occupants require for evacuation, sometimes up to 2 hours. Thus, it is not feasible for occupants to use the stairs for exit (Ding et al., 2021).

There is appropriate data currently available about the estimated evacuation times for high-rise buildings. However, the existing research related to simulation is not accurate, in comparison to actual real life evacuation results. This is attributed to the fact that simulation tools fail to consider factors such as the psychological state of the occupants, as well as their familiarity with the surrounding environment. Another significant factor in emergency evacuation is the social relationship among the groups, which the simulation does not consider. Therefore, more research needs to consider human behavior during emergency evacuation, to predict accurate simulation results, similar to real-life scenarios. The selection of building material, as well as the façade is critical, as the selected material and the design of the facade can increase or decrease the spread of fire. The main conclusion from the previous work is that each high-rise building is different, and the physical environment plays a vital role in the evacuation.

2.6.2 Previous studies on Occupant behavior in emergency evacuation

2.6.2.1 Research output from 1980 to 1990

With the modernization and advancement in architectural engineering technology, complex buildings have started to emerge which are sometimes complex which makes it difficult for the occupants when a fire breaks out. Occupant behavior is very random and difficult to predict as there are many variables and factors which have an impact on their behavior. In this section occupant behavior will be discussed from the published literature review in the last 42 years.

In 1985 (Khisty, 1985) conducted a study in which they performed test evacuations to study the occupant behavior during fire emergencies. Key points from the study were that they noticed the differences in the stairways which did no cause changes in the flow or speed of the occupants. One interesting fact they observed from the study was that the daytime evacuation appeared to have been much easier without any panic and confusion, while during the night in spite of having proper illumination, some crowding happened at the stairways and passaged which slowed down the evacuation. The author highlighted that it is important to keep the tread and riser dimensions uniform for easier evacuation to avoid tripping and falling.

(Maclennan, 1986) investigated the various different egress and evacuation models existing during that time and in what way human behavior was studied. For evacuation models it is hard to program the human behavior, so you have to make generalizations while doing simulations. There are several factors which need to be though about such as the start time of the evacuation which is when the occupant identifies it's an emergency and decided to start the evacuation, then the time which it will take the occupant to move toward the exit and finally the actual time for the occupant to utilize emergency stairs to evacuate the building. The author mentioned the group behavior and choosing the method of exit are critical parameters for evacuation. Another factor which could impact he occupant behavior during emergency evacuation is his prior training during emergency. From the data that was available on human behavior it was not possible to predict accurate evacuation times.

Five case studies on human behavior during evacuations were conducted by (Huang and Fan, 1989). These studies were done to find out the realistic evacuation time predictions so that one can accurate calculate the delay time for the occupants before they start their evacuation. Key components, which need to be studied and taken into account, are the occupants' pre-movement and notification time. An assumption in evacuation models is made that the occupants start their evacuation once they hear the sound of the fire alarm which is not true. A time delay exists from when the occupants hear the fire alarm and decide to start evacuation. From the 5 case studies it was noted that if there was no proper or poor alarm system it can take up to 8 minutes or more for the occupant to start their evacuation. Similarly, the least duration for occupants to start the move to evacuate is from two to three minutes. It is important to reduce the delay time which can be done by training, preparation and involving fire wardens.

A simulation done by (Weinroth, 1989) also confirmed that the evacuation time can be decreased if the time taken to begin the evacuation is reduced. This can be achieved by having good alarm systems which notify the users along with having proper fire evacuation training for the occupants. In the end the author mentioned it's not easy to model the occupant behavior since for example people could be sleeping or busy with other things which can delay their evacuation time.

2.6.2.2 Research output from 1991 to 2000

A simulation program called EvacSim which is used for building evacuation was used by (Poon, 1994) to simulate a variety of different human behavior movement using both deterministically and probabilistically approached and a mixture of both. The simulation program takes input data such as the severity of the fire and the physical scale along with the physical attributes of the building. It also considers the occupant profile, their response rate and their building knowledge. Although it considers all these different factors it is still difficult to simulate for residential buildings which comprise of individuals who might be sleeping, babies or old aged occupants who will need assistance for which it is difficult to model.

A similar simulation program called EXODUS has the possibility to simulate the behavioral characteristics overlooked in previous evacuation simulations. Such as the characteristic of group bonding, role of the fire warden and the rescue operation which take place by the firefighting team (Owen, Galea and Lawrence, 1997).

Research on emergency evacuation was done by (Johnson and Feinberg, 1997) by using a simulation which models the social behavior responding to a fire alarm. They found that the familiarity of the occupants to the surrounding area as well as having multiple exit options has a positive impact on the efficiency of the evacuation and egress time.

(Proulx and Pineau, 1996) conducted an experiment to study the egress time and the user’s movement in two different office buildings to compare it with the evacuation fire drills done in apartment buildings. The occupants’ behavior and movement was observed, and the results presented that occupants in the apartment building delay their evacuation time more than office building tenants because of extended preparation time or they did not hear the fire alarm from their apartments. Travelling speeds were also found to be slower in apartment buildings which had a higher population and a diverse demographic. To reduce the evacuation times, it was suggested to involve fire wardens during evacuation and access to fire safety information is made easier, which can increase the efficiency and effectiveness of evacuation process.

Another study which was done on high-rise apartment buildings by (Brennan, 1997) found that the delays in evacuation were due to slow response of the occupants and a long time for preparing to evacuate. Age was also a considerable factor.

(Saunders, 1997) investigated the impact of occupant decision making during fire emergencies. The author used a film accompanied by a questionnaire to get information on the decision making of the tenants throughout the early stages of the building fire emergency. The outcomes showed that the occupants preferred behavior during a case of fire was to inform others and help others rather than evacuating the building immediately. Just like the previous authors concluded, the author reiterated that the evacuation period can be shortened if the occupants are well trained for fire emergencies.

(Meacham, 1999) discusses the issue of engineering of fire safety design. When making the design they usually consider the type of facility, assumptions about the fuel load and fire spread potential and design according to that. The main point which was heighted was that when designing buildings for fire safety, engineers usually follow the set guidelines which the code mandates. They do not consider other external factors of how human behavior can have an impact on the evacuation. If the designers also recognize the occupant behavior, they can design better fire safety plans. Another study also supported this fact saying majority of the architectural design is completed based on prescriptive requirements of the building codes (Lo and Fang, 2000).

Similarly a study done by (Shields and Proulx, 2000) mentioned that the fire safety regulations must not be based on the fire loading and fire severity, rather should be based on the appropriate occupant characteristics. Because then you can study the occupant flow rates and their relationship with the building according to their demographics.

A study was done on occupants behavior during a fire incident to understand the human factors as well as their response during fire emergency (Proulx, 1999). The author collected in person interviews as well as questionnaires from the occupants to get the data. The fire took place in a twenty-five-story tall building in Canada. Once the structure was caught on fire the fire alarm system went off from the collected data it was interesting to note that only 4 percent of the building occupants-started their evacuation after hearing the fire alarm. Another study also indicated that only 3 occupants from 16 started evacuation after hearing the fire alarm from which we can assume that occupants don't take the initial fire alarm sound seriously (Shields et al., 1999). Continuing with the evacuation in the 25 story Highrise building around 85% only started evacuation once they heard instructions over voice communication from the building management. It can be learned that people take voice commands more seriously than the fire alarm since many occupants think it's a false alarm or there is testing going on.

The fire alarm and the voice communication system was very good in the building with 95% respondents saying they could clearly hear the instructions clearly. Some occupants because of their disability decided to stay inside their rooms and wait for fire rescue team. While others tried to evacuate with some being successful and some being forced back due to the stairways filling up with smoke. This caused them to head back to their lodgings or find refuge in other neighboring accommodations.

(Shields and Boyce, 2000) listed the factors which are most likely to have an impact on the human behavior and their movement as follows: their acquaintance with the building, their attentiveness, mobility, social relationship, knowledge of focal points inside the building, position in the building, role and responsibility and their commitment. Although they can be categorized, they can vary from one person to another. From the author's study it was found that to improve the evacuation the training of the staff is vital and has many benefits as they can ease the evacuation process.

2.6.2.3 Research output from 2001 to 2011

(Purser, 2003) discussed the occupant behavior with the surroundings. The author defined two major components of fire escape. First is the "required safe escape time (RSET)" and the other is the "available safe escape time (ASET)". While the former it's placing emphasis on the travel time and physical activity of the evacuees during evacuation, while the latter is focused on the time that is available for the occupant to evacuate the building safely without getting effected from the toxic smoke and irritants.

(Yang, Fang and Fan, 2003) studied the occupant evacuation efficiency by using a cellular automata model. It was identified that the coexistence of different demographics and their different movement speeds greatly reduced the evacuation efficiency. While movement that is steady and in order is incredibly effective, yet difficult to attain in emergency. One person slowing down slows all other occupants so its suggested a special area or pass be dedicated for the slow man to make the evacuation smoother. The widening of the corridor at some degree helps but doesn't solve the problem completely. It is highly recommended that occupants take part in evacuation training which will enhance their evacuation efficiency. Knowledge of the building surroundings also greatly improves the evacuation efficiency (Yang et al., 2004).

Many studies were done relating to occupant behavior and emergency evacuation during this time period on the "World Trade Center (WTC)" which was among the largest evacuations from high-rise buildings (Kuligowski and Mileti, 2009). From the studies and simulation, it was understood that it would take over 100 minutes to evacuate if the building has over 50% occupancy roughly around 15,000 people (Averill et al., 2005). There were various factors which had an impact on the evacuation such as individual (training and familiarity with the building), organizational (communication) and environmental (smoke, debris, crowdedness) which affected the evacuation (Gershon et al., 2007).

(Yang et al., 2005) examined kin behavior during emergency evacuations. Kin behavior is very common during evacuations, it refers to closely related people going together as a group. From the simulation revealed that crowd-following behavior during evacuation is not necessarily detrimental. It was discovered that the proper kin behavior helps to increase the overall evacuation process. Social interaction between groups and the surrounding crowd plays an important role during evacuation and has a considerable effect on the performance of egress. The vast majority of the authors claim that the occupant behavior during emergency conditions is complicated and difficult to understand due to the variety of factors at play. (Shi, Ren and Chen, 2009) (Luo et al., 2008) (Pan and Han, 2006).

Another psychological factor is that during emergencies humans react differently. A study done by (Proulx and Reid, 2006) found that during an emergency fire evacuation in tall building, 85 percent of the occupants had previously received prior fire safety training while only twenty percent correctly grasped the proper evacuation strategy.

During the past decade a lot of numerous facts and data was collected regarding human characteristics as well as their movement speed. A study was done by (Muhdi, Davis and Blackburn, 2006) in order to determine the maximum walking speed, and normal and maximum crawling speed. The findings revealed that the average typical walking pace was 1.32 m/s. This, however, does not account the difference of age and the fatigue and health level of the occupants.

The difference in demographics also has an impact on the time required prior to the evacuation. Results from a study (Adams and Galea, 2011) displayed that adults spend time seeking information than younger generation. The place where tenants were located also had an impact on the evacuation as the tenants at lower floors received information much quicker and have a faster route of escape.

Another interesting study was done by (Yasemin, Doğan and Bayramlı, 2009) which identified that clothing would also impact the evacuation time. This study was done in Saudi Arabia where women will be wearing religious clothing because of which their movement speed is significantly reduced especially when ascending and descending the stairways.

2.6.2.4 Research output from 2012 to 2022

Evacuation of building users in high-rise residential buildings is not the same when compared to other tall buildings. Occupants' behavior is mainly dependent on three factors which are the building characteristics including characteristics of the fire. When the fire alarm goes off, occupants in high-rise residential building could be sleeping, cooking, not dressed which can increase their time before the start to evacuate (Ronchi and Nilsson, 2013).

In addition, selection an appropriate route is a critical factor in reducing the egress time (Chen et al., 2013). This depends on how much information the occupants have and their familiarity with the surroundings.

Even if we know how and what are the key factors which impact the evacuation time, occupant behavior is something which is difficult to predict. Even though a lot of research, simulation and fire drills were done to predict the evacuation time, it was still difficult to study and predict the crowd behavior in emergency situations. There can be arching which is defined as "when a large crowd with high velocity tried to escape through the door" and clogging when trying to escape as well as chance of stampede if the area is densely populated. (Almeida, Rosseti and Coelho, 2013).

From the literature it is quite evident that residents frequently disregard the fire alarm. as well as the smoke and instead focus their time on getting more information and investigating before beginning their evacuation. This increased pre-evacuation time could be fatal as egress could become congested or could allow smoke to fill up the area.

Some engineers use hand calculations and computer tools and simulations software's which try to calculate and predict the evacuation time using many different methods for safety analysis, but none of them account for human behavior mainly because of its uncertainty. They consider only deterministic values and try to make it as real as possible. In the end engineers make assumptions and simplifications about the occupant behavior which is probabilistic. (Kuligowski, 2013) (Zhang, Li and Hadjisophocleous, 2013).

Recently a lot or research is trying to push for the usage of elevators in tall buildings for emergency evacuation. Elevators are not used during emergency evacuations because there could be power failure. The residential building comprises of people of different demographics and differently abled people with limited mobility. Using stairs is not a viable option for these occupants so they either must wait for the help from the fire safety team to rescue or they can use help of other occupants to escape the building, but this can put both the occupant helping the person with disabilities with risk and could also risk the disabled person getting injured. By using both the staircases and elevator, the time for evacuation will be greatly reduced, and it could potentially save many lives (Groner, 2014) (Kinateder and Kuligowski, 2014) (Bukowski, 2012).

An experiment was done by (Zhu and Shi, 2016) to comprehend how people behave in critical circumstances and the impact of the choices they make. It was noted that during fire emergency humans tend to follow the crowd. Their knowledge of the surrounding and their choice of exit also greatly reduced the evacuation time (Kinateder et al., 2014).

A lot of interest and effort has been made to recognize the occupant behavior during the last decade. The main consensus is that it is something which is very volatile, and it is difficult to simplify and generalize. The interaction of the occupant with the surrounding environment varies from building to building and knowing how the occupant will react in a given situation is very difficult. There are some things which can be generalized from the past examples and data which has been collected from which at least we can get an idea of what exactly impacts the decision making of the occupants (Chu and Law, 2019) (Lin et al., 2020) (Wang, Kyriakidis and Dang, 2021).

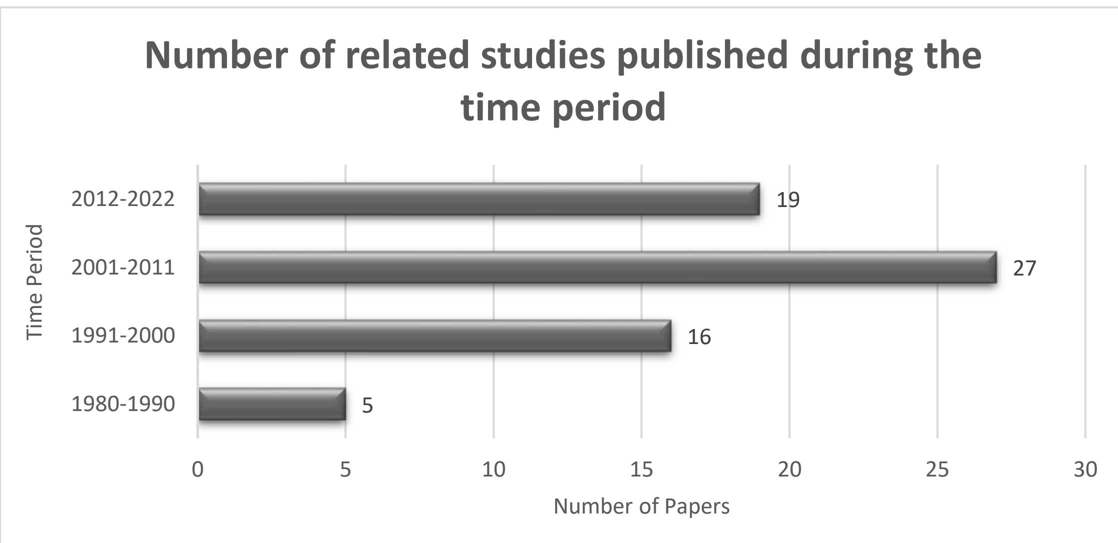


Figure 3 Reviewed literature references on Occupant behavior in emergency evacuation. Distribution by Time Period

2.6.2.5 Analysis and discussion of the previous studies on occupant behavior in emergency evacuation

The literature highlights the importance of factors such as building design, alarm systems, occupant training, and social behavior in determining evacuation efficiency. The studies also emphasize the complexity of predicting occupant behavior during emergencies due to various factors at play.

Previous studies highlighted that occupant demographics, behavior and building characteristics, impact the total evacuation time in high-rise residential buildings. Clothing, location, and familiarity with surroundings also play a crucial role. Predicting occupant behavior is difficult, and architects and fire safety engineers often make assumptions and simplifications.

Few of the studies discussed the potential use of elevators for emergency evacuation. While elevators may be a viable option, there are several risks involved. The paper notes that understanding occupant behavior is volatile and difficult to generalize, but previous data can provide insight and guidelines which can help in making accurate assumptions.

Overall, the literature highlights the importance of considering various factors when designing emergency evacuation plans. Building design, alarm systems, occupant training, and social behavior all play a vital role in determining evacuation efficiency. It is recommended that regular fire safety training and evacuation drills can improve occupant response during emergencies, assisting in improving the evacuation efficiency.

2.6.3 Previous studies on BIM-based simulation tools for occupant evacuation

2.6.3.1 Research output from 2000 to 2011

During this time period, seven studies were identified. The main reason for this shortage of studies in this domain, was attributed to the lack of availability of BIM-based simulation tools, as they were progressively emerging. Kannala (2005) analyzed the building escape routes, utilizing Solibri Model Checker (SMC) to visualize the evacuation model and investigate the efficiency of the escape routes against the defined requirements of the building fire code. This study aimed to enable the fire safety designer to easily identify any violations of the code and resolve in the layout of the building, to satisfy the requirements of the fire safety code.

Rüppel and Abolghasemzadeh (2009) assessed the BIM-based simulation tools which can be utilized in the building construction industry for fire safety design and evacuation simulations. Using “Fire dynamic simulator” (FDS), along with “Autodesk Revit” can provide a realistic visualization in 3D of the simulation, will help the fire safety engineer and the architect to obtain more visual realistic data to modify the conceptual design of the building. This study aimed to identify the requirements of simulation programs and develop a new BIM interface which can have an immersive output. Through this development fire safety engineers and architects can get more accurate visualization of the emergency evacuations. This will further help them in identifying shortcomings in the evacuation plan and finding new opportunities to reduce the evacuation time.

Xu et al. (2010) suggested using a fire prevention virtual reality (VR) model. The model integrates the architectural layout with a 3D network game engine, with the goal of using VR to prevent fires and injuries, during a fire emergency. The VR model was based on the FDS and the 3D digital city model. The VR model provided a simulation framework, which was implemented on a prototype. The simulation framework integrated the fire growth rate along with the crowd dispersal and potential injuries to occupants. The study concluded that the prototype needed more optimization and development to provide accurate simulation results.

Rüppel and Schatz (2011) developed a BIM-based serious game for fire safety evacuation to observe the human behavior during an emergency situation. The study acknowledged the difficulty in predicting the occupants' behavior during fire emergencies, and that simulation programs could not accurately simulate occupants' evacuation. Hence, the occupants of a building were requested to participate in playing the serious game to study how their reaction and behavior during a fire emergency evacuation. The study concluded that this interactive game could potentially assist in simulating different scenarios, aiming that occupants would escape from the building in the shortest amount of time. The outcomes of the study would facilitate in determining the required training measures, in case of future fire emergency.

Sagun et al. (2011) investigated the crowd behavior in fire emergency situations, to develop guidelines for the design of circulation routes and improve occupants' safety. The study acknowledged that the design of every building is different, however, the building codes are applied to the design of all buildings. Thus, the study compared the multiple performed simulations with building code requirements, for enhancing the evacuation performance of the building. These simulations served to identify shortcomings in building design, which may lead to overcrowding, and hence avoiding injuries and fatalities during fire emergency events. The study concluded that running simulations early during the design phase can help the fire safety engineers and architects identify any potential shortcomings in the design, to mitigate the occurrence of future injuries and fatalities due to ineffective building design.

Shen and Shen (2011) developed a framework to apply a BIM-based user pre-occupancy evaluation method to facilitate the efficiency and effectiveness of the interaction between the client and the designers, during the architectural design stage. The BIM-based model aims to assists the designers to explain their thought process and their requirements for obtaining proper feedback on the design. The study concluded that by using BIM-based simulation tools, information during the design stage can be easily shared with the client, who sometimes might not understand 2D drawings properly.

2.6.3.2 Research output from 2012 to 2017

During this time period, fourteen studies were identified. The main reason for this growth of studies in this domain, was attributed to the awareness about the benefits of BIM-based simulation tools, as they were gaining popularity. Wang et al. (2012) developed an interactive BIM-based simulation model by integrating a BIM model with a Discrete Event systems Specification simulation tool. These tools enable the fire safety engineer and architect to visualize the building in 3D, and run the simulation for the evacuation model. The developed BIM-based simulation model can be utilized to the fire emergency evacuation for different buildings, with different geometry. The integrated model can assist designers during the pre-design stage to identify the lapses in the building design stages, in relation to the applicable fire safety code, as well as other shortcomings, which have not been accounted for. The study concluded that the simulation could potentially analyzes bottlenecks and determines the maximum occupancy of the building, for creating an efficient evacuation plan.

Similar to the previous study by Rüppel and Schatz (2011) which introduced the use of a serious game to help in fire evacuation, Wang et al. (2014a) also introduced the use of serious game through a BIM-based VR model to identify multiple key issues pertaining to building emergency management. The game provided real time fire evacuation guidance. The results of the study showed that this can provide effective training and build awareness about fire evacuation for the occupants and could potentially provide an innovative solution for effective emergency management.

Adding to the serious gaming use for human evacuation, Schatz et al. (2014) also conducted a study to investigate the feasibility of using a computer game to predict human evacuation behavior. The study found that this is an innovative way for studying human behavior in emergency situations and developing an interactive game with appropriate capabilities to improve the simulations for evacuation models.

Wang et al. (2014b) investigated the application of BIM-based simulation tools in designing fire evacuation. The study focused on four aspects. The first is personnel safety evaluation. The second is the escape route planning. The third is the equipment maintenance. The fourth is the education and training module. The BIM model will generate 3D images, which will assist the users in identifying the evacuation information.

This was further supported by Zhang and Issa (2015) who highlighted the advantages of using BIM-based serious gaming for fire safety design. By using this method designers and fire safety engineers can better understand the human behavior and collect the evacuation performance data to improve he fire safety design of the building.

Tan et al. (2015) presented an agent-based evacuation model, which can simulate the behavior of individuals according to their level of knowledge about the buildings' geometry. The incorporation of the evacuation model will provide a more realistic movement of the occupants.

The occupants' movement can be simulated during different fire scenarios, according to their behavior, in light of different spatial accessibility. The study found that the predicable spatial change can positively affect the evacuation efficiency. However, this study did not consider factors such as the influence of fire, smoke and toxic gases on the movement speed of the occupants.

Wang et al. (2015b) conducted a study of similar nature, utilizing a BIM-based model, which can identify and demonstrate data effectively for the assessment of fire safety planning and management. The model has the capability to store information, which can be utilized by the facilities management team of the building.

A study was done by Wang et al. (2015a) utilizing Pathfinder to study the emergency guidance evacuation of the occupants in high-rise buildings. The software simulates the evacuation behavior by combining different parameters such as the smoke spread velocity and the CO concentration along with the visibility inside the building. The study found that in the beginning of the evacuation, the evacuation was slow due to congestion, but as the time goes on, the evacuation speed increases along with the evacuation efficiency. The study suggested providing an induction for occupant evacuation and using elevators in case of fire to ensure smooth evacuation.

Ahn et al. (2016) analyzed BIM-based evacuation simulation models, using agent-based modeling to determine the optimum evacuation time. This simulation was carried out for different cases according to the human group behaviors and their knowledge of the building. The study simulated the effects of varying the widths of the fire exits on the total evacuation time. The study concluded that increasing the width of the fire exit doors did not significantly improve the evacuation time. The study concluded that the evacuation distance to the nearest fire exit is a critical factor, in comparison to the width of the fire exit.

Chen et al. (2017) utilized Revit and PyroSim applications to create a visualization system for fire disaster simulation, in order to analyze the intensity and trend of the fire. The visual representation can assist the users and fire safety team to acquire information about the current building efficiently. The building users can utilize this BIM-based simulation model to increase knowledge and spread awareness to guide the building users by providing an optimal path for escape from the building. Fire fighters can also utilize this model to obtain real-time data about the fire situation to prepare their evacuation plan.

2.6.3.3 Research output from 2018 to 2022

BIM and VR tools are increasing in popularity among design professionals and building users. Previous studies have demonstrated that the utilization of these tools for emergency evaluation has facilitated the implementation of optimized building layouts and improved the overall safety of the building occupants. Park et al. (2018) explored the use of BIM and VR tools along with human behavior simulation during emergency evacuations. The study focused on visually analyzing the interior of the building, which provided new insights, which could not have been known before, for occupants' safety during emergency fire evacuation. The simulation minimized the uncertainties related to building evacuation, through visualization of the building layout during fire emergencies, which enabled occupants to make informed decisions during the evacuation. The study concluded that visualization enabled designers to alter the design, to improve the efficiency of the evacuation.

Sun (2018) conducted a simulation using a BIM-based FDS software, combined with agent-based modeling (ABM) system to simulate the fire growth and the emergency evacuation. The study focused on investigating the reliability of using the FDS BIM-based software for developing an effective solution for fire evacuation and improving the overall building fire safety management strategy. The study demonstrated that the utilization of FDS, as a BIM-based tool provided fire safety engineers and architects, with knowledge of the occupants' evacuation behavior, which assisted in optimizing the fire safety plans of the building.

Marzouk and Al Daoor (2018) presented a framework for emergency evacuation from construction sites during project execution. The BIM simulation model is able to visualize labor evacuation times at any point throughout the project duration. The MassMotion software was utilized to forecast the labor evacuation times. The evacuation plan was developed and evaluated using the estimated evacuation times obtained from the simulation software. The study concluded that utilizing the BIM model would help the contractor in preparing an effective evacuation plan. In addition, the model can highlight deficiencies in the current evacuation procedures, which impacts the overall evacuation time.

Zhou et al. (2019) investigated a multi-user voice-driven BIM-based navigation system for responding to fire emergencies. The study utilized the string-matching method to extract spatial information from the BIM model to generate escape plans for the building. A framework was developed, and an experiment was conducted based on virtual reality (VR) to validate the suggested navigation system. The study concluded that utilizing the voice driven BIM system will help occupants during evacuation by guiding them through the shortest route to the exit.

Lovreglio and Kinateder (2020) conducted a literature review to present the potentials and limitations of utilizing Augmented Reality (AR) and VR tools to improve the building evacuation during fire emergencies. The study indicated that although VR and AR are gaining a lot of interest in the recent years, they still have not widely utilized and adopted in the domain of fire safety design and management. The study also concluded that VR tools were being utilized in most cases as training tools to simulate the real evacuation process.

Ma and Wu (2020) investigated the practice of building fire emergency management, taking into consideration the different behavioral decisions made by the occupants during a fire emergency. The study focused on integrating the occupants' behavior utilizing a BIM-based platform, to collect and analyze the evacuation data and provide an optimal path, for the occupants. The BIM-based platform served to identify an obstacle-free, and minimum-distance evacuation path to the nearest fire exit, through performing calculations based on the user location, in relation to the origin of the fire. The study concluded that the evacuation time guided by the BIM-based simulation was 30% shorter, in comparison to the evacuation time of another group, which was not guided by the BIM-platform.

Sun and Turkan (2020) developed a BIM-based simulation framework which implemented the FDS and ABM to simulate the growth of fire and evaluate the evacuation performance for different building layouts. The study highlighted the importance of the original drawings of the buildings, as they present a source of input data that can be utilized to optimize the evacuation efficiency and minimizing injuries and fatalities.

Xu et al. (2020) investigated the influence of occupant physical collisions (OPCs) during indoor fire evacuations. The study utilized an integrated BIM-based tool with computational fluid dynamic simulations, to visualize the development and propagation of smoke in the building during the evacuation. The simulation included non-player characters (NPCs) with the building occupants during the evacuation to assess the impact of the OPCs on the safest evacuation path. The study concluded that the evacuation time increased, considering the OPCs.

Chen et al. (2021) developed an application, which utilized a combination of BIM, VR, AR and IoT systems for fire safety. The application focused on identifying the location of the occupants during an indoor fire, so that firefighters begin their rescue. The study concluded that utilizing the combination of the BIM tool along with the other systems could potentially reduce the occupants' evacuation time through guiding firefighters of the exact whereabouts of the occupants inside the building.

Fang et al. (2021) focused on the Internet of Things (IoT) application in building fire evacuation. The study investigated the benefits and discrepancies of the current smart buildings fire evacuation systems. An IoT-aided fire evacuation control system was developed, to monitor the fire development and propagation according to the occupants' location inside the building. The study developed a conceptual design based on IoT to guide the occupants during the evacuation, with the aid of the IoT system. The study concluded that the developed system is not fully reliable, as more data collection and optimization need to be carried out, for the system to function effectively.

Safayet et al. (2021) developed an automated real-time fire alert system utilizing BIM. Using the real time data which is available in the server, anyone with an Android phone or display monitor may view the precise location of the fire inside the building. The proposed BIM-based fire alert system was implemented on a prototype building project to examine its effectiveness. The study concluded that it is feasible to incorporate a fire alert system into BIM, as an efficient and useful way to detect fires and notify the building's occupants.

Lotfi et al. (2021) examined a high-rise building to assess the feasibility of providing a safe evacuation environment for its occupants under post-earthquake fires (PEF). BIM and PyroSim simulation software were used to create a 3D model of the building, to measure the escape routes, smoke, and fire developments. Simulations were performed to examine the effect of fire and smoke on occupants' evacuation. The findings from the simulations indicate that the building cannot implement a guaranteed evacuation plan, requiring the utilization of additional suitable equipment to aid the evacuation. The study provides a framework which can be utilized as a realistic model for assessing the evacuation needs of high-rise building occupants. A similar framework for evacuation was proposed by Zhang et al. (2019) which utilized a Bluetooth low energy (BLE)-based indoor real-time location system (RTLS) and a BIM model to dynamically send customized evacuation route suggestions to building occupants' smartphone devices. The study highlighted that collecting personal physical characteristics of the building occupants and integrating it with the framework can provide more accurate results.

Wehbe and Shahrour (2021) presented a smart fire evacuation system that integrates smart technologies and building information modeling (BIM). The smart system can detect fires early, evaluate the environmental data, suggest an optimal evacuation path, and inform occupants about the safest evacuation routes. IoT and smart technology were utilized to identify fires quickly and minimize false alarms. The system was tested in a building to verify the results. The study highlighted the importance of BIM tools for visualizing the building environment, which will help in tracking occupants in real time. This will also assist in alerting the occupants by providing them with the optimal evacuation path during emergency evacuation.

Zhang and Long (2021) conducted an evacuation simulation study in densely crowded places using BIM and Pathfinder. The study highlighted that examining the characteristics of buildings and evacuation procedures for densely inhabited places can serve as a guide for emergency planning. The simulation results from the study demonstrated that increasing the width of emergency doors and controlling the evacuation speed of evacuees in different areas can significantly improve the evacuation efficiency.

Arias et al. (2022) conducted a study on evacuation behavior in virtual reality (VR) and physical experience. In order to validate VR as a study method in the area of human behavior in fire, the results from the VR studies must be compared to those from practical investigations. A high-rise building with evacuation elevators has undergone a series of studies involving analogous evacuation situations. Pre-evacuation time, identifying escape routes, walking paths, choosing an exit, waiting times for the elevators, and eye-tracking data pertaining to emergency signage were analyzed. The data from the physical trial could be replicated by the head-mounted display (HMD) experiment, but the Cave Automatic Virtual Environment (CAVE) experiment's findings were very different. The study concluded that mobility and spatial direction in the virtual environment are two examples of potential elements that could alter the data generated via VR.

Clever et al. (2022) analyzed the pedestrian flow during evacuation and proposed a framework for real-time pedestrian evacuation prediction. The BIM model uses the floorplan of the building and simulation settings as input and predicts the crowd evacuation time by utilizing a modular neural network architecture. A Convolutional Neural Network and Multilayer Perceptron was also utilized for the simulation. The results from the study concluded that it was possible to reach a mean prediction accuracy of 15%.

Sabbaghzadeh et al. (2022) developed a BIM-based simulation framework for obtaining a set of suitable fire safety measures, while considering their implications for a safe evacuation and financial constraints. The effectiveness of the framework was assessed using a case study technique in two different projects. The study highlighted that the framework provides a useful method for fire safety engineers and architects, to alter building designs in terms of safe evacuation at the design stage, by utilizing fire protection measures efficiently and affordably.

Wong et al. (2022) developed a voice driven BIM-based multi-user system for navigation during emergency fire evacuations. The system is comprised of four modules. These included voice-based command processing, inertial sensor-based continuous location, interior route planning, and a multi-user sharing environment. The system was implemented in a real-life case study to assess its feasibility. The results from the study indicated that the system was able to guide the users in real-time by providing instructions through voice commands. The occupants were able to reach the emergency exit faster, thus avoiding any risk of injuries.

Lorusso et al. (2022) also developed a VR model and integrated it with a simulation software to replicate an emergency scenario. The VR model served to acquaint the occupants with building emergency plans, to assist them in their decision making. The study concluded that utilizing the proposed VR model, by training the building occupants on the different fire emergency scenarios, can assist in reducing the evacuation time. The VR model can be utilized as a training tool for firefighters, to make informed decisions.

From the reviewed literature, the most common BIM tool used for simulations was Autodesk Revit as it can be seen in table 1 and figure 2. Table 1 lists all the software simulation tools, which have been used in the covered literature review. The table presents 28 simulation tools. These tools were reviewed out of the studies that reported on their use. The table presents the utilized simulation method, the analyzed parameters, the building type and its attributes, the type of algorithm used and its scalability. The table also reports on their interoperability and limitations.

2.6.3.4 Analysis and discussion of the previous studies on BIM-based simulation tools for occupant evacuation

During the early 2000's, not many papers were published related to the utilization of BIM-based tools for fire evacuation. Although the interest was there, the simulation programs were limited in their ability, due to the lack of available occupants' data, which hindered the accuracy of the results obtained from the simulations. Over the years, as more data was obtained, the simulation programs became more refined and hence provided accurate results. By 2012, more data was readily available as input data in the simulation programs, for aspects such as occupant response time and movement speed. During this time, improved 3D programs were available, which facilitated visualizing the occupants' behavior during the fire evacuation. The 3D programs also assisted fire safety engineers and architects to better understand the variables affecting the evacuation process, which was difficult to understand from the 2D drawings (Wang et al., 2012).

Serious games were developed, where the building occupants participated (Rüppel and Schatz, 2011). These games facilitated the occupants' interaction with the building surroundings. The games also enabled associating the demographics of the different type of occupants in the simulation models, which allowed fire safety engineers and architect to understand the occupants' behavior in the specific layout of any given building (Pargeter, 2018).

In the last 4 years, the research has focused on IoT and the utilization of AR and VR for building evacuation along with using smart fire evacuation management systems (Zhang et al., 2019). Previously, serious games which have been developed can now be played by users in a 3D environment, which has replicated the exact building layout (Menzemer et al., 2022). Different fire scenarios were simulated to observe the occupants' behavior. Other NPC's were integrated in the serious game, to depict real life scenarios, where the simulations took into consideration the effect of crowdedness and congestion during an emergency evacuation (Xu et al., 2020). These simulations enabled better understanding of the occupants' evacuation. Shortcomings which have not been identified before were highlighted after tuning the simulations. Thus, new perspectives were observed by fire safety engineers and architects on the emergency evacuation behavior of the occupants (Ronchi, 2021).

From the reviewed literature, the most common BIM tool used for simulations was Autodesk Revit as it can be seen in Table 1 and Figure 4. Table 1 lists all the software simulation tools which have been used in the covered literature review. The table presents 28 simulation tools. These tools were reviewed out of the studies that reported on their use. The table presents the utilized simulation method, the analyzed parameters, the building type and its attributes, the type of algorithm used and its scalability. The table also reports on their interoperability and limitations. The reason for Revit being used to most could be due to its ability to allow users to model shapes and building structures in 3D with parametric accuracy to replicate real life scenarios. Different Revit models can be utilized with varying detail. This is known as level of development (LOD) which defines the development stages of the different systems in BIM. The LOD can range from 100 to 500 with varying levels of details. Mostly in simulations, the LOD of 200 or 300 was utilized where the elements are defined with exact dimensions along with their relative positions. Revit is also interoperable, owing to the file format of the Industry Foundation Classes (IFC). This allows fire safety engineers and architects to export the Revit files into different programs and run the simul

Table 1 Summary of BIM based simulation tools

Reference	Kannala (2005)	Xu et al. (2010)	Rüppel and Schatz (2011)	Sagun et al. (2011)
Limitations	- Some modelling errors when running the	Optimization of fire development and fire and	Additional information needs to be retrieved	Big difference in simulation of low rise
Other Notes: (Interoperability)	The module could be expanded further to include accessibility	The basic system prototype of architecture has	Improvements can be made to interoperability between BIM models	Not mentioned
(Scalability of the algorithms) Capabilities of the program	Can be used in different types of buildings	Can be widely used in different fire safety	Can mimic real life scenario to get human	Each building must be modelled
Type of algorithms used.	Constructive area geometry (CAG)	Finite state machine (FSM) model (A*, Barrier,	Not mentioned	Not mentioned
Building attributes considered	- Building Layout/Geometry	Structure of the building	Building structure and geometry.	- Building Layout/Geometry
Building Type	- Office Building	Virtual (digital city)	House	Office Building
Analyzed Parameter or Effectiveness Metric	Validation of escape routes against the building fire codes.	Fire development, personnel's injury and fire spread	Building condition on human behavior	Evacuation time / Exit preference during evacuation
Simulation method	High level architecture of the escape route	Virtual environment / 3D network game engine	Serious gaming / 3D visualization	crowd modelling software
Simulation Tool Used	Solibri Model Checker (SMC)	FDS (Fire Dynamics Simulator)	Autodesk Revit Ogre3D	buildingEXODUS

Reference	Wang et al. (2012)	Wang *et al.* (2014a)
Limitations	Reusability and accessibility can be	The proposed system was tested on a small scale and needs more future work to validate its usability and actual effectiveness.
Other Notes: (Interoperability)	More work is needed to improve the interoperabili ty	IFC interface instead of Revit API can be used to build a universal data component to adopt different BIM packages.
(Scalability of the algorithms) Capabilities of the program	Can be used for different types of buildings	Further work on bigger scale is currently being carried out to assess the scalability.
Type of algorithms used.	CD++	Dijkstra's algorithm, best-first search, and A*
Building attributes considered	- Building Layout/Geo metry	- Building Layout/Geometry
Building Type	Office Building	University building
Analyzed Parameter or Effectiveness Metric	Impact of door location/num ber on the evacuation	Improving building emergency management
Simulation method	BIM 3D Visualization	BIM based virtual environment (BIM-VE)
Simulation Tool Used	Autodesk Revit, DEVS simulation and 3ds Max	Autodesk Revit & Unity3D

Reference	Wang et al. (2014b)	Tan *et al.* (2015)	Wang *et al.* (2015a)	(Wu et al., 2015)	Ahn *et al.* (2016)
Limitations	The simulation considered only the	Movement and evacuation through	Elevators were not taken into consideration	The program only considers 3 factors,	Impact of fire and smoke on evacuation
Other Notes: (Interoperability)	Not mentioned	Many simplifications were made in order to conduct the	Not mentioned	A system was developed for data interchange between BIM	Not mentioned
(Scalability of the algorithms) Capabilities of the program	The presented model is feasible and	The model was a prototype and needs	The simulation software had no issues	A pilot test proved the new developed	Can be used for other buildings but needs further
Type of algorithms used.	Specific formulas were used which are	Route planning algorithm was	Not mentioned	A combination of Floyd algorithm	Special formula mentioned in paper.
Building attributes considered	- Building Layout/Geometry	- Building Layout/Geometry	Building structure, layout, and fire sources.	Building structure, layout and fire sources.	Varying width of exit doors and building
Building Type	Public high-tech factory	Campus building	Commercial center of Guangzhou	Office Building	Shopping Center
Analyzed Parameter or Effectiveness Metric	Escape route generation and guidance.	Impact of building knowledge and spatial arrangement	Evacuation behavior smoke propagation, fire	Fire and smoke spread through the building structure.	Occupant evacuation time.
Simulation method	BIM 3D Visualization	Agent-based modeling	3D Visualization	Fire and Smoke simulation / 3D	Agent-based modeling
Simulation Tool Used	Autodesk Revit, Fire Dynamics Simulator	ArcGIS software and Agent Analyst	Pathfinder.	Autodesk Revit, CFAST and SmokeView	Test Bed

Reference	Chen *et al.* (2017)	(Marzouk & Al Daoor, 2018)	Park *et al.* (2018)
Limitations	IoT and different sensors can be used to	The simulation is not designed for outdoor	The simulation did not consider the building structure and the effect of materials.
Other Notes: (Interoperability)	Not mentioned	All the programs could work with each other due to IFC format.	Interoperability of BIM and VR simulation systems will need to incorporate computer language programming APIs, and IFC support system
(Scalability of the algorithms) Capabilities of the program	The BIM model can be utilized for different	The model can detect congestions and calculate	More data needs to be collected with realistic parameters to conduct accurate simulations.
Type of algorithms used.	Not mentioned	Not mentioned	Not mentioned
Building attributes considered	- Building Layout/Geometry	Building structure and layout.	Building layout and fire sources.
Building Type	Campus building	Housing building	Educational facility
Analyzed Parameter or Effectiveness Metric	Impact of temperature, space, visibility, and CO	Evacuation time	Occupants movement, fire and smoke propagation inside the building.
Simulation method	3D Simulation / Visualization of Fire	4D modelling	3D visualization, human behavior and fire dynamics simulation and immersive VR.
Simulation Tool Used	Autodesk Revit and PyroSim	Autodesk Structure Revit and Mass-Motion	Autodesk Revit PyroSim Oasys mass motion

Reference	Sun (2018)	(J. Zhang et al., 2019)	(Zhou et al., 2019)	Ma and Wu (2020)	Sun and Turkan (2020)
Limitations	Simulation results did not match with real life	Personal physical characteristics of the	More deep learning methods need to be	Active guidance of the trapped people relies	There is a discrepancy between the simulation
Other Notes: (Interoperability)	The software's used in the simulation all had interoperabili	Not mentioned	IFC data is used in the model for interoperability.	Interoperability between modules and databases is implemented in the entire	FDS software used in the study is interoperable with Revit
(Scalability of the algorithms) Capabilities of the program	Different buildings need further studies as the	A better algorithm can be developed to	Not mentioned	Fire monitoring has robust scalability	More buildings need to be simulated in
Type of algorithms used.	Linear regression model	Breadth-first search algorithm	CAVE system	Dijkstra's algorithm, NNSS algorithm	Linear regression model
Building attributes considered	Building layout and population density.	- Building Layout/Geometry	- Building Layout/Geometry	- Building Layout/Geometry	- Building Layout/Geometry
Building Type	Nightclub	Office Building	Residential building	Office Building	Nightclub
Analyzed Parameter or Effectiveness Metric	Fire growth and human behavior	Providing safest evacuation route	route planning and intuitive navigation command	Providing safest/shortest evacuation route	Required safe egress time (RSET)
Simulation method	Agent-based Modeling (ABM) / 3D Simulation /	BIM and Smartphone module along with real-	string-matching method, VR	BIM 3D Visualization	Agent-based modeling (ABM) / 3D
Simulation Tool Used	Autodesk Revit, PyroSim, AnyLogic	Autodesk Revit, Autodesk Forge	Unity3D Tridify	Autodesk Revit Fire Sense,	Autodesk Revit, PyroSim

Reference	Xu *et al.* (2020)	(Chen et al., 2021)	(Safayet et al., 2021)	(Wehbe & Shahrour, 2021)	(Lotfi et al., 2021)
Limitations	technical details will be different if other fire	Integrates limited number of heat	Not mentioned	Further data needs to be collected to provide best	For accurate results, fire simulations must be done
Other Notes: (Interoperability)	Revit model can be converted into VR my exporting in FBX format.	Trainees reported that the developed framework is	Can be easily integrated as files as converted to IFC.	Not mentioned	FDS software used in the study is interoperable with Revit
(Scalability of the algorithms) Capabilities of the program	The proposed method allows users to experience	Not mentioned	Not mentioned	The developed system works well and	The framework can assess high-rise
Type of algorithms used.	Smoke visualization algorithm based on fire	A*	Arduino board	ML algorithm implemented in Dynamo	Not mentioned
Building attributes considered	- Building Layout/Geometry	- Building Layout - Location of	- Building Layout/Geometry	- Building Structure, layout and geometry.	- Building Structure, layout and geometry.
Building Type	Dormitory building	Office Building	Residential building	Research campus building	High-rise building
Analyzed Parameter or Effectiveness Metric	Evacuation path considering occupant collision	- Situational awareness	-fire notification	Early fire detection, identification of evacuation path	Providing safe exit routes based on fire scenarios.
Simulation method	BIM 3D visualization using non-player	3D Simulation (AR/VR)	3D Simulation	BIM 3D Visualization	3D visualization of smoke and fire.
Simulation Tool Used	Autodesk Revit, Unity PyroSim	-Revit SDK (Software Development Kit), and	- Revit (LOD 300)	Fire Dynamic Simulation (FDS) and	Autodesk Revit Pyrosim

Reference	(Arias et al., 2022)	(Clever et al., 2022)	(H. Zhang & Long, 2021)	Lorusso *et al.* (2022)
Limitations	Study was conducted on a small sample size.	Cannot predict pedestrian trajectory	The simulation did not take into account	VR platform can improve verification of emergency
Other Notes: (Interoperability)	More in-depth assessment is required to study the application	More optimization is required to improve accuracy.	The software's used in the study are interoperable.	Revit model can be converted into VR my exporting in FBX format.
(Scalability of the algorithms) Capabilities of the program	Limited to simulated building.	Not mentioned	Pathfinder has the capability to perform	The system can reproduce real life fire scenarios
Type of algorithms used.	CAVE method Physical	Neural network architecture	Not mentioned	Not mentioned
Building attributes considered	- Building Layout/Geometry	- Building Layout/Geometry	- Building Layout/Geometry	- Building Structure, layout and geometry.
Building Type	Mixed occupancy High-rise	Train Station	Hospital	School Building
Analyzed Parameter or Effectiveness Metric	Evacuation behavior	- Pedestrians' behavior and walking times	Safe evacuation and the impact of occupants'	Fire and smoke propagation inside the building and
Simulation method	3D Simulation (AR/VR)	Deep Learning (DL) methods	3D visualization, Agent-based evacuation	3D visualization, VR and Agent-based
Simulation Tool Used	VR head-mounted display	Autodesk Revit - Dynamo	Autodesk Revit Pathfinder	Autodesk Revit Unity3D

Reference	(Sabbaghzadeh et al., 2022)	(Wong et al., 2022)
Limitations	The study did not consider the materials’	Only limited voice commands were tried
Other Notes: (Interoperability)	BIM software used is interoperable to conduct the	Not mentioned
(Scalability of the algorithms) Capabilities of the program	Results from the study verify that the	The system can robustly generate the navigation
Type of algorithms used.	Billiards-inspired Optimisation Algorithm	Dijkstra’s algorithm and A*
Building attributes considered	- Building Layout/Geometry	- Building Layout/Geometry
Building Type	Residential building and a Hospital	Dormitory building
Analyzed Parameter or Effectiveness Metric	Safe evacuation versus costs of fire safety measures	Pathfinding guidance in real time during emergency
Simulation method	3D visualization, graph extraction	3D visualization, IFC BIM-based indoor
Simulation Tool Used	Autodesk Revit CFAST	Autodesk Revit Solibri

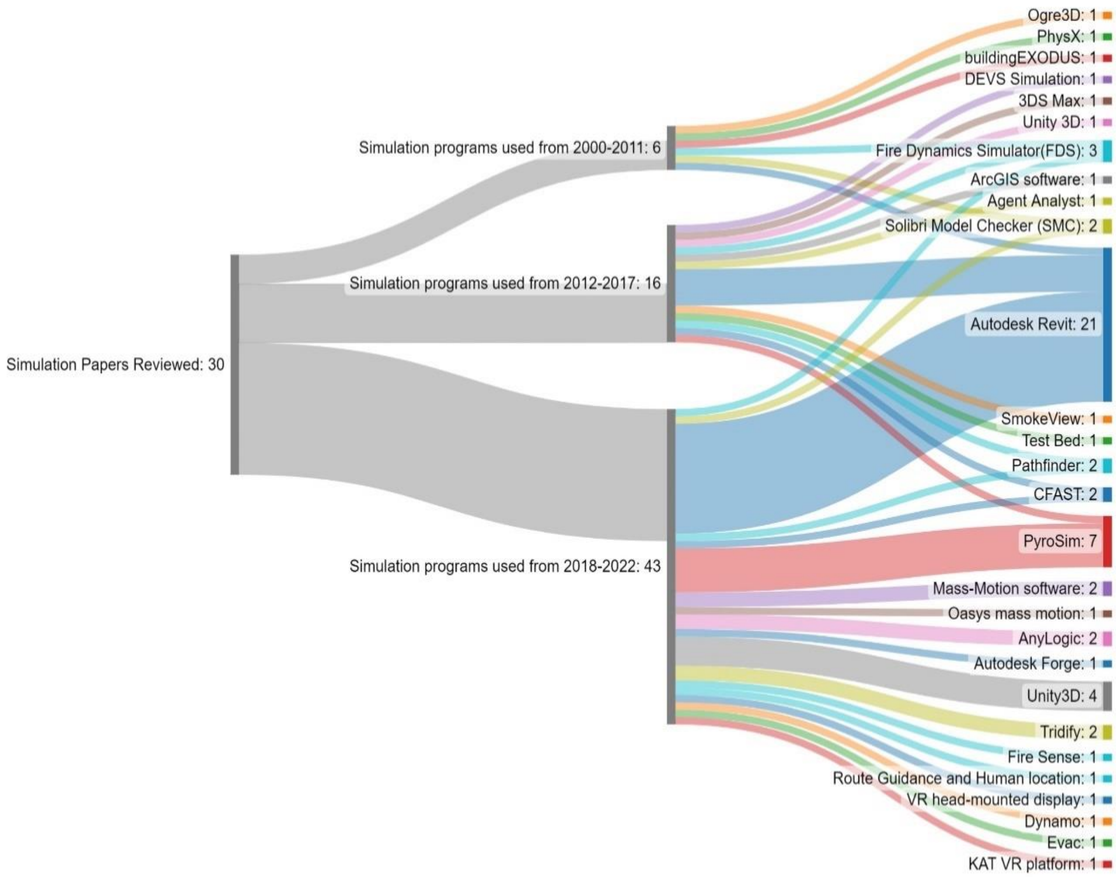


Figure 4 Sankey diagram of the reviewed BIM based evacuation simulation tools

2.6.4 Previous studies on Smart fire detection and evacuation in buildings

2.6.4.1 Research output from 2000 to 2011

During the early 2000's technology was quite limited in terms of smart fire detection systems. The main challenge during this time was to increase sensitivity of fire alarms and their dynamic response while decreasing false alarms (Liu and Kim, 2003). It is important to have proper firefighting systems which can detect smoke and other gases early to alert the occupants as early as possible to save as many lives as possible.

(Filippidis et al., 2006) introduced and defined the concept of "visibility catchment area (VCA)". VCA was defined as "the region of space over which it is possible to visually receive information from the object." The study highlighted that it is critical that during evacuation occupants should be able to find the signage and interact accordingly. My determining the correct placements of the signage systems this makes the evacuation process quicker. Designers will also benefit from knowing where exactly to place the signage where it can be detected by the evacuees even through smoke and other toxic gases.

(Chen, 2009) presented an "intelligent integration supervisory system (IISS)" and "emergency indicator boards (SEIB)" which uses a fuzzy-based evacuation strategy. The wireless sensors inside the building can locate the crisis area, which then alerts the system which determines choosing the safe evacuation routes using a fuzzy system.

(Pessiot et al., 2010) investigated the development of fire detection systems in intelligent buildings. The author highlighted that new technology which consists of wireless sensors will reduce the expenditure as well as decrease the number of false alarms and reduce fire related losses. This is because of the availability of the internet and real time control monitoring thought the fire safety and building service systems. This increases the efficiency and reduces the costs for the building management team. Although some challenges still are prevalent such as the sensor being able to distinguish between fire and non-fire dangers and the fire safety system needing to be secure to prevent any false fire alarms.

2.6.4.2 Research output from 2012 to 2017

The primary objective of a fire alarm system is to alert building users early of fire warning. to the occupants so they can start evacuation. Most people suffer injuries or death due to toxic gases and smoke instead of fire burns (Elbehiery, 2012). (Baddewithana et al., 2013) discusses the smart and automated fire monitoring systems. The system is able to detect fires and alert the users to evacuate as well as send alarms to predetermined recipients. The system can also differentiate between non-electrical fires and electrical fires and upon detection it will enable the fire extinguishing system of that particular location.

(Ran, Sun and Gao, 2014) introduced a new concept called “intelligent evacuation guidance system (IEGS)” that employs an algorithm to get dynamic evacuation routes and improved he evacuation efficiency. The results demonstrated that during mass evacuations, the exit sign facing the evacuation route is most frequently used. Having a constant distance with good visibility also helps in improving the evacuation performance. When comparing visual signals with audio signals it was found that visual signals have a higher evacuation efficiency than the installation of visual signs within 3m of the exit. Increasing the number of exits and width was discovered to increase the evacuation's overall effectiveness. IEGS was also used by (Shields and Boyce, 2000)(Bernardini et al., 2016) to monitor the human behavior and provide proper direction by identifying the nearest evacuation path.

(Hsu et al., 2014) developed a smart system, which combines real-time escape route guidance with wireless sensor networks and radio frequency identification. to guide the people to safety by avoiding danger. This intelligent system uses digital signage to guide the users to a safe exit. The system also provides the fire fighters with real time environmental information in order for the team to better prepare for the rescue operation. A similar study was done by (Ryu, 2015) which used IoT to guide the users safely outside the building. One more model was used which has an algorithm find the shortest path to safety route for the evacuees this is then displayed by the use of control lighting display to guide the occupants (Yang, Shi and Han, 2015).

(Iftekharul et al., 2016) developed a smart self-controlled fire extinguishing system which has several sensors and is run by the “micro-controller unit (MCU)”, this program is called Safe from Fire (SFF). The system can detect false alarms in circumstances like welding and cigarette smoke. Once the fire alarm detects a real fire it notifies the firefighting team by sending text messages and phone calls. It also alerts the occupants in the affected location to evacuate. In order to stop the spread of the fire, it also destroys the electrical circuits in the affected area and releases extinguishing gas at the fire's source.

Tall and large buildings are sometimes complex, and people can get lost in them. During emergency evacuations it can create problems, to solve this, an intelligent evacuation system was suggested by (Ortakci et al., 2017). His system has three main components. First is the positioning system, which detects the occupant's position, a navigating system which uses artificial neural network that receives the environmental conditions inside the building to provide according to the circumstances, the best escape path. Lastly the graphic user interface provided by the mobile application for Android devices, which accesses the smart evacuation system. The evacuee can be directed to the closest safe exit point by this system, which can update in real time.

A study was done by (Cheng et al., 2017)which uses intelligent fire prevention system based on BIM that incorporates information of the occupants location, uses route optimization with the help of Bluetooth based technology and guides the users by mobile phones in real time to direct them to an efficient evacuation. This will also help facilitate the firefighting team to control the fire and rescue the occupants.

(Lujak et al., 2017) stated this it is important for buildings to have a smart system to avoid additional evacuation injuries and injuries because of the shortcomings in the traditional evacuation process. The fire wardens might not always be present and its not efficient to rely on them to always be there for the occupants during emergencies.

2.6.4.3 Research output from 2018 to 2022

(Johnsaida, Rahul and Shalini, 2018) (Kodali and Yerroju, 2018)presented an intelligent fire emergency response system powered by IoT which has the ability to monitor and control the path by providing directional guidance intelligently to the occupants according to their location. Wireless sensor networks are utilized to accomplish this. (Majumder, O'Neil and Kennedy, 2018) highlighted that there are not many commercial products available in the market which can be used in building to implement the smart fire evacuation system. Many other authors suggested using intelligent fire emergency response system powered by the Internet of Things which can guide the users safely outside the building (Kodali and Yerroju, 2018) (Ferraro and Settino, 2019)(Yan et al., 2019)(Khan et al., 2019).

(Atila et al., 2018) created a system called SmartEscape, a mobile evacuation solution that is real-time dynamic intelligent and user centric. This is used in emergency cases and the system automatically calculates and provides the user with an exit route. This system also takes into account the environmental surroundings of the evacuee by using “artificial neural network (ANN)” to determine the risk and provide the safest path. The system instructs the evacuee by voice and visual instruction on their mobile devices. The location of the evacuee is identified using radio frequency identification. The results showed that the system is extremely accurate and may simultaneously evacuate a large number of people by showing them the quickest and safest way.

(Gholizadeh, Behzad and Memarian, 2018) used a cyber-physical system (CPS) which improves the integration of real time even monitoring and information communication and identification of danger along with intelligence guidance. The system has a fire detection sensor network, which monitors the fire propagation. The other network sensors all connection, which give feedback in real time about the traffic flow and the crowd along with the danger present in the area. By using this system, both the amount of time required for evacuation and the number of fatalities are greatly reduced.

Large buildings often have hundreds of fire extinguishers located in the building. Manual periodic inspections often need to be done by the facility managers or the fire safety inspector to ensure the fire extinguisher is in acceptable condition. It can be difficult to always monitor them hence (Garcia-Martin, González-Briones and Corchado, 2019) devised a mechanism that can assess the extinguishers' condition by calculating the environmental factors and pressure changes. If there is a deviation, then it send a notification that it needs to be changed. This system can be beneficial for large buildings and possibly save lives.

Overcrowding in large building is a big problem when evacuating buildings. (Nguyen et al., 2022) developed a smart system model which can represent the hazard intensity as well as the crows congestion information in each floor of the building. By using his smart system, total egress duration was reduced by up to 30%.

(Birajdar et al., 2021) developed a system that uses vision to detect fire situations and count how many people are still inside the building. This is by using advanced technology along with the help of a web application which updates the user in real time about the events and the reaming people inside the building.

In tall buildings, it is often difficult to utilize the stairs to evacuate especially for old and disabled people. (Wang et al., 2021) suggests the utilization of elevators can significantly reduce the time for evacuation. A simulation was done where 10% used the elevator, which comprised of elderly people and small children while the other 90% used the stairs. The results showed that by using this strategy evacuation efficiency could be significantly increased.

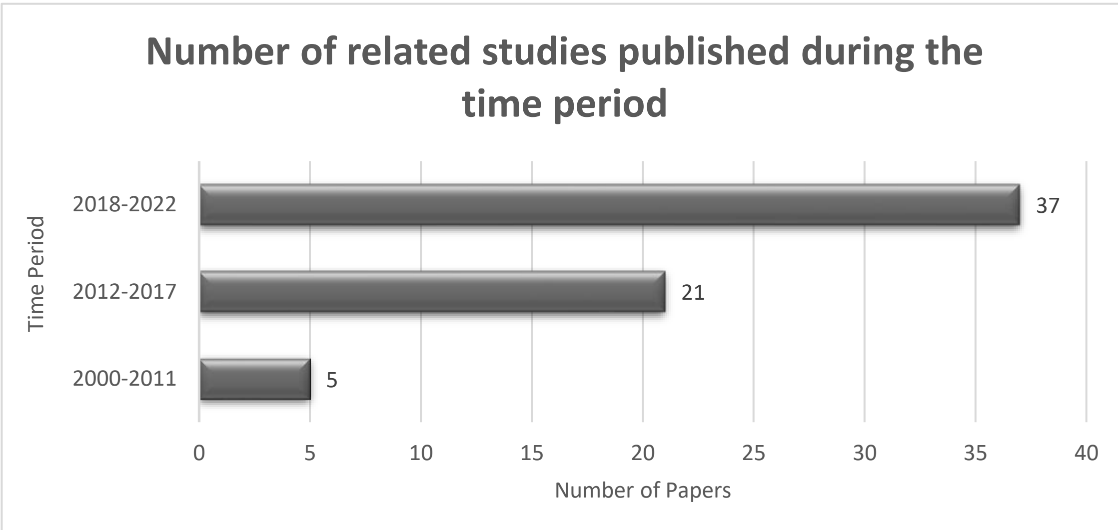


Figure 5 Reviewed literature references on Smart fire detection and evacuation in buildings. Distribution by Time Period

2.6.4.4 Analysis and discussion of the previous studies on Smart fire detection and evacuation in buildings

Studies on this topic have focused on increasing the sensitivity of fire alarms, decreasing false alarms, and improving evacuation efficiency. Researchers have introduced concepts such as visibility catchment area, intelligent integration supervisory system, and intelligent evacuation guidance system. They have also developed smart self-controlled fire extinguishing systems, intelligent fire emergency response systems powered by IoT, and mobile evacuation solutions. Other studies have focused on utilizing elevators for evacuation and assessing the condition of fire extinguishers.

The literature highlights the importance of improving the safety and efficiency of fire detection and evacuation in buildings. The studies discussed aimed to achieve this goal by utilizing advanced technologies and innovative solutions. For example, the intelligent integration supervisory system integrates various fire detection and alarm systems to provide a comprehensive and efficient fire detection and evacuation solution. The intelligent evacuation guidance system provides real-time guidance to occupants' during an emergency, improving their chances of safe evacuation.

The literature also discusses the importance of assessing the condition of fire extinguishers and utilizing smart sensors which can constantly monitor the state of the fire systems. These solutions can significantly improve the efficiency of fire detection and evacuation in buildings. There has been significant contributions to improving the safety and efficiency of fire detection and evacuation in buildings. However, there is still room for further research and development in this area. Future studies should focus on developing more advanced and innovative solutions to improve the safety and efficiency of fire detection and evacuation in buildings.

2.7 Discussion

Different strategies and methods were proposed, and a great number of factors were identified which has an impact on the evacuation in high-rise buildings. Many different options were explored through the help of real-life evacuation drills and computer modelling and simulations. There are many factors which influence the evacuation such as the occupant behavior and demographics also have a critical impact on the evacuation time. The higher up the occupants are the more difficult it is for them to evacuate as there are more chances of fatigue which will lower their movement speed.

Other factors which came with height were in some cases the location of fire alarm was not appropriate causing some to not hear the fire alarm at all whiles for other it was too loud that they could not communicate with the fire fighters or hear them and had to move to some other location. This can be a problem for disabled people since they cannot move easily. More studies are trying to push for the use of elevators for emergency evacuation since for very tall buildings it is not feasible to use the stairs for exit (Ding et al., 2021). Building occupants having training for fire emergency evacuation was deemed to be very important in lowering the evacuation time as well.

Evacuation simulations are also quite popular nowadays since there is enough appropriate data currently available about the estimated evacuation times, but the existing research related to simulation is not accurate when you compare it with actual real life evacuation results. This is mainly because the simulation fails to take into accounts factors such as psychological state of occupants as well as their familiarity with the surrounding environment.

Another factor that is important in emergency evacuation is the social relationship among the groups which the simulation does not take into account for. Therefore, more future research can be done on simulations taking into the human behaviors as well as comparing It with real life results. Additional rising research area is allowing high-rise buildings to use elevators for evacuation, since it significantly lowers the evacuation time especially for the people occupying the upper area of the building. The main thing which can be concluded from the previous work is that each and every high-rise building is different, and the physical environment plays an important role in the evacuation.

2.8 Passive and active fire protection measures in high-rise buildings

Passive and active fire protection measures play crucial roles in high-rise residential buildings. These measures can ensure the safety of occupants during emergency fire evacuation and can significantly reduce occupants' evacuation time. The literature discussed passive and active fire protection measures that can be implemented in high-rise building and how they these measures will help in reducing the evacuation time.

Passive Fire Protection Measures include:

- Fire-Rated Construction: High-rise buildings are constructed with fire-resistant materials, such as fire-rated walls, floors, and doors. These elements help contain the fire and prevent its spread, providing additional time for evacuation.
- Compartmentalization: Building compartments are designed in order to separate different areas, limiting the spread of fire, smoke, and toxic gases. Compartmentation delays fire progression, allowing occupants to evacuate safely.
- Fire Doors: Fire-rated doors are installed in emergency staircases. These doors are designed to withstand fire and smoke for a specified period usually 1 or 2 hours depending on the type of building.
- Fire-resistant Glazing: Windows and glass partitions can be made fire-resistant, reducing the risk of fire spread and protecting escape routes.

- Smoke Control Systems: High-rise buildings employ smoke control systems, including smoke dampers, smoke exhaust systems, and pressurization systems. These systems help limit smoke accumulation and maintain tenable conditions in escape routes.
- Evacuation Signage: Clear and visible evacuation signage provides guidance to occupants, helping them locate exits and evacuation routes quickly and effectively.

The Saudi building code requires the implementation of passive fire protection measures according to the classification of the building. For residential occupancies group R-2, the SBC provides guidelines and requirements related to fire safety, such as means of egress, fire-resistant construction materials, fire alarm systems, and fire suppression systems. These requirements vary depending on factors like building height, occupancy load, and the number of dwelling units. Compliance with these requirements is essential for obtaining permits, certifications, and insurance coverage.

Active Fire Protection Measures include:

Fire Sprinkler Systems: Sprinkler systems are highly effective in controlling and suppressing fires. They activate automatically upon detecting heat, reducing fire intensity and providing additional time for evacuation.

Fire Alarm Systems: Early detection of fires through fire alarm systems is crucial for rapid evacuation. These systems trigger audible and visual alarms, alerting occupants to the presence of a fire.

Emergency Lighting: Adequate emergency lighting systems ensure that escape routes remain well-lit during power failures or low visibility conditions, facilitating safe evacuation.

Public Address Systems: Clear and intelligible public address systems can be used to relay emergency messages and instructions to occupants, directing them to evacuate in an orderly manner.

Pressurized Stairwells: High-rise buildings may employ pressurization systems in stairwells to maintain smoke-free evacuation routes, enhancing occupant safety during evacuation.

The combination of passive and active fire protection measures in high-rise residential buildings is essential to minimize the spread of fire, control smoke, and provide safe evacuation paths for occupants. Building codes and regulations often mandate the implementation of these measures to ensure the highest level of safety. Having proper fire emergency systems can aid in minimizing the evacuation time in high-rise residential buildings.

CHAPTER 3

EVACUATION MODELLING

3.1 Introduction

3.1.1 Autodesk Revit

Revit is a software tool used in architecture, engineering, and construction (AEC) industries for building information modeling (BIM). It allows users to create intelligent 3D models of buildings and structures with various components such as walls, floors, roofs, doors, windows, and more. Revit is designed to streamline the entire process of building design and construction.

It enables AEC professionals to work collaboratively on a single, shared platform. The software also provides a range of features, such as modeling tools, annotations, schedules, and visualizations, that can help users to make informed decisions about the design, construction, and maintenance of buildings. Revit allows users to create and modify designs in real-time, and automatically updates all relevant components, schedules, and documentation. It also supports interoperability with other software tools, such as AutoCAD, Navisworks, and SketchUp.

Revit is a powerful tool that helps AEC professionals to create, manage, and share intelligent 3D models of buildings and structures.

3.1.2 Pathfinder

Pathfinder is a software tool that is used for simulating the movement of people during a fire emergency evacuation. It is specifically designed to aid in the evacuation planning process by providing a visual representation of how people will move through a building in the event of an emergency. The software uses advanced algorithms to simulate the behavior of people during an evacuation, considering factors such as the building layout, exits' locations, and the behavior of individuals in emergency situations. It can model various evacuation scenarios and provide insights into the movement of people, congestion points, and evacuation times.

Pathfinder offers a user-friendly graphical user interface that allows users to create and edit models of buildings, define occupant properties, and simulate the movement of people during an evacuation. It also provides a range of output options, such as 2D and 3D visualizations, time-to-evacuation statistics, and evacuation route analysis.

Occupant properties such as the walking speed of occupants can be defined based on different factors such as age, gender, or mobility impairment. The number of occupants per unit area, which affects the congestion levels and movement patterns can also be defined. The physical dimensions of occupants can be assigned, which impact their ability to navigate through spaces and passageways.

Overall, Pathfinder is a tool which enables engineers and building designers to optimize evacuation plans by providing accurate and reliable simulations of occupant behavior during an emergency. Designers can identify potential bottlenecks and evacuation hazards and make informed decisions to improve the safety of the building occupants.

This study utilized the student version of Pathfinder version 2023.2.0816. Pathfinder offers compatibility with various 3D modeling and simulation software through industry-standard file formats and plugins, assisting in data exchange for comprehensive evacuation analysis. Pathfinder runs on Windows operating systems and requires at least 4GB RAM to run smoothly.

3.1.3 PyroSim

PyroSim is a computational fluid dynamics (CFD) software that allows users to create complex fire simulations for engineering and safety analysis purposes. It is developed and distributed by Thunderhead Engineering, a company that specializes in software for fire and smoke modeling.

With PyroSim, users can create 3D models of buildings, structures, and other objects, and simulate the behavior of fires within those environments. The software uses advanced algorithms to calculate the flow of heat, smoke, and gases, as well as the spread of flames and combustion reactions.

PyroSim is commonly used in a variety of industries, including architecture, engineering, and construction, as well as by architects, fire safety professionals, and regulatory agencies. It allows users to analyze fire risks, develop fire protection strategies, and evaluate the performance of fire protection systems.

In this study PyroSim will be used to see the effect of smoke propagation on the evacuation time of the occupants. As smoke can decrease the visibility and make the evacuation process difficult.

3.2 Case Study Building Selection as per Saudi Building Code

To select a case study building, local high-rise residential buildings were examined which could be compared with the Saudi building code. The high-rise residential building selected for the case study is located in Khobar, Saudi Arabia and was constructed in 2012. The building is often referred to as “Suwaiket Tower” or “Dhahran Tower” (Figure 6). It is the tallest building in the eastern province with a height of over 100 meters. The building has 46 floors and comprising of 291 luxurious apartments.

Figure 6 (a) Exterior view of the selected building in real life and (b) 3D render of building

3.2.1 Discussion of the Saudi building code

In the Saudi Building Code (SBC), the use and occupancy classification of residential buildings is categorized under Group R. Group R pertains to residential occupancies, including single-family dwellings, multi-family dwellings, apartments, and other similar residential buildings. The SBC provides guidelines and requirements for ensuring the safety and functionality of these residential occupancies. Buildings in the Residential group R-2 contain sleeping units or more than two dwelling units with occupants who are generally permanent. The occupants will have a good understanding of their surroundings.

The SBC emphasizes the importance of fire safety and the protection of occupants within residential buildings. While the code does not provide specific details on the classification of Group R occupancies into subgroups such as R-1, R-2, or R-3, it sets forth general requirements that apply to residential occupancies. Key considerations and requirements related to residential occupancies in the SBC include:

Means of Egress: The SBC mandates proper design and provision of means of egress systems, including safe and unobstructed paths of travel, stairways, corridors, and exits. These elements ensure the safe evacuation of occupants during emergencies.

Fire-Rated Construction: The SBC outlines requirements for fire-resistant construction materials, including fire-rated walls, floors, and doors. These measures help contain the spread of fire and provide a level of protection to occupants and property.

Fire Alarm Systems: The SBC may require the installation of fire alarm systems to provide early detection and warning of fire incidents within residential buildings. The specific requirements for fire alarm systems may vary depending on factors such as building size and occupancy load.

Fire Suppression Systems: Depending on the size and type of residential occupancy, the SBC may require the installation of fire suppression systems such as automatic sprinklers or other suitable fire suppression measures. These systems help control and extinguish fires, enhancing occupant safety.

Ventilation and Smoke Control: The SBC may include provisions for proper ventilation systems within residential buildings to ensure adequate air quality and smoke control in the event of a fire.

3.2.2 Egress requirements for R-2 occupancies

The SBC adopts a performance-based approach rather than a prescriptive approach, focusing on general fire safety principles and requirements for buildings. The design of egress is based on the occupant load which can be calculated from table 1004.1.2 provided in the SBC. The table specifies that the floor area in square meters per occupant is 19 gross for residential buildings. The floor area of the typical floors for the selected case study building is 1,850m^2. This means that the maximum occupancy for each floor is 99 occupants. Further, the SBC provides details to calculate the egress width based on the occupants served. The case study building is equipped with a sprinkler system. Thus, the occupant load is multiplied by 5.1, which gives a total of 505mm width. Furthermore, the SBC provides a factor of 7.5mm per occupant, which could be used to determine the total width of the egress, which comes out to be 743mm.

Although the calculated width for the means of egress was 743mm, section 1009.3 in SBC specifies that the clear width between handrails should be 1200mm. This does not include buildings which are equipped with automatic sprinkler systems. The selected case study building has sprinkler system installed so this does not apply to this building.

The SBC also provides the minimum number of exits required as per occupant load (Table 4). Furthermore, the travel distance to the nearest exit is also mentioned. For buildings with sprinkler system, the maximum allowed travel distance is 76.2 meters from the furthers point (Table 5).

Table 2 Minimum number of exits required as per SBC

MINIMUM NUMBER OF EXITS FOR OCCUPANT LOAD	
OCCUPANT LOAD	**MINIMUM NUMBER OF EXITS**
1-500	2
501-1,000	3
More than 1,000	4

Table 3 Maximum allowed travel distance as per SBC

EXIT ACCESS TRAVEL DISTANCE		
OCCUPANCY	**WITHOUT SPRINKLER SYSTEM (meters)**	**WITH SPRINKLER SYSTEM (meters)**
R – Residential	61	76.2

The size of doors is also mentioned in the SBC section 1010.1.1, which is based on the occupant load. The minimum clear width required for the doors is 800mm and the height of the doors should not be less than 2000mm. The minimum corridor width was also specified where it should not exceed 1100mm for group R-2 occupancies.

Direction of swing is also mentioned in section 1010.1.2.1 where the doors are required to swing in the direction of egress travel where the occupant load is 50 or more.

Table 4 Minimum corridor width as per SBC 801

3.3 Case Study Building Modelling

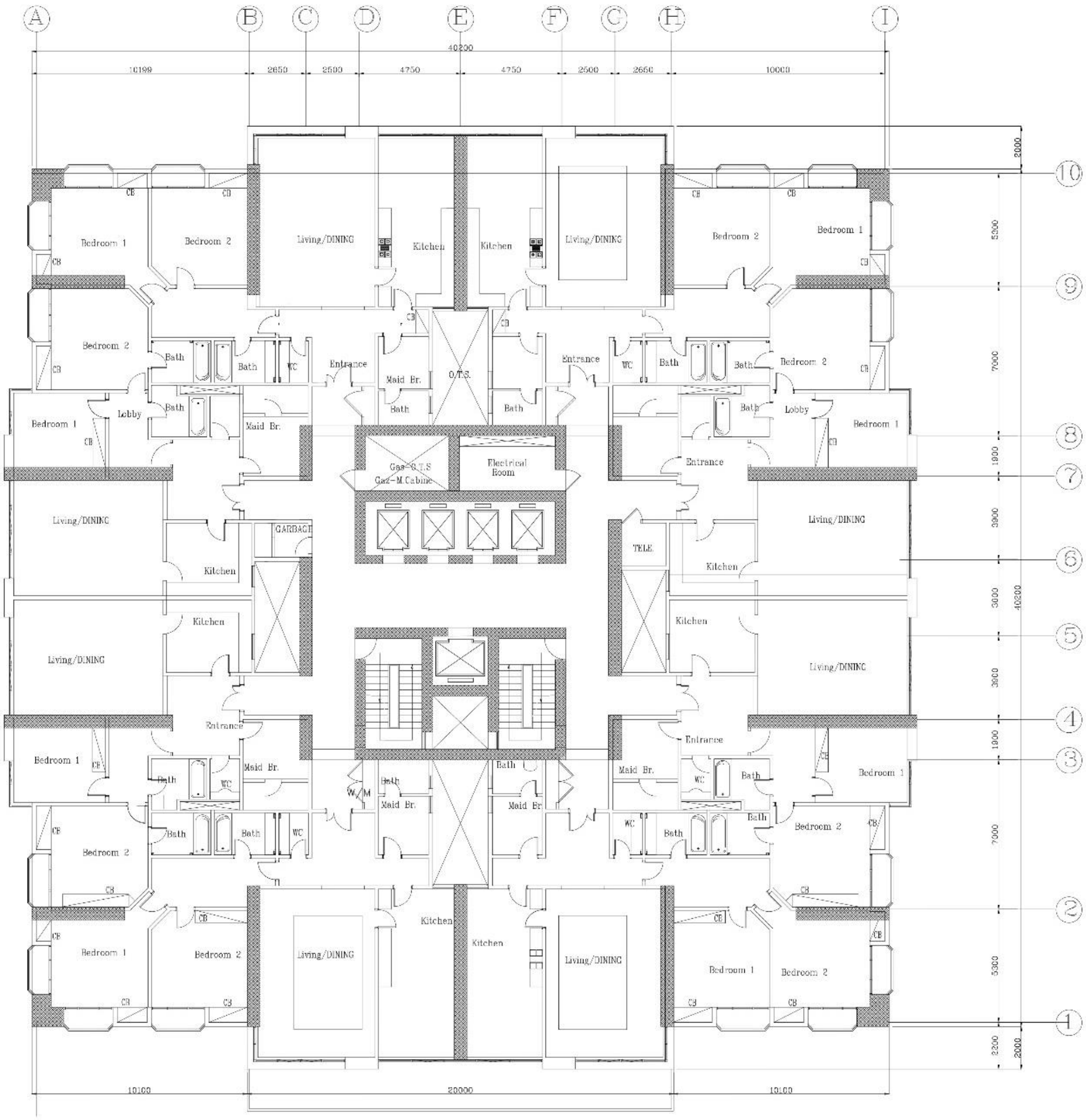
OCCUPANCY	MINIMUM WIDTH (mm)
Any facilities not listed below	1100
Access to and utilization of mechanical, pluming or electrical systems or equipment	600
With an occupant load of less than 50	900
Withing a dwelling unit	900
In Group E with a corridor having an occupant load of 100 or more	1800
In corridors and areas serving stretcher traffic in occupancies where patients receive outpatient medical care that cause the patient to be incapable of self-preservation	1800
Group I-2 in areas where required for bed movement	2400

As-built drawings of the building were obtained (Figure 11), and the building was modelled using Autodesk Revit (Figure 13). Each typical floor had 8 apartments as shown in (Figure 14).

The building components modelled were only the fire escape stairs, floors, fire exits and walls of the building. The model was subsequently imported into Pathfinder (Figure 10) using the IFC file format in order to run the simulations. The building was also compared with the Saudi building code to see its compliance to the code (Table 6). From the comparison it was observed that the building satisfied most the code requirements, except for the staircase width where the requirement was 1100mm.

Table 5 Comparison of the Case study building with the Saudi building code

Egress code requirements vs Selected case study building			
Specification	Saudi Building Code Requirement	Existing building	SBC Reference
Egress stairs width	1100mm	1000mm	1005.2, 1009.3
Number of exits	2	2	Table 8.18.1
Exit Access Travel Distance	76.2 (meters)	46 (meters)	Table 8.15.1
Clear width of doors	800mm	1000mm	1010.1.1
Minimum corridor width	1100mm	2000mm	1020.2



AS BUILT TYPICAL FLOOR PLAN

Figure 7 As built drawing of the typical floor plan

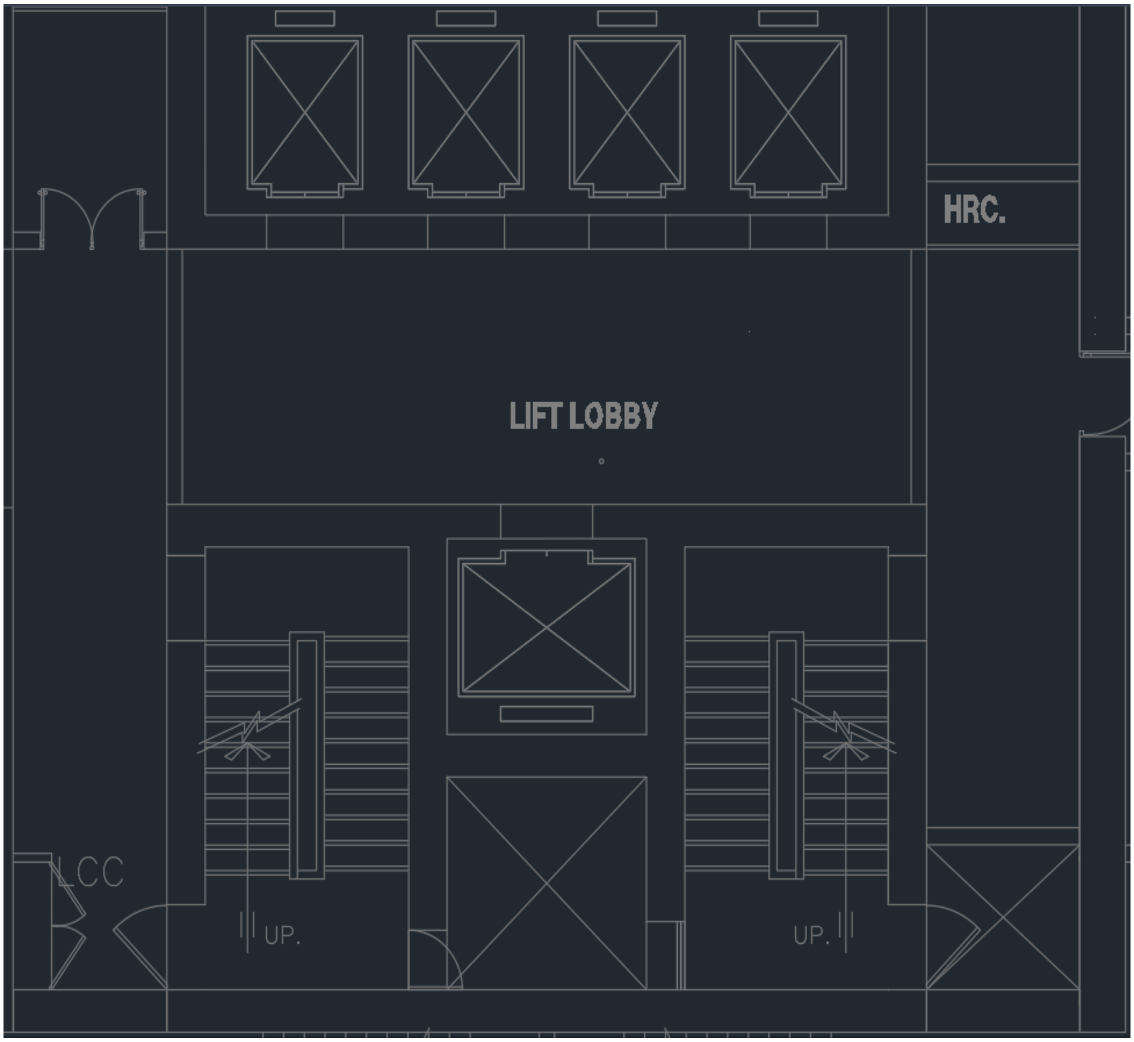


Figure 8 Ground Floor plan of the building

Figure 9 3D view of the building in Revit

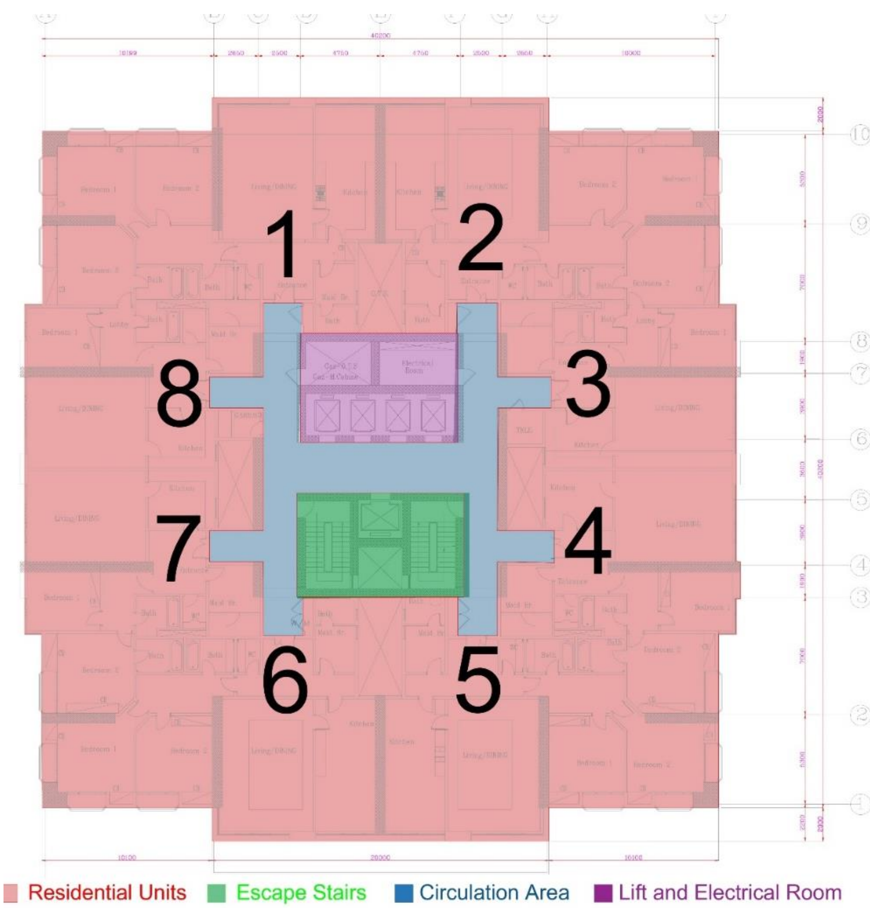


Figure 10 Zones inside the typical floor plan

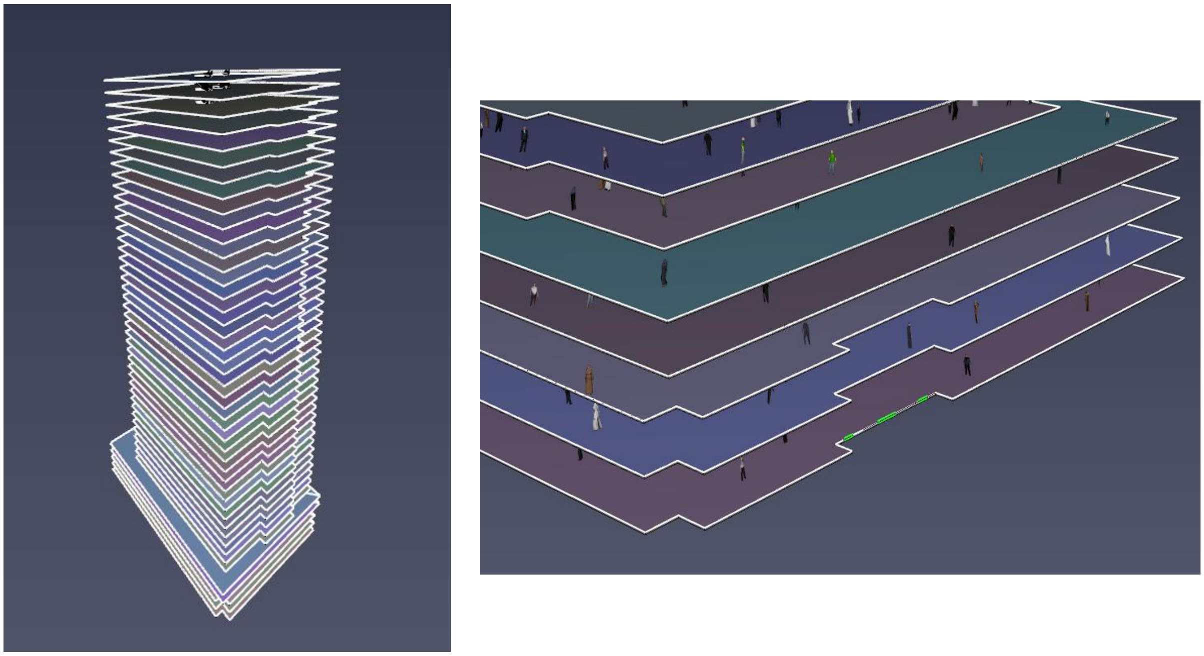


Figure 11 Imported model of the building in Pathfinder

Three separate case studies were conducted, where the width of the fire exit stairs (Figure 11) was changed in order to see the difference in the total evacuation time.

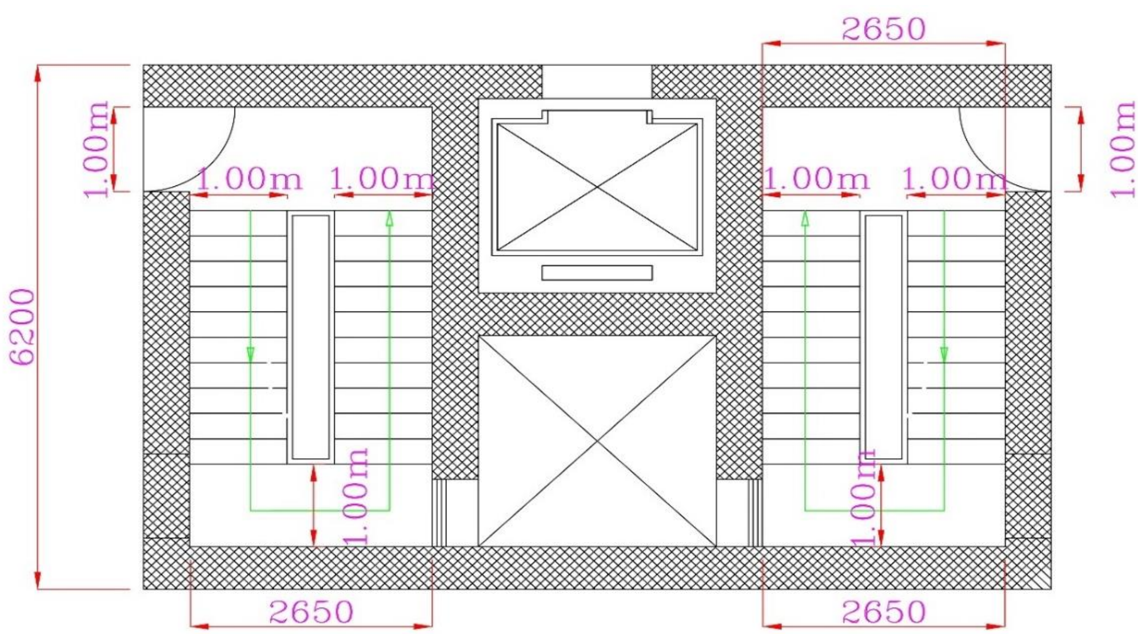


Figure 12 As Built drawing of the stairs for Case Study 1

The case study calculated the evacuation time for maximum occupancy as well as at 60% occupancy which is the most likely scenario as it is shown in Table 8.

Table 6 Distribution of occupants across the floors

Floor Level	**Maximum Occupancy**	**Assuming 60% occupancy**
Ground Floor	20	12
Mezzanine Floor	35	21
3rd Floor – 5th Floor	60 (20 on each floor)	36
6th Floor – 17th Floor	384 (32 on each floor)	231
18th Floor – 45th Floor	896 (32 on each floor)	538
Roof Floor	5	3
Total	**1400**	**841**

The primary exits were located at the entrance of the building as shown in Figure 12, while the blue dots represent the occupants'. The main door had a width of 1.8 meters while the other 2 door on either side had a width of 1.0 meters. There was an additional emergency exit with a width of 1.4 meters located on the west side of the building.

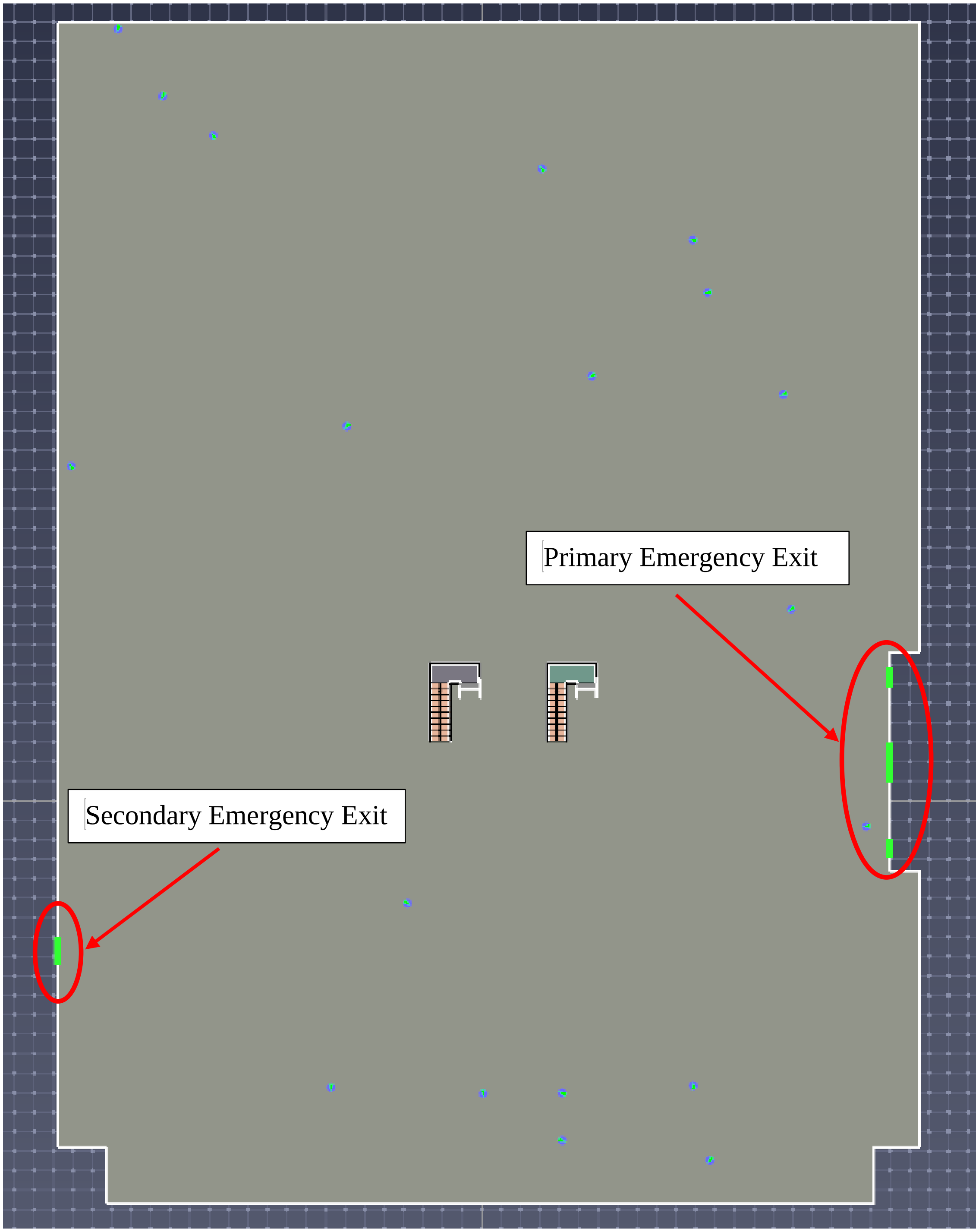


Figure 13 Emergency Exit Locations on the Ground Floor Plan

3.4 Pathfinder Evacuation Simulation Input

In order to perform the evacuation simulation, occupants (agents) need to be added on each floor. Occupants need to be assigned their movement speed. Occupants are assigned to each floor based on maximum occupancy of the building as well as assuming 60% of occupancy, which can be seen in Table 2. The occupants profile has to be selected for the evacuation simulation. Pathfinder allows the selection of pathway the occupants should take as well as defining the occupants' movement speed and their physical properties Figure 18. In this study the occupants were simply asked to go to the nearest exit. A study was conducted by (Almejmaj and Meacham, 2014), to collect the walking speed based on gender in Saudi Arabia. The study indicated that males have a movement speed of 1.05m/s while females have a movement speed of 0.90m/s when wearing the traditional clothes worn in Saudi Arabia. This data was adopted for this simulation modelling and occupants are assigned their movement speed based on their gender.

Pathfinder allows for more detailed occupant modelling such as adding an acceleration time, slow factor, social distancing Figure 19, these factors was not modified and taken as defaults. Occupants' behavior can also be assigned such as adding a delay time before they start their evacuation as well as asking them to go to a specific exit or follow a group of occupants Figure 20. For this study, only the movement speed was assigned to the occupants' and as for their behavior they were asked to go to any nearest exit.

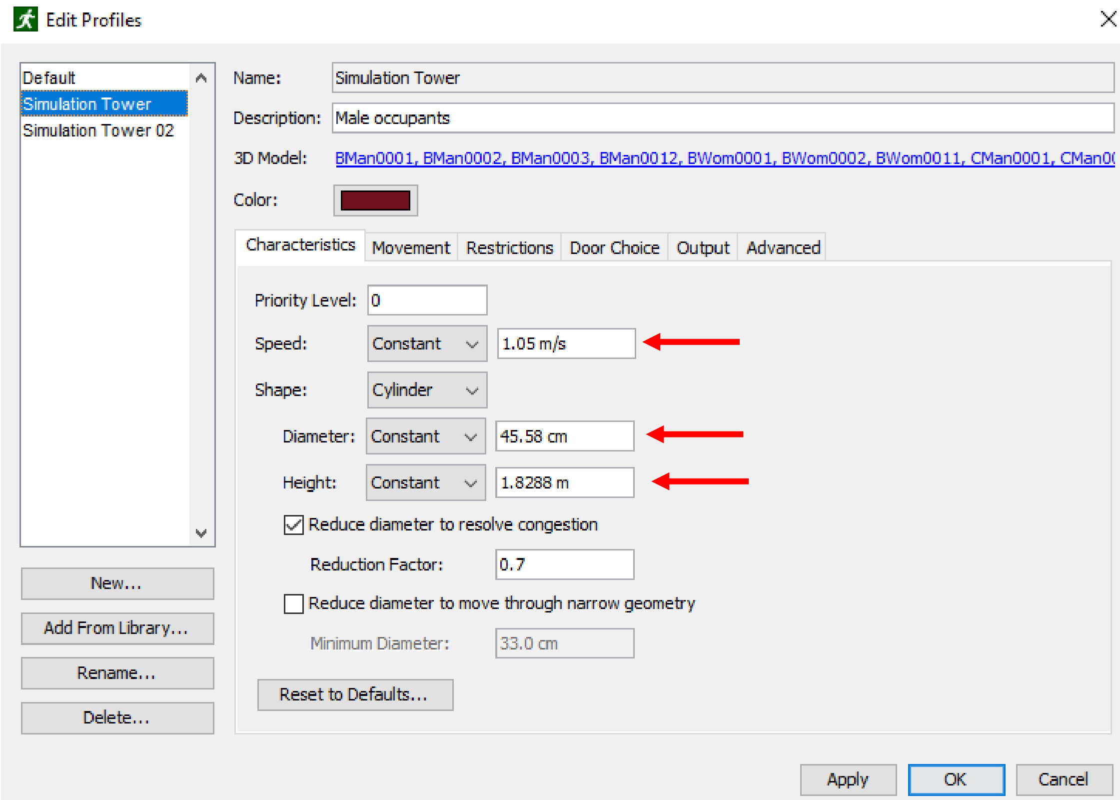


Figure 14 Characteristics input options for the occupants in Pathfinder

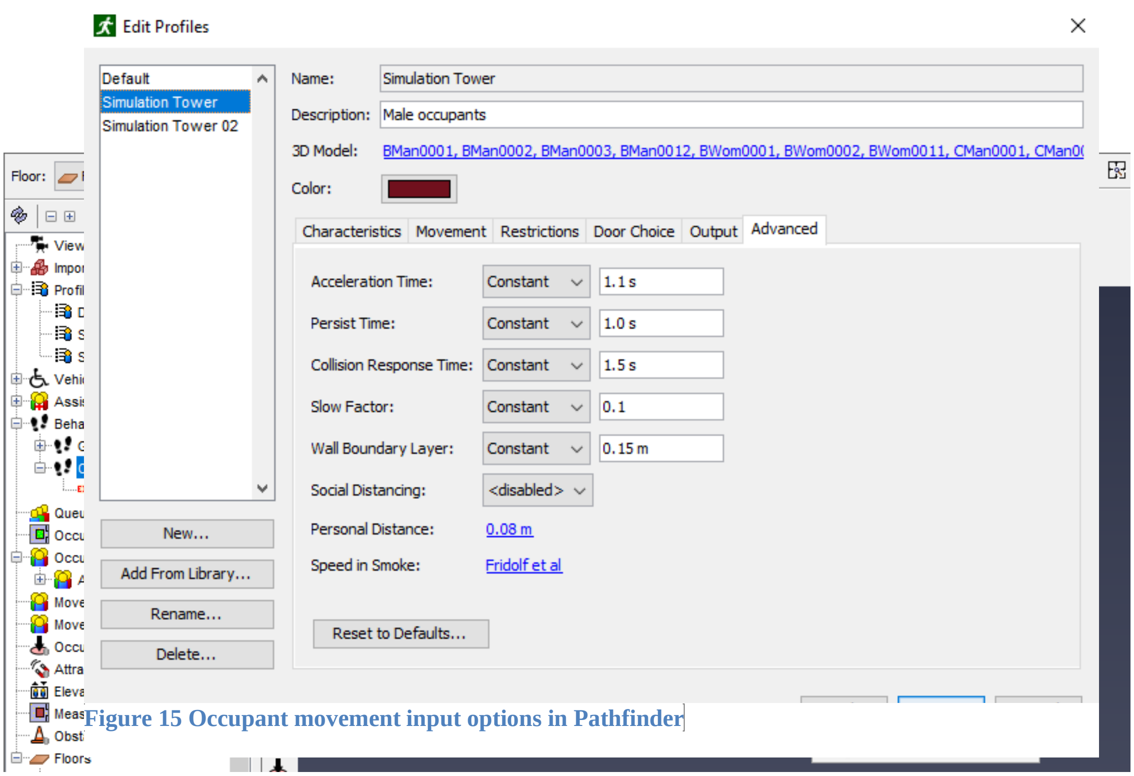


Figure 15 Occupant movement input options in Pathfinder

Figure 16 Occupant behavior input options in Pathfinder

3.5 PyroSim Evacuation Simulation Input

PyroSim offers a wide range of parameters and settings that can be adjusted to create detailed and accurate fire simulations. Some of the key parameters available in PyroSim include adding material properties such as thermal conductivity, specific heat, and density of building materials that influence fire behavior and spread. Parameters related to the ventilation system, such as airflows, ducts, fans, and openings. Fire sources can be simulated, their size and location can be modified along with their fire growth rate and the heat release rate (HRR). Smoke production rate and characteristics, such as the yield, visibility, and density of smoke can also be specified. Environmental settings can also be set such as the ambient temperature, pressure, and relative humidity (Figure 24). PyroSim requires specifying a mesh which is a three-dimensional computational grid or mesh that is used to separate the geometry of a building or structure for fire simulation purposes. The mesh divides the space within the building into small elements or cells, allowing for the calculation of fire and smoke behavior based on various parameters. The mesh is composed of individual cells. Smaller cell sizes result in a more detailed and accurate representation of the geometry but require more computational resources and will increase the simulation time. The cell size selected for the mesh in this study is 0.7m in X, Y and Z direction (Figure 21). For this study we will take the default available fire which has a heat release rate of 1000.0 kW/m^2 (Figure 23). The fire source for the case study was done on the ground floor, as it is the most critical part of the building and can significantly impact the evacuation by blocking the stairways with smoke. The study assumes for the case study that it is a fire caused by electrical short circuit as it is the most common type of fire in residential building according to the statistics published by the ministry of civil defense of

Saudi Arabia Table 9. Other common causes of fire in residential building include stove combustion and irresponsible behavior.

Table 7 The causes of fire in different types of buildings for the year 1439 AH (2018) from the Ministry of Civil Defense

المجموع	حالة حرب	عدم وجود حادث	تحت الاجراء	التخلص من النفايات والمخلفات	جنائي	تفاعل مواد كيميائية	الانفجار الغازي أو الغباري	ظواهر طبيعية قدرية	اشتعال ذاتي	تسرب مواد بترولية	احتراق وسائل النقل	احتراق مواقد	مصدر حراري متوهج وبطيء	العبث	التماس كهربائي	الأسباب / النوعية
15,034	1	415	229	160	269	5	46	16	42	189	4	2,395	926	1,932	8,405	السكنية
3,355	1	7	21	867	96	1	1	46	27	2	2	31	457	1,509	287	زراعية وحيوانية
2,231	0	74	57	2	28	3	12	4	20	42	2	709	174	78	1,026	محلات تجارية
237	0	19	5	2	6	4	4	1	4	117	3	3	16	4	49	المنشآت البترولية
271	0	11	20	13	8	5	0	0	3	8	7	8	65	12	111	الصناعية
150	0	6	18	2	6	2	1	2	2	9	0	1	29	13	59	المصانع
382	0	17	8	8	9	0	1	0	2	3	0	34	54	69	177	الترويحية
170	0	20	8	2	2	2	2	1	0	2	0	4	7	9	111	الصحية
386	0	9	57	13	27	5	0	2	3	2	1	10	67	38	152	المستودعات والتخزين
661	0	62	11	17	17	5	0	1	3	1	0	8	30	48	458	التعليمية
2,417	1	114	188	3	206	1	1	2	28	213	880	8	87	160	525	وسائل النقل
543	0	24	20	10	27	1	0	3	7	9	0	11	27	40	364	الدوائر الحكومية
314	0	10	15	2	22	0	1	0	2	12	0	9	26	16	199	المؤسسات والشركات الأهلية
4,064	0	139	86	4	16	0	0	9	7	4	0	1	8	23	3,767	الوحدات الكهربائية
80	0	1	3	0	10	0	0	0	5	6	19	0	10	3	23	المعدات الثقيلة
11,146	0	68	43	2,509	38	1	0	4	17	2	1	7	1,174	7,231	51	النفايات والمخلفات
2,219	0	1,796	7	10	0	0	1	0	0	22	6	35	9	28	305	عدم وجود حادث
29	28	1	0	0	0	0	0	0	0	0	0	0	0	0	0	حالة حرب
43,689	31	2,793	796	3,624	787	35	70	91	172	643	925	3,274	3,166	11,213	16,069	المجموع

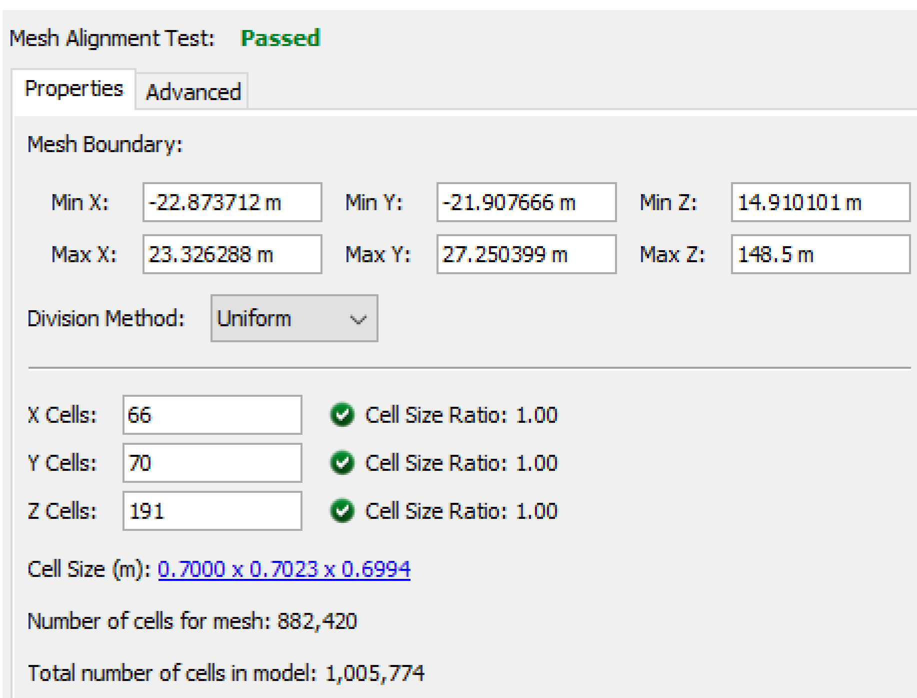


Figure 17 Mesh and Cell size selection in PyroSim

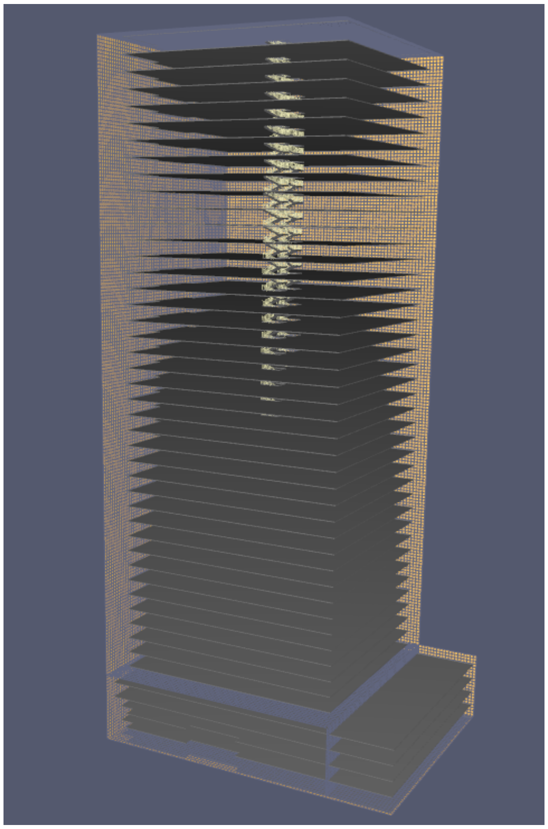


Figure 18 Building model in PyroSim with generated mesh of 0.7m in 3 directions.

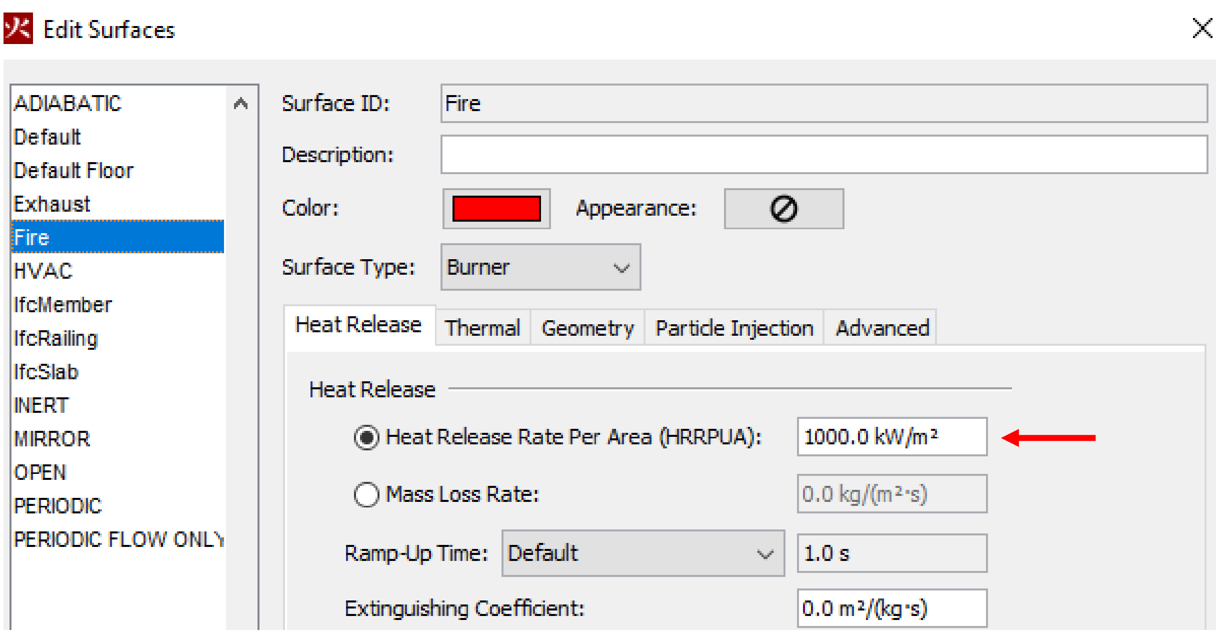


Figure 19 Adding a fire source in PyroSim with the heat release properties

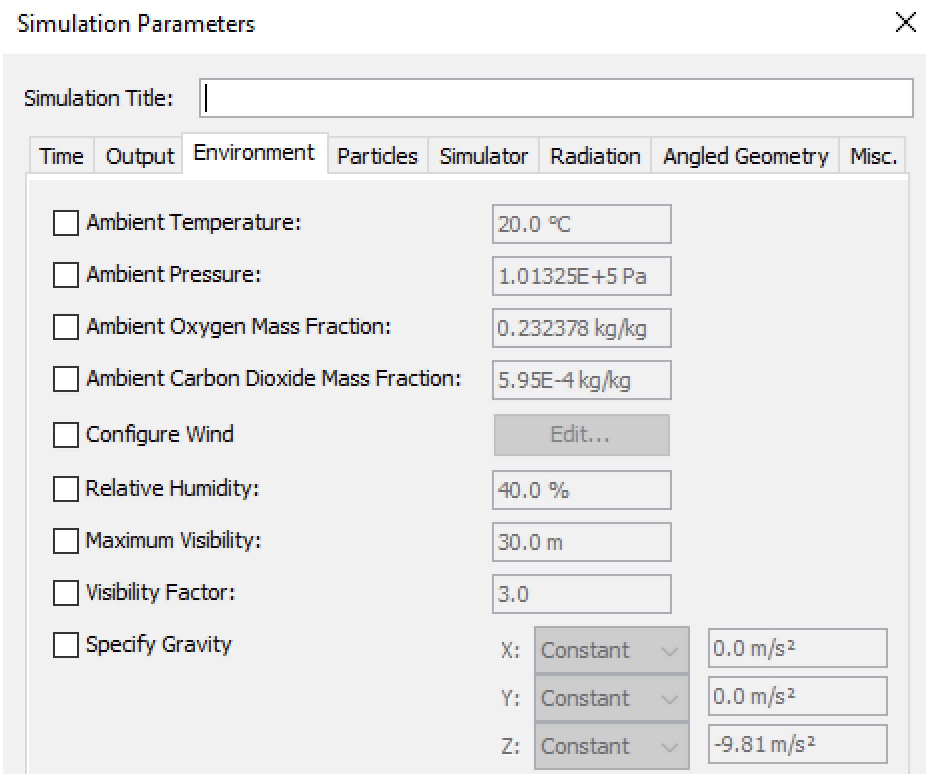


Figure 20 Adding a fire source in PyroSim with the heat release properties

3.6 Simulation Scenarios

First the existing building was modelled exactly as it is from the obtained as-built drawings. Then based on the building occupancy the evacuation will be simulated to see the evacuation time for 60% occupancy as well as for full occupancy.

Once the two simulations are done, the width of the run will be increased by .25cm and.50cm respectively and simulation will be carried out again to see the impact of increasing the width of the run.

Other parameters which will be investigated include the location of stairs as well as the number of stairs present inside the building for evacuation. Then the buildings exit doors width will also be increased to see if it has an impact on the evacuation time and efficiency.

As for PyroSim simulation, a fire will be created at the ground floor to see the spread of the smoke. Although fire should not be allowed to enter the staircases, we will assume the worst-case scenario where it does enter the egress to see how fast it spread inside the building. An evacuation simulation with both Pathfinder and PyroSim will be carried out for 5 floors to see the impact of smoke on the evacuation time.

CHAPTER 4

RESULTS & DISCUSSION

4.1 Pathfinder simulation results for staircase width

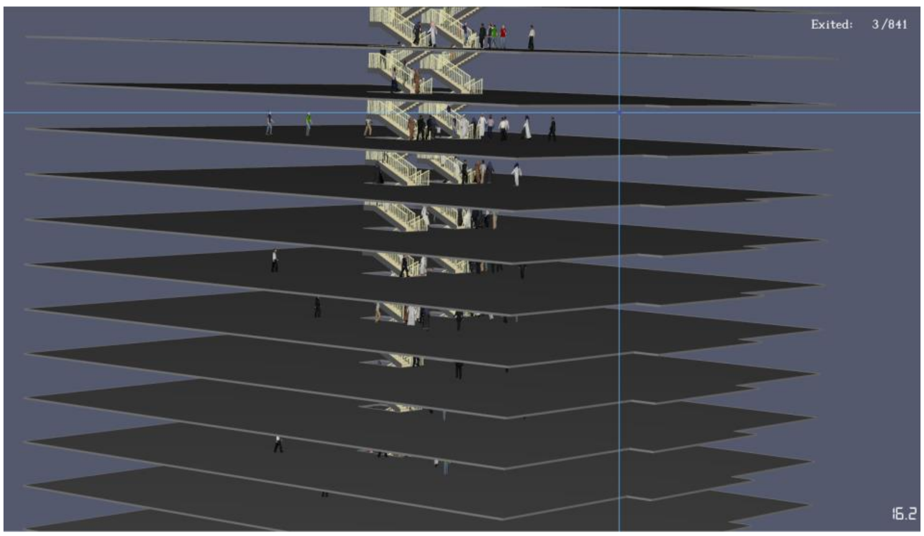
Two separate evacuation simulations were carried out based on the occupancy of the building as shown in table 10 and 11 respectively. In the first case study with the existing design of the emergency stairs, it takes approximately 15:09 minutes for complete evacuation of the building considering an occupancy of 60%. While increasing the width of the run by .25m and .50m did not provide any significant improvements in the overall evacuation time. The same simulation done on fully occupied building showed that an increase in the run by .50m could reduce the evacuation time by 3 minutes approximately as it can be seen in figures 10 and 11. As per the Saudi building code, the minimum requirement of the width run is 1100mm.

Table 8 Simulation of Occupant Evacuation (60% occupancy)

Simulation No.	Width of run	Time for total evacuation
1	1.00m	909s (15:09 mins)
2	1.25m	901s (15:01 mins)
3	1.50m	856.5s (14:16 mins)

Table 9 Simulation of Occupant Evacuation (Full occupancy)

Simulation No.	Width of run	Time for total evacuation
4	1.00m	1201s (20:01 mins)
5	1.25m	1097.0s (18:17mins)
6	1.50m	1008.8s (16:48 mins)



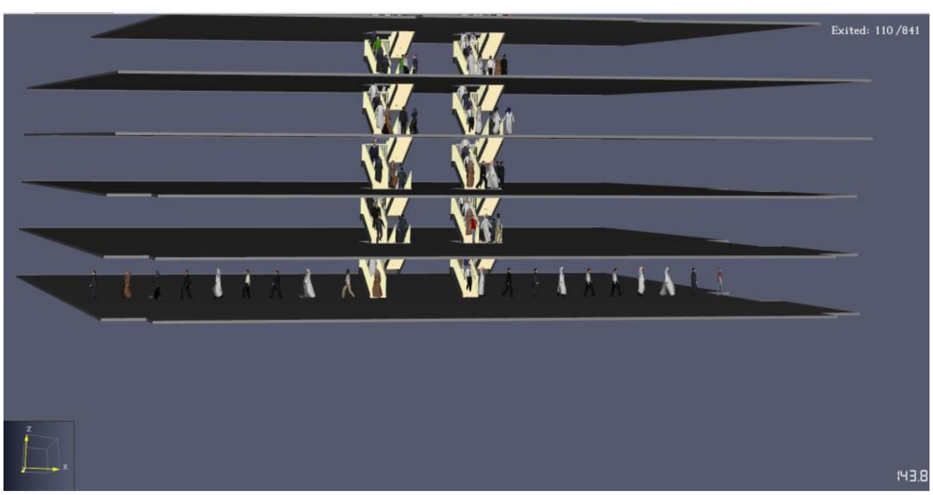


Figure 21 Occupants evacuating from the building using stairs in Pathfinder for Case Study 1 with 60% occupancy.

4.1.1 Pathfinder simulation results for staircase scenario 1

An additional staircase was added for egress at the right side of the building (Figure 26). All three staircases had a run width of 1.00 meters. The simulation first was run with 60% occupancy followed by full occupancy. The occupants' movement speed was the same as before where males had a movement speed of 1.05m/s and females with 0.90m/s. The behavior input was also the same where occupants' were directed to go to the nearest exit.

Table 10 Simulation of Occupant Evacuation with 3 stairs

Simulation No.	Width of run	Occupancy	Time for total evacuation
7	1.00m	60% (841)	900.0s (15:00 mins)
8	1.00m	100% (1400)	1155.0s (19:15mins)

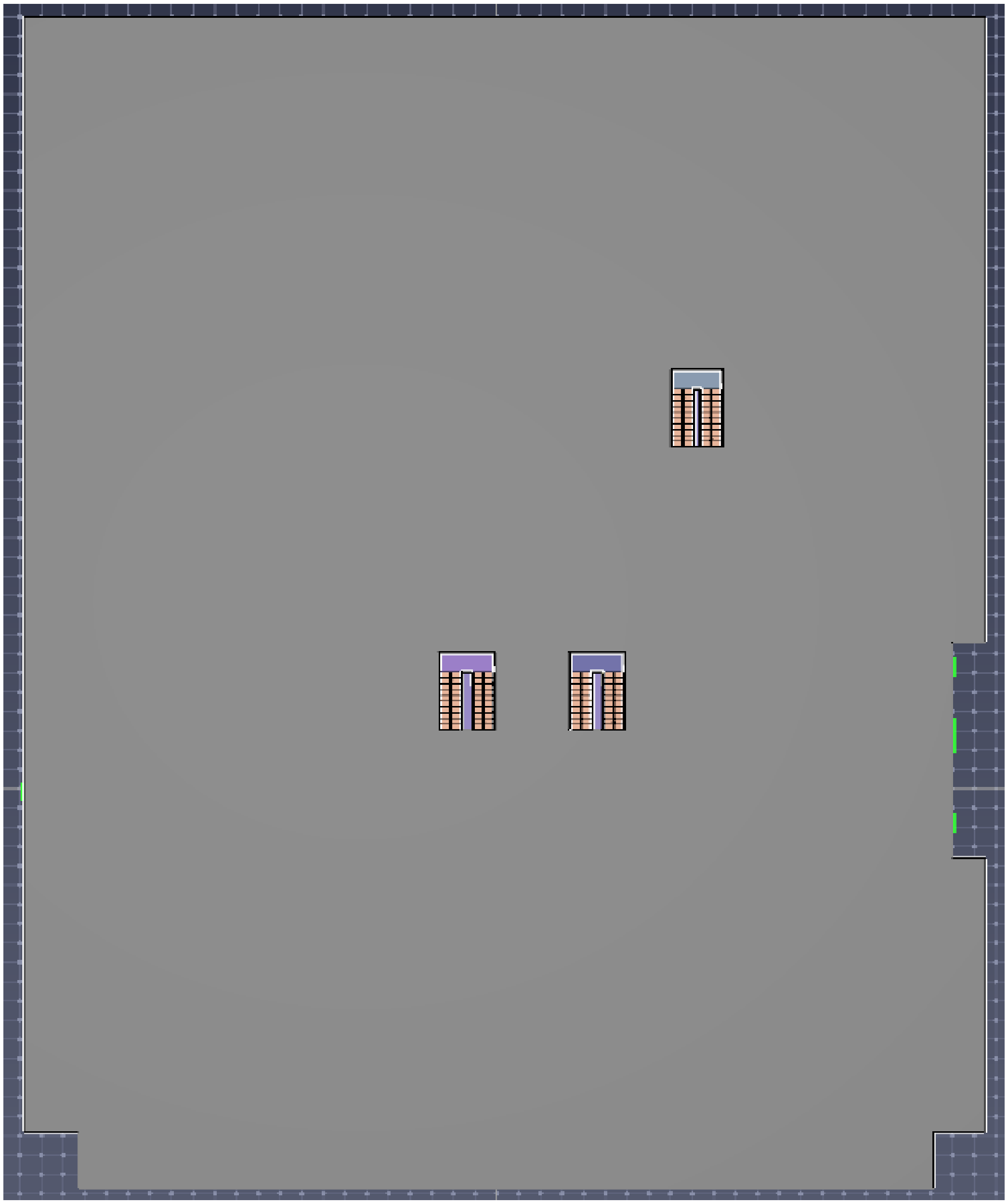


Figure 22 Additional staircase added to the original building layout

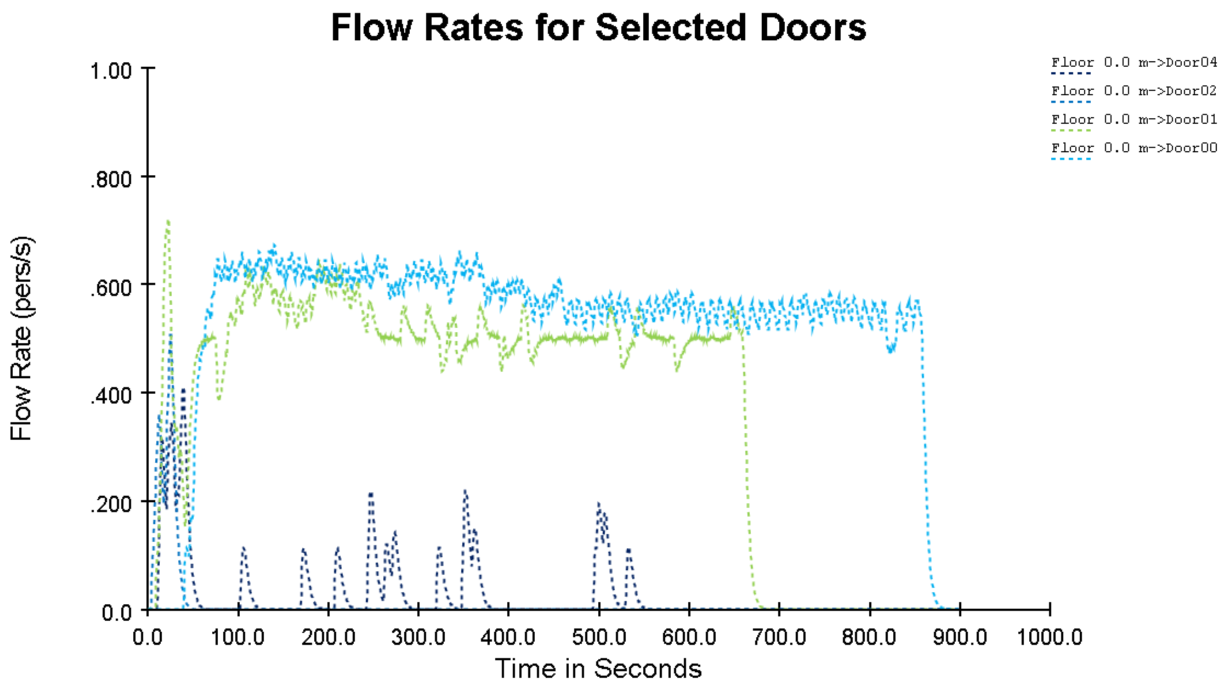


Figure 24 Flow rates for the fire exit doors for Simulation 7

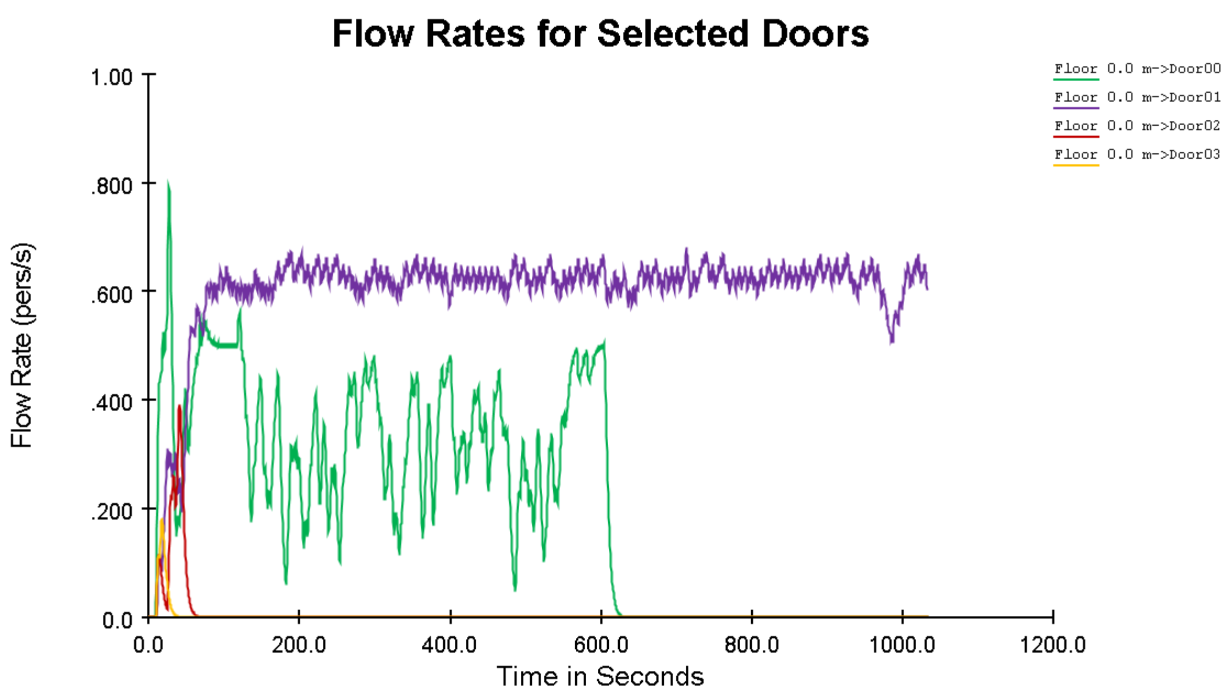


Figure 23 Flow rates for the fire exit doors for Simulation 8

The flow rates for the emergency doors were averaging around 0.6 persons/s for both the simulations 7 & 8. The main door which had a width of 1.8 meters was the most used until the last occupant exited the building while the second most common used door was door located at the other side of the building. The other two doors with a width of 1 meter which were located next to the primary exit door of 1.8 meters. Therefore, it makes sense that during the start occupants were opting to use the other doors available to exit the building but as time went by and the occupant load decreased, they stopped using it.

4.1.2 Simulation results of staircase scenario 2

The layout of staircases in this scenario was modified where the 2 emergency exits were located further from each other.

Table 11 Table Simulation of Occupant Evacuation with 2 stairs at a distance

Simulation No.	Width of run	Occupancy	Time for total evacuation
9	1.00m	60% (841)	1042.3s (17:23 mins)
10	1.00m	100% (1400)	1606.5s (26:46mins)

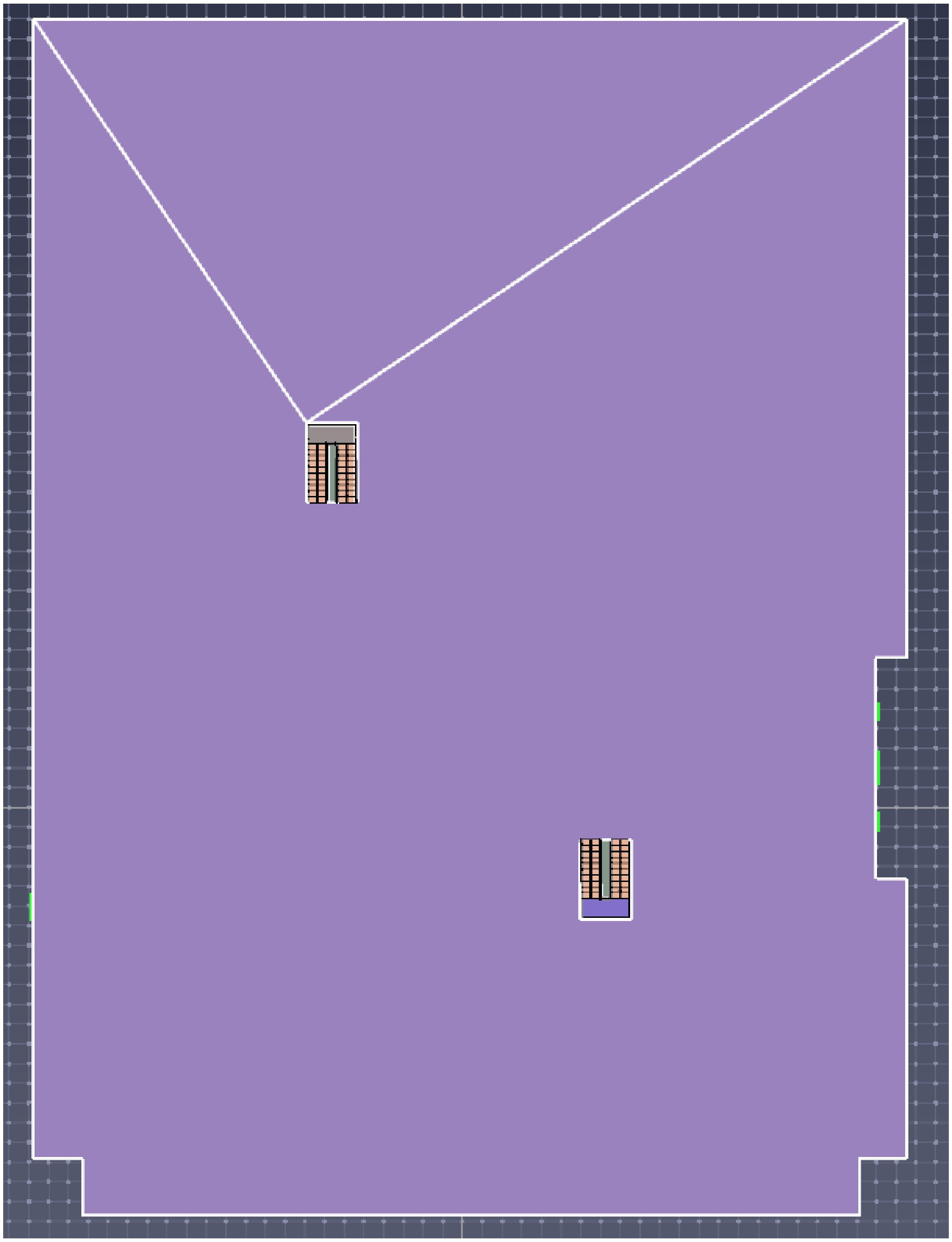


Figure 25 2 staircases were located at a distance to each other

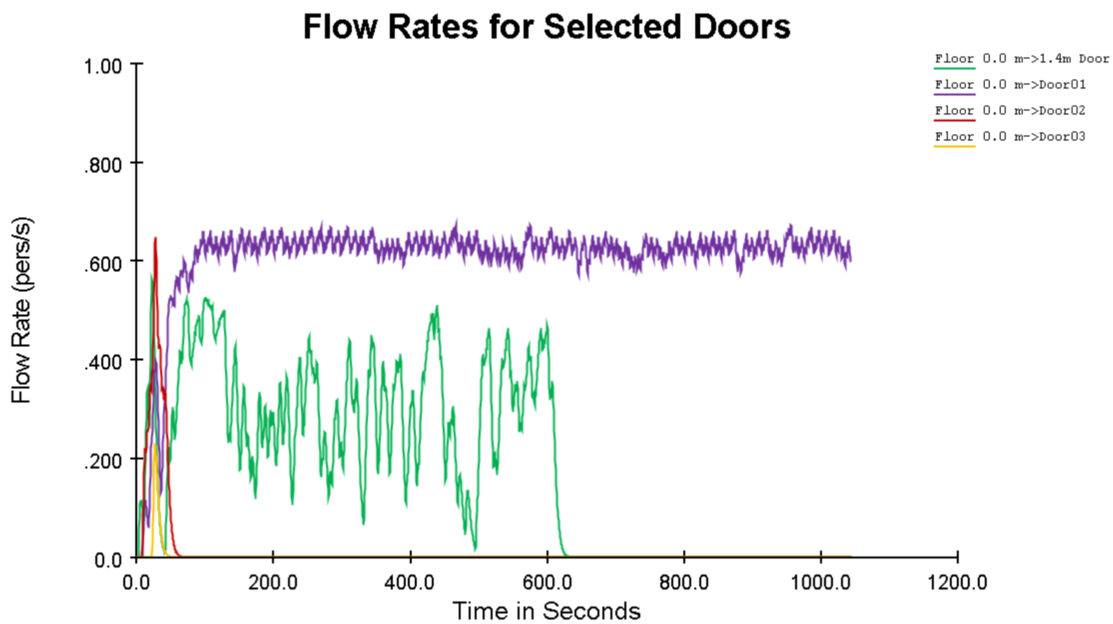


Figure 26 Flow rates for the fire exit doors for Simulation 9

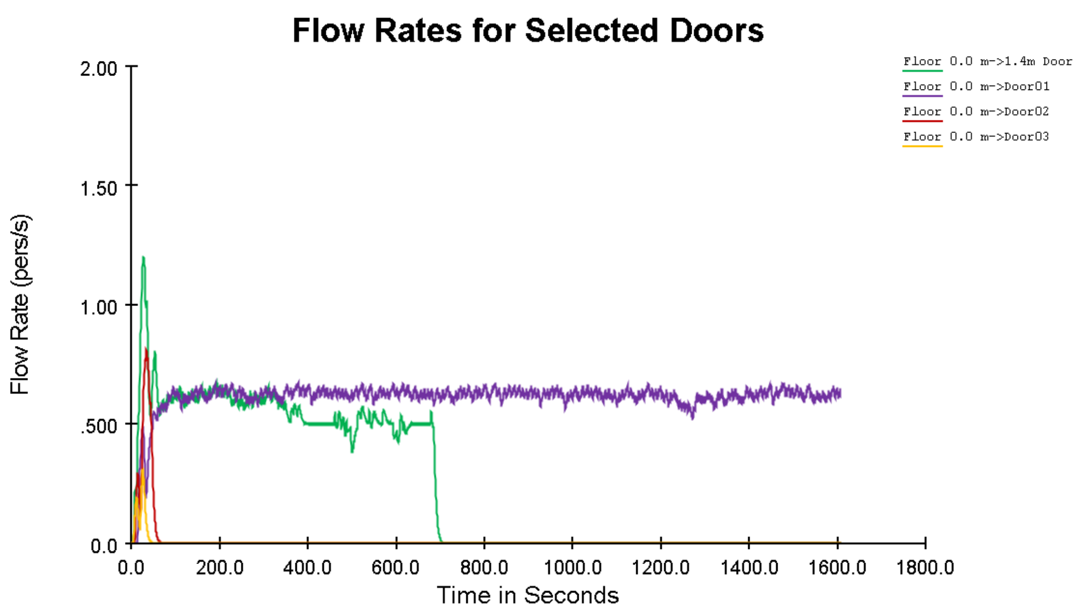


Figure 27 Flow rates for the fire exit doors for Simulation 10

4.1.3 Simulation results of staircase scenario 3

The layout of staircases in this scenario was modified where the 2 emergency exits were located at the edges of the building. This type of egress will not be influenced by smoke as the stairways are outside the building.

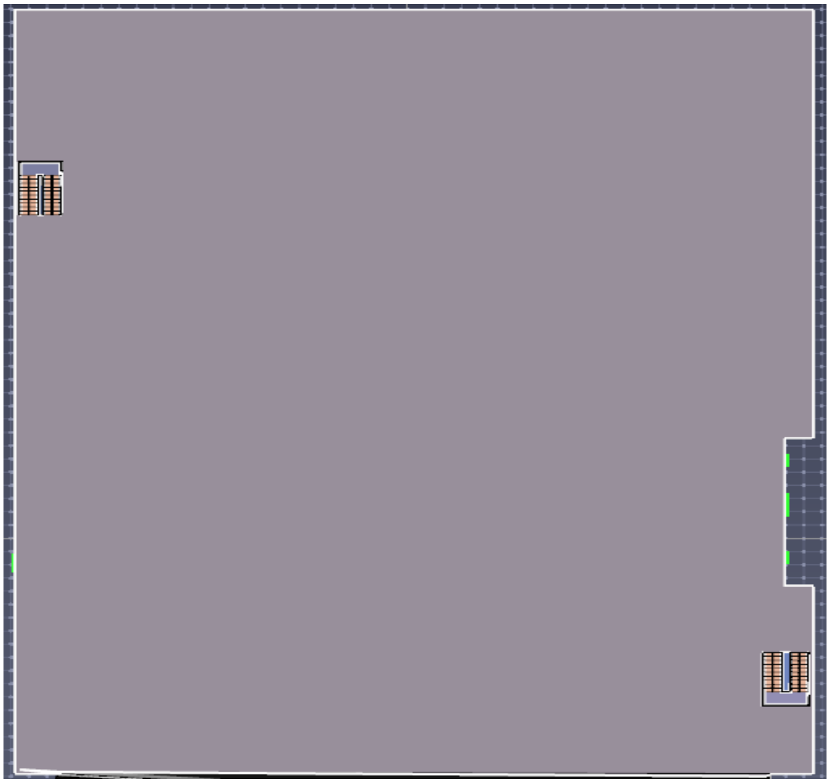


Figure 28 2 staircases located at the edges of the building

Table 12 Simulation of Occupant Evacuation with 2 stairs at edges

Simulation No.	Width of run	Occupancy	Time for total evacuation
11	1.00m	60% (841)	993.3s (16:33 mins)
12	1.00m	100% (1400)	1456.2s (24:16mins)

4.1.4 Simulation results of staircase scenario 4

The layout of the plan was modified to assign every 2 apartments with 1 emergency egress. The typical floor plan layout has 8 apartments therefore, 4 egress routes were added as shown in figure 33.

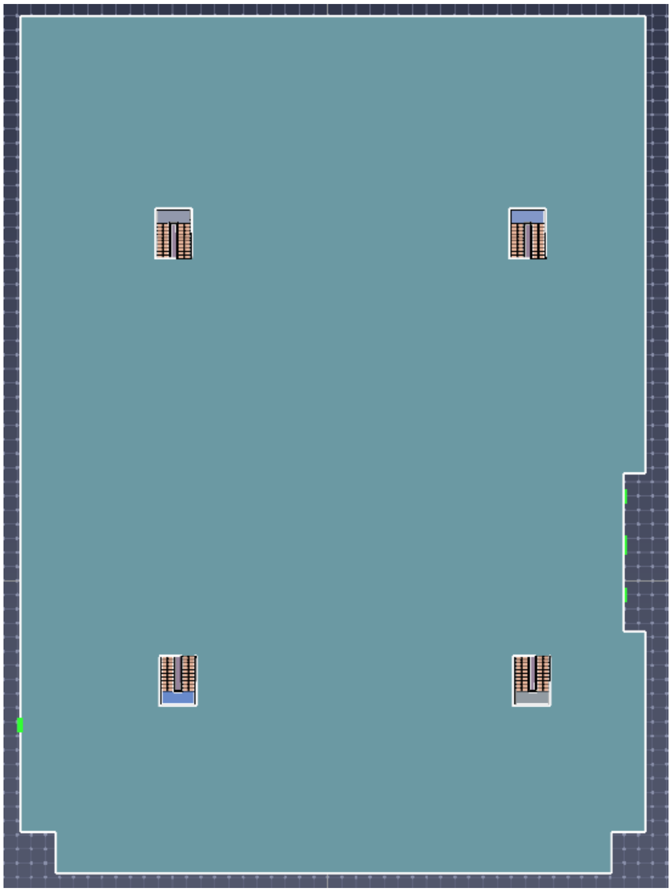


Figure 29 4 staircases located at the four sides of the building

Table 13 Simulation of Occupant Evacuation with 4 stairs

Simulation No.	Width of run	Occupancy	Time for total evacuation
13	1.00m	60% (841)	745.2s (12:25 mins)
14	1.00m	100% (1400)	772.6s (16:12mins)

4.1.5 Simulation results of staircase scenario 5

In the original plan of the building, the core was located at the center, and the stairs were next to each other. For this scenario the stairs were kept at the left and right side of the building to see if it has an impact on the evacuation time. Additionally, the width of the corridors was increased by 1 meter.

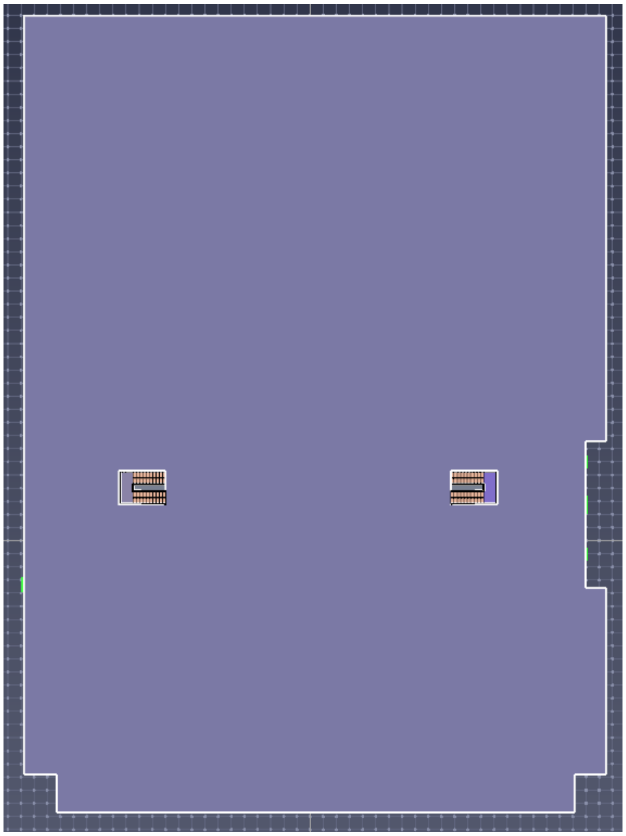


Figure 30 2 staircases located at opposite of each other

Table 14 Simulation of Occupant Evacuation with 2 stairs at opposite

Simulation No.	Width of run	Occupancy	Time for total evacuation
15	1.00m	60% (841)	883.4s (14:43 mins)
16	1.00m	100% (1400)	1162.7 (19:22mins)

4.1.6 Simulation results of staircase scenario 6

The scenario for this simulation involved selecting the minimum design requirements for the egress set out by the SBC. The minimum requirements were adopted for the design as mentioned in the SBC.

Table 15 Simulation of Occupant Evacuation with minimum design requirements

Simulation No.	Width of run	Occupancy	Time for total evacuation
17	1.00m	60% (841)	1185.0s (19:45 mins)
18	1.00m	100% (1400)	1631.1s (27:11 mins)

4.1.7 Simulation results of staircase scenario 7

This scenario was run with the original design of the building. Only two occupants' were added in the simulation at the top floor to see the time for evacuation if no crowd is present. The movement of the male occupant was set to 1.05m/s and for the female to 0.9m/s.

Table 16 Simulation of Occupant Evacuation with 2 Occupants

Simulation No.	Width of run	Occupancy	Time for total evacuation
19	1.00m	2	607.5s (10:07 mins)

4.2 Pathfinder simulation results for building exit doors width

There are 4 main egress doors available for occupants to evacuate from. The width of the exit doors was increased by 20% to see the impact on the total evacuation time. The comparison will be made with simulation 7 and 8 since they had the fastest evacuation time to further see the improvement which can be made.

Table 17 Modifying the door width for Full occupancy evacuation

Door No.	Original Width of Exit Door	Increased door width (20%)
Door 01	1.00m	1.20m
Door 02	1.80m	2.20m
Door 03	1.00m	1.20m
Door 04	1.40m	1.70m
Original evacuation time: 1155.0s (19:15mins)		
Evacuation Time after modification: 1095.3s (18:15mins) (5%)		

Table 18 Modifying the door width for 60% occupancy evacuation

Door No.	Original Width of Exit Door	Increased door width (20%)
Door 01	1.00m	1.20m
Door 02	1.80m	2.20m
Door 03	1.00m	1.20m
Door 04	1.40m	1.70m
Original evacuation time: 900.0s (15:00 mins)		
Evacuation Time after modification: 875.5s (14:35mins) (2.7%)		

Figure 31 Flow rates for the fire exit doors after increasing door width

Results from the simulation indicate that increasing with width by 20% only improved the evacuation time by 5%. The evacuation time was not reduced significantly with the increase in the width of the doors. There was no major difference in the flow rate as it remained close to 0.6 persons/s.

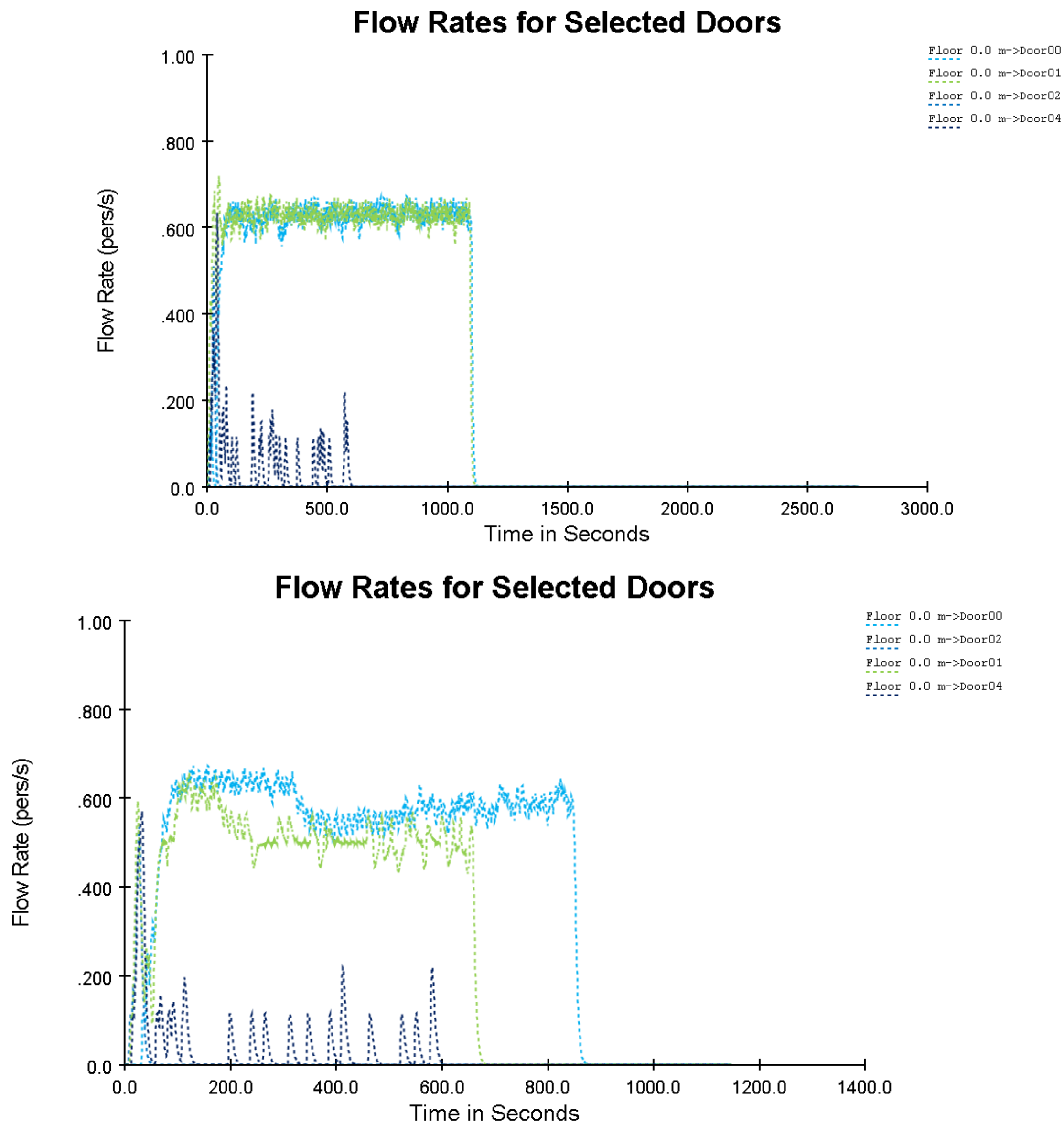


Figure 32 Flow rates for the fire exit doors after increasing door width

4.3 Pathfinder simulation results for egress doors width

In the original design of the building the egress door had a clear width of 1.00 meters. The door size was changed and keeping the same original design of the staircase with 1.00-meter width run to see the impact of the egress door width on the evacuation time.

Table 19 Modifying the egress door width for 60% occupancy evacuation

Width of Egress Door	Evacuation Time	Improvement
0.80m	1046s (17:26 mins)	(-15%)
1.00m	909s (15:09 mins)	-
1.20m	888s (14:48 mins)	2.3%
1.50m	833s (13:53 mins)	8.3%
2.00m	736s (12:16 mins)	19%
Original evacuation time: 909s (15:09 mins)		

Table 20 Modifying the egress door width for Full occupancy evacuation

Width of Egress Door	Evacuation Time	Improvement
0.80m	1376s (22:56 mins)	(-14%)
1.00m	1201s (20:01 mins)	-
1.20m	1158s (19:18 mins)	3.5%
1.50m	1122s (18:42 mins)	6.5%
2.00m	1029s (17:09 mins)	14%
Original evacuation time: 1201.3s (20:01 mins)		

4.4 PyroSim smoke simulation results

A fire was created near the stairs on the ground floor to see the spread of smoke across the building and through the staircases as shown in Figure 17. Since the maximum total evacuation time of the occupants was 20 minutes, the fire and smoke propagation were also done for 20 minutes to observes it's spread across the building. Figures 18 and 19 show the spread of fire after 3 minutes and 20 minutes respectively.

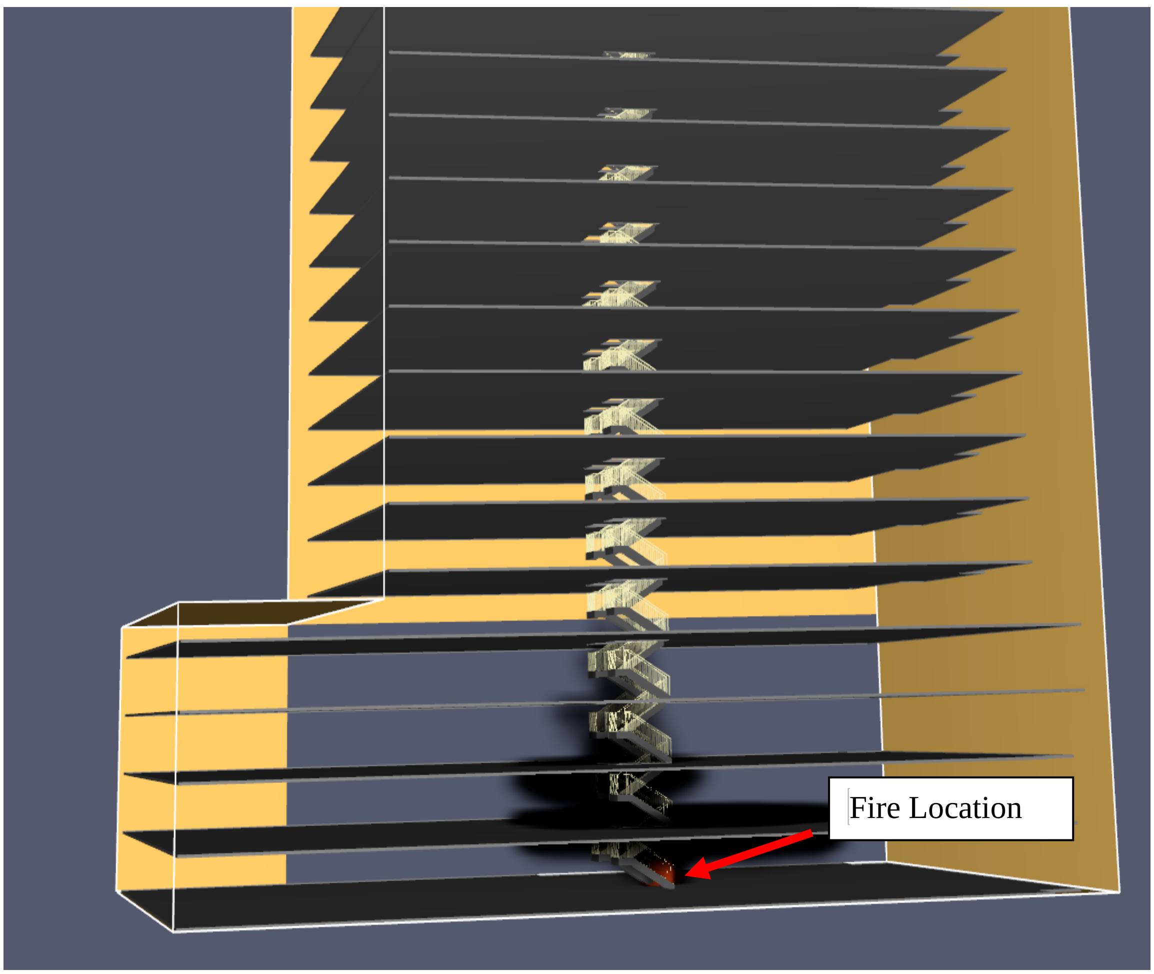


Figure 33 Fire Location and spread inside the building.

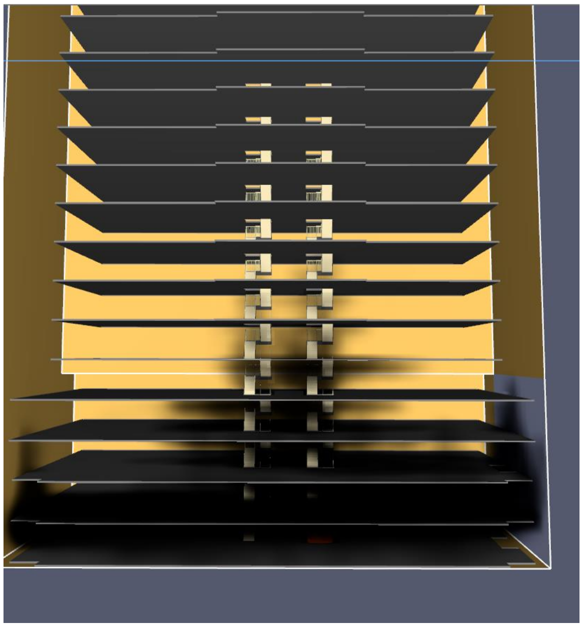


Figure 34 Smoke diffusion after 3:00 minutes of fire

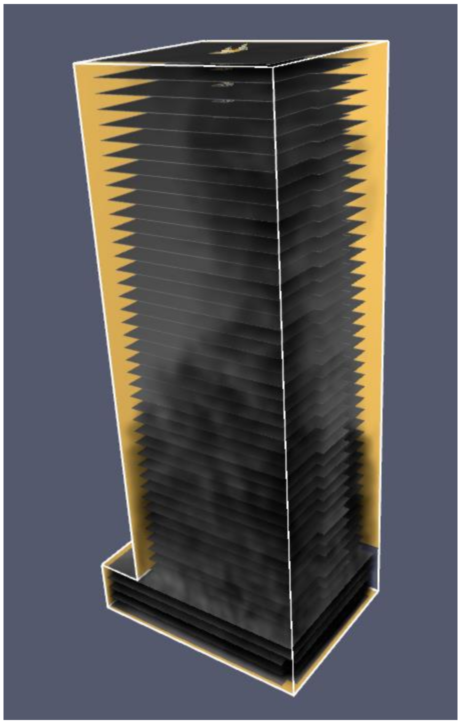


Figure 35 Smoke spread inside the building after 20:00 minutes of fire

4.5 PyroSim integration with Pathfinder

The first 5 floors of the building were modelled in Revit and imported into PyroSim. The reactions added were same as the case study where majority of the things were taken as default settings. The fire was ignited on the ground floor to see the impact of the smoke on the evacuation.

First the evacuation was carried out in Pathfinder for the 5 floors with an occupancy of 80 occupants. The movement speed was assigned 1.05m/s for males and 0.9m/s for females. The occupants' were assigned to go to the nearest exit. The pathfinder evacuation simulation was completed, and occupants exited the building within 134.5 seconds that is 2 minutes and 15 seconds (Figure X).

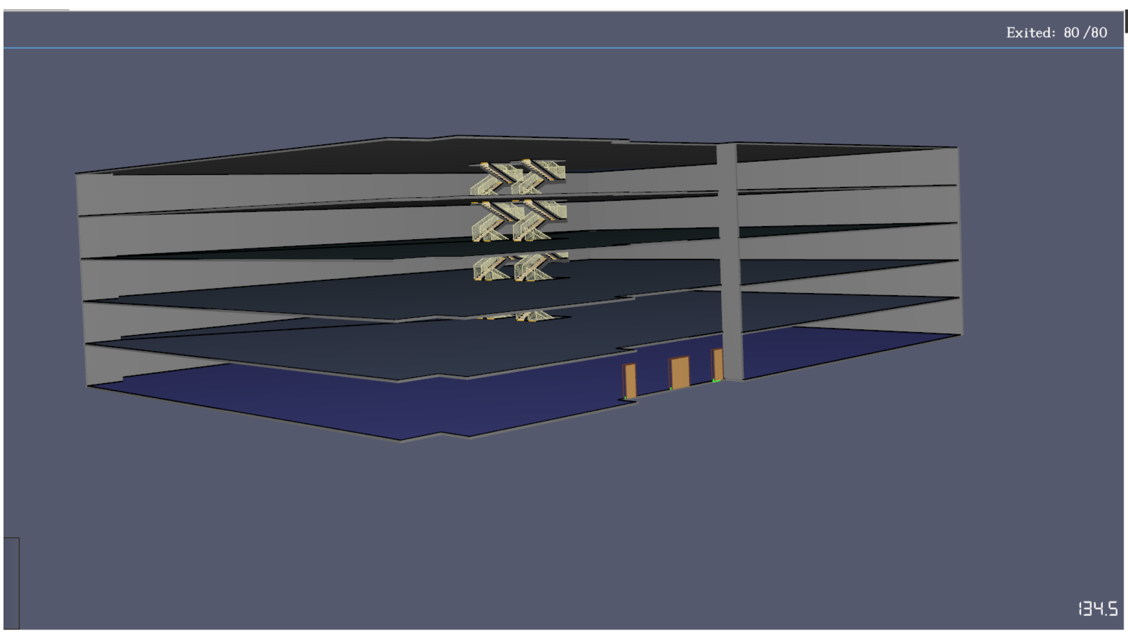


Figure 36 Number of occupants exited in 134.5 seconds

After completing the pathfinder simulation, PyroSim model was imported into the pathfinder software to see the effect of smoke on the evacuation.

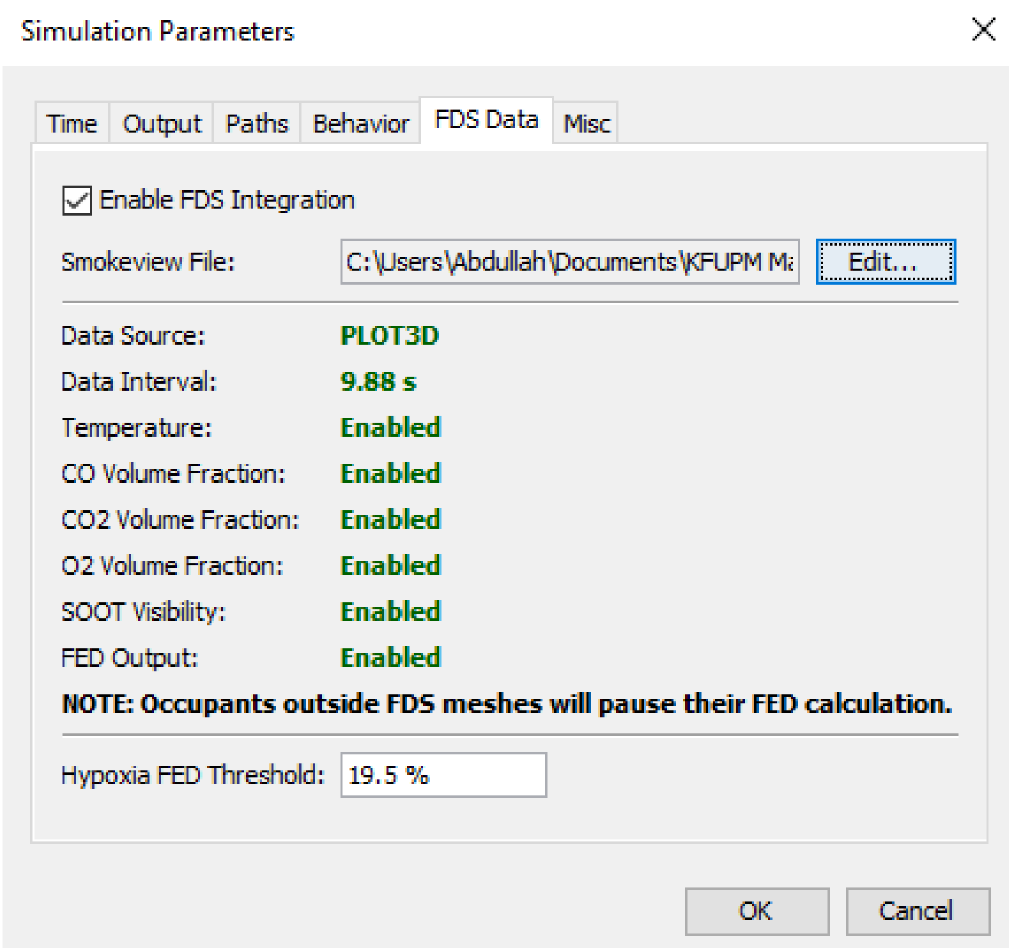


Figure 37 FDS integration settings in Pathfinder

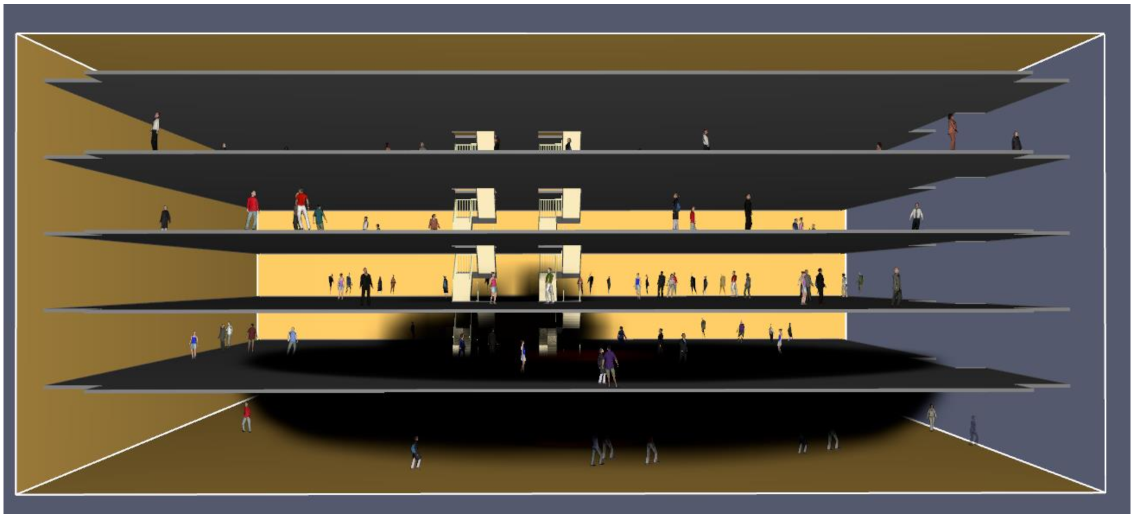


Figure 39 Smoke spread inside the building in 30 seconds

Figure 38 Smoke spread inside the building within 2 minutes

During the simulation, the smoke was allowed to enter the emergency egress, which caused the occupants at the upper floors to halt their evacuation which can be due to lack of visibility. The smoke spread across the ground floor within the first 30 seconds (Figure 40) and reached up to the 5th floor within 2 minutes (Figure 41). Only 12 occupants were able to evacuate in 3 minutes, mainly those who were located on the ground floor. This shows that smoke entering the stairways is a critical issue and can significantly impact the evacuation of the occupants'.

4.6 Discussion

4.6.1 Pathfinder Evacuation

Increasing the width of emergency stairs can have significant benefits for emergency evacuations, such as increasing the capacity of the stairway to accommodate more people and reducing the likelihood of overcrowding, tripping, or falling. The evacuation time with the original design of the building with 60% occupancy was 15:09 minutes. However the design of the stairs was not complying with the Saudi building code as the minimum required width has to be 1100mm. Increasing the width of the stairs to comply with the SBC did not have a significant impact on the reduction of the evacuation time. Although when the simulation was done for full occupancy, the results indicate that an increase in .5m of stairs run width can potentially lower the evacuation time by 4 minutes. However, there are costs associated with widening emergency stairs, such as the cost of materials, labor, and potential disruption to the building's structure.

Simulation for scenario 1 was done by adding an additional egress stair in the building layout, the third staircase did not have a major impact on the evacuation time as the overall evacuation time was reduced by less than 5%. The staircase did not provide any value as only a few occupants' used the egress who were close to it.

Simulation results for the 2nd scenario where the two staircases were placed further from each other had a negative impact on the overall evacuation time. The evacuation time was increased for the original building layout with 60% occupancy by 2 minutes and 6 minutes for full occupancy. The last scenario where the emergency stairs were placed at the edges had a better evacuation efficiency than the 2nd scenario but still worse than the original simulation. The time for evacuation for full occupancy was more by 4 minutes and for 60% occupancy by 1 minute.

The simulation results indicate that adding additional egress was not beneficial, whereas widening emergency stairs can be a worthwhile investment for buildings with high occupancy and frequent evacuations. The cost of widening the stairs should be weighed against the potential benefits in terms of increased safety and improved evacuation times. Building owners and facility managers should consult with experts in building design and safety to determine the best course of action for their specific building and needs.

There are other factors which still must be considered such as the pre-evacuation time. This is the time which the occupants take before actually beginning their evacuation. The delay could be attributed to either investigating the authenticity of the fire incident or being in a state of unconsciousness. In a survey conducted by (Almejmaj and Meacham, 2014) the mean delay time was 90 seconds with a deviation of 30 seconds.

In high-rise buildings, it is important to have a plan in place for pre-evacuation, to ensure that everyone knows what to do in case of an emergency, and to minimize pre-evacuation delays. Authorities and building management should have effective communication channels and systems in place to alert people of an emergency, assess the situation, and give clear and concise instructions for evacuation. By minimizing pre-evacuation delays and having effective evacuation plans in place, people can increase their chances of evacuating safely and efficiently during an emergency.

Crowdedness during emergency evacuation is a significant concern, as it can lead to delays, confusion, and potential safety hazards. When a large number of people are trying to evacuate a building or area at the same time, the flow of movement can be slowed or even come to a complete stop, resulting in potentially dangerous situations such as stampedes or overcrowding in certain areas. From the results of the simulation, the stairs didn't get crowded by the occupants and the flow was smooth. This can be due to the fact that there are 2 separate stairs cases present for emergency evacuation which reduces the crowdedness. Although in real life there can be problems of crowdedness due to human behavior during emergency scenarios.

One more factor which can affect the accuracy of the simulation is the running speed of the occupants. Some occupants might move faster than usual while others might slow down. Fatigue will also come into play especially for those occupants who occupy the higher floors of the building. Wider doors allow for a greater flow capacity, enabling more individuals to evacuate quickly. In contrast, narrow doors can restrict the flow and slow down the evacuation process, potentially leading to congestion and delays.

Results from increasing the building exit doors width were also not significant. As an increase in 20% of the door width resulted in an increase of only 5% in the overall evacuation time. The width of egress doors was also increased to see the impact on the evacuation time. Doubling the width of the egress door improved the evacuation time by 19% for 60% occupancy and by 14% for full occupancy. This is logical as the width of egress doors directly affects the flow capacity.

The flow rates for all the simulations were constant at around 0.65 persons/m. Increasing the building exit door did not improve the flow rate. A study done by (Gwynne *et al.*, 2009) observed an average of 0.77 persons/s flow rate for occupants during an emergency evacuation. Similarly, (Fang *et al.*, 2010) conducted an experiment to analyze the flow rates of the occupants'. The average flow rate of occupants' was 1.25m/s. If we compare the previous data, the flow rate of the case study building seems to be low. There can be many reasons for this, such as the occupant density and crowdedness along with their movement speed. After running all the simulations (Table 23), the original design of the building seemed to be optimum. The increase in number of stairs did not significantly improve the evacuation time and would seem waste of space any money for the building designers and owners.

Additional simulation scenarios were carried out to see the variation of evacuation time with the increase in the number of occupants (Figure 44). It was observed the that the evacuation time increases with the number of occupants' added, however there was not much difference between an occupancy of 1000 and 1400. The occupants' were distributed evenly on each floor according to the occupant load for each floor and after 1400 occupants were added, all the floors had an equal number of occupants. The simulation was carried out for occupancies of 1600, 1800 and 2000. The occupants' were distributed from top to bottom by adding 20 occupants on each floor. This resulted in the increase in the evacuation time significantly as more occupant's were added.

Table 21 Simulations of Staircase design scenarios with 60% occupancy

Simulation No.	Design	Width of run	Evacuation Time (minutes)	Improvement
1	Original plan	1.00m	15:09	-
2	Original plan	1.25m	15:01	.08%
3	Original plan	1.50m	14:16	5.8%
7	3 Stairs	1.00m	15:00	0.1%
9	2 Stairs at distance	1.00m	17:23	(-14.7%)
11	2 Stairs external	1.00m	16:33	(-9.24%)
13	4 Stairs	1.00m	12:25	18%
15	2 stairs at opposite with increased corridor width	1.00m	14:43	2.8%
17	2 Stairs minimum design	1.00m	19:45	(-30%)
19	Only 1 occupant	1.00m	10:07	33%

The Saudi building code currently provides basic guidelines and limitations, which limits the improvement opportunity for the overall safety of the building. Architects and fire safety engineers can further study other important details such as the design of stairs and the optimum door width which results in a lower evacuation time.

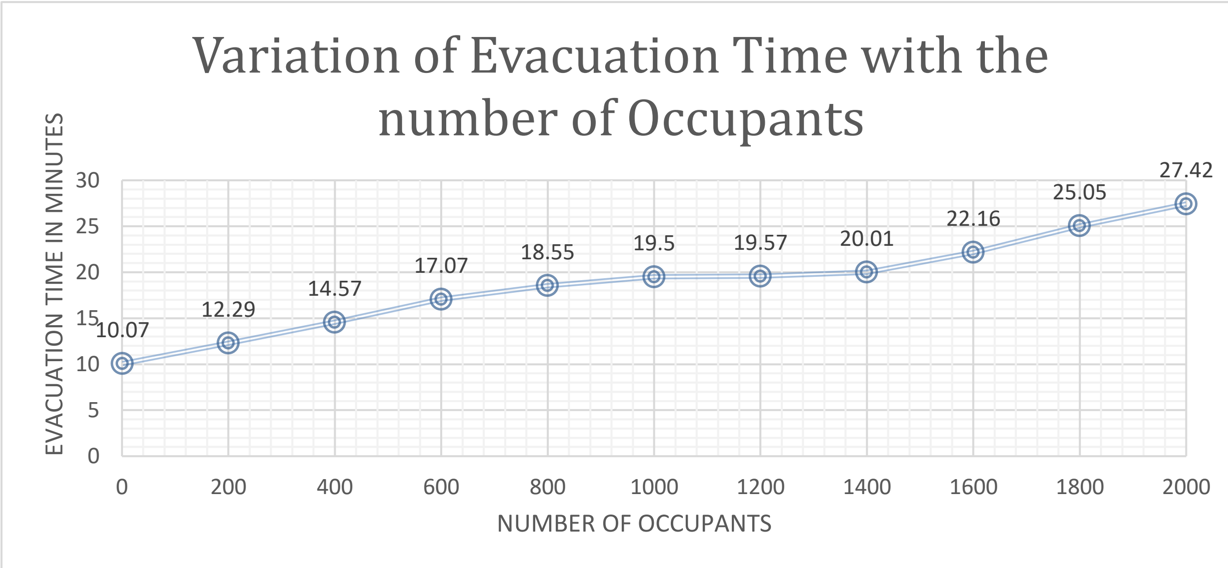


Figure 40 Variation of Evacuation Time with the number of Occupants

4.6.2 PyroSim Smoke Simulation

Smoke can have a significant impact on evacuation time in a fire emergency. Smoke is a major contributor to fire-related deaths and injuries, as it can impair visibility and breathing, making it difficult for people to navigate their way to safety.

When smoke is present, it can reduce visibility and make it difficult for people to see escape routes and obstacles in their path. This can slow down evacuation time as people move more cautiously and may need to feel their way around to avoid tripping or falling. Smoke can also make it difficult for occupants to breathe. If people are struggling to breathe, they may move more slowly and be less able to assist others, which can further delay evacuation efforts.

Furthermore, smoke can create confusion and panic, leading to a breakdown in orderly evacuation procedures. People may become disoriented or unsure of where to go, or they may be tempted to take shortcuts that put them at greater risk. Panic can also lead to congestion and bottlenecks, making it more difficult for people to escape quickly. It is important for facility managers and occupants to have a clear plan in place for dealing with smoke, including measures such as smoke alarms, ventilation systems, and evacuation procedures, to minimize the risk of smoke-related injuries and fatalities.

A fire source was created on the ground floor of the building to access how smoke propagates through the building. Within 3 minutes of the start of the fire, the ground floor and the first floor were fully occupied by smoke as it can be seen in Figure 18. The simulation was run for 20 minutes (Figure 19) as this was the longest time which was needed for occupants to evacuate the building completely. The results indicate that approximately half of the building was filled with smoke and the upper floors had a few particles of smoke as well. While smoke simulation is a powerful tool for improving fire safety and evacuation planning, there are some challenges associated with this technology. PyroSim integration with Pathfinder displayed how smoke can be detrimental if it enters the staircases. Smoke can hinder occupants' evacuation and can put their lives at risk by exposing them to toxic gases and fumes.

The behavior of smoke can vary greatly depending on factors such as the location of the fire, the source of fire, and the materials used in the construction of the building. It can be difficult to accurately model all of these variables and account for their impact on smoke movement. This study does not focus on the interaction of fire with the building materials.

What is beneficial from the simulation is the time it takes for the smoke to spread and how it can be mitigated or managed. Ventilation systems can help to manage smoke by removing it from the building and providing fresh air for occupants to breathe. Fire safety engineers and architects should consider the placement and capacity of ventilation systems to ensure that they can effectively manage smoke in different emergency scenarios.

Additionally, evacuation routes should be designed to minimize the exposure of occupants to smoke. For example, stairwells should be located away from the source of the fire to reduce the amount of smoke that occupants must navigate. In this case study building, both the stairs are next to each other, and it the fire source is close to the stairs then it can be extremely dangerous as it can completely block the escape route.

4.6.3 Smoke control systems

Smoke control systems are crucial in ensuring the safety of occupants' during an emergency fire. One important aspect of these systems is preventing smoke from entering the stairwells, as they serve as vital evacuation routes in high-rise buildings. Smoke-free stairs help maintain visibility, reduce the risk of smoke inhalation, and facilitate safe evacuation. There are several ways to control the smoke from entering the egress. The most commonly used is pressurization systems. This system uses mechanical means to maintain a higher air pressure inside the stairways compared to adjacent spaces. By creating a pressure difference, these systems prevent smoke from infiltrating the stairways. Pressurization can be achieved by using fans or blowers that introduce fresh air into the stairways, pushing out any smoke attempting to enter the space.

Another approach to smoke control involves the use of exhaust systems. These systems remove smoke from the stairs by creating a negative pressure differential. The stairways are maintained at a lower pressure compared to the nearby spaces, causing smoke to be drawn out of the stairs and expelled through dedicated exhaust outlets. Smoke curtains or doors can also be used which act as a physical barrier. These are designed to prevent smoke from migrating into the stairways. These barriers are typically deployed automatically in response to smoke detection or fire alarm signals. They can be made of fire-rated materials and are installed at the entrances to the stairways. When activated, smoke curtains or doors descend or close, creating a barrier that hinders smoke movement.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Answering the research questions

5.1.1 Factors pertaining to emergency evacuation in high-rise buildings

Emergency evacuation in high-rise residential buildings presents unique challenges due to the height of the building, the number of occupants, and the complexity of the building layout. The key factors to consider when planning for emergency evacuation in high-rise residential buildings are as follows:

Building design and layout: The design and layout of the building can greatly impact evacuation times and efficiency. Factors such as the number and location of egress, the width and capacity of the stairs, the location of fire alarms and emergency exits, and the use of fire-resistant materials can all influence the effectiveness of evacuation.

Occupant awareness and education: Occupants of high-rise residential buildings should be aware of emergency procedures and evacuation plans. This may include information on how to safely evacuate the building, where to go once outside, and how to communicate with emergency responders.

Fire detection and suppression systems: Early detection of a fire can greatly reduce the time available for occupants to evacuate the building. Smoke detectors and fire alarms should be installed throughout the building, and suppression systems such as sprinklers can help to contain and extinguish fires before they spread and cause problems.

Emergency response procedures: Effective emergency response procedures are critical for ensuring the safety of building occupants during a fire emergency. The facility management team should have a clear plan for responding to emergencies, including procedures for notifying occupants, coordinating with emergency responders, and managing the evacuation process.

Accessibility and mobility issues: During an emergency evacuation, occupants who have disabilities or mobility issues may need special assistance due to accessibility and mobility issues. Procedures should be in place for the facility management team to assist and accommodate the needs of these occupants.

Communication and coordination: Improved evacuation efficiency can be achieved through effective communication and coordination among building users. Procedures should be in place for the facility management team to communicate with occupants during emergencies and coordinate with emergency responders.

These are some of the key factors to consider when planning for emergency evacuation in high-rise residential buildings. By carefully accounting for these factors, facility managers, fire safety engineers and architects can develop effective emergency evacuation plans and improve overall building safety.

5.1.2 How do the occupants in different facilities behave during emergency evacuations?

Occupants' behavior is critical during emergency evacuations. Occupants behave differently depending on their environment and the type of building they are occupying. Residential building occupants will be more aware of the building layout as compared to a public space. In public spaces such as shopping malls or stadiums, occupants may not be familiar with the emergency procedures and may be disoriented by the unfamiliar surroundings and panic. This can lead to confusion and delays in the evacuation process. Occupants in office buildings are often familiar with the layout of the building and might have participated in emergency fire drills beforehand.

It is important for facility managers to be aware of the potential behaviors and needs of occupants in different types of facilities during emergency evacuations. By understanding how occupants are likely to behave and what their needs may be, fire safety engineers and architects can develop more effective emergency plans and procedures to ensure the safety of all occupants.

5.1.3 What are the inherent limitations in BIM-based simulation for occupant evacuation?

BIM is a powerful tool which can aid in planning and preparing for emergency situations. But there are still some limitations with BIM such as the accuracy of the BIM models itself. The quality and accuracy of the model depends on the data input which can affect the simulation results. Developing a BIM model for a building can be time-consuming and costly. In addition, running simulations using the model can also be time-consuming and may require specialized software and hardware. BIM based models cannot simulate occupant behavior and often have to make assumptions. This can lead to inaccuracy of the simulation results.

BIM-based simulations are based on pre-defined data, and thus it can be difficult to capture real-time data during an actual emergency. This means that the simulation may not accurately reflect the actual conditions of the emergency, which can impact the accuracy of the results. Although BIM-based simulations can model basic smoke and fire dynamics, they may not be able to accurately predict the complex interactions between smoke, fire, and the building environment. This can impact the accuracy of the simulation and limit its usefulness in evaluating fire and smoke dynamics.

5.1.4. What are the future research directions for utilizing smart fire detection and evacuation methods and systems in buildings?

There are several future research directions for utilizing smart fire detection systems and evacuation methods in buildings. First would be the integration of IoT devices such as sensors, cameras, and smart building systems to enhance the effectiveness of fire detection and evacuation methods. Future research could focus on developing new ways to integrate these devices into existing systems and identifying the most effective ways to use these devices in emergency situations.

Real time data processing is also very beneficial in the domain of fire evacuation. By analyzing data in real-time, machine learning and artificial intelligence technologies can enhance fire detection and evacuation methods and provide automated responses to emergency situations directly to the occupants' mobile phones.

Virtual reality and simulation technologies can also be used to create immersive and interactive training programs for emergency responders and building occupants. Future research could focus on developing new training programs that utilize these technologies to enhance the effectiveness of emergency response and evacuation methods. The facility management team of the facility can collect occupant data and run simulations to see the interaction of the occupants with the surroundings.

Lastly, integrating smart fire detection and evacuation systems with existing emergency response systems such as 911 call centers and fire safety team can help to improve the response time and effectiveness of emergency services. Future research may focus on developing new ways to integrate these systems and improving communication and coordination between the building occupants and the fire safety team.

5.2 Conclusion and recommendations for future work

In conclusion, occupant evacuation in high-rise buildings is a complex and challenging process that requires careful planning, design, and execution. Evacuating a large number of people quickly and safely in an emergency situation is a critical concern for building owners, managers, and occupants.

Simulation tools such as PyroSim and Pathfinder can be useful in assessing the effectiveness of evacuation plans and identifying potential hazards and bottlenecks. These software tools allow fire safety engineers and architects to visualize and analyze evacuation scenarios and make informed decisions about building design, layout, and emergency preparedness.

For this case study building, the evacuation time is long, and it can be dangerous to evacuate for occupants living on the higher floors. Smoke should not be allowed to enter the emergency stairs as it's the only way to escape from the building. As seen in the simulation, if smoke enters the egress, it can completely stop the evacuation process and put the occupants' lives at risk. Design of ventilation systems is critical in high-rise buildings and must be paid attention to.

The staircase location and design of the original case study building was adequate when compared to other scenarios which did not improve the evacuation efficiency significantly to warrant a change in design. Therefore, it is recommended that the emergency stairs be located close to each other for buildings which have a similar layout to the case study building studied. Although when the width of the egress door was modified there was an improvement in the evacuation time which shows the importance of having a wider door. This will aid in reducing the crowdedness at the doors and will ease the flow of evacuation. Other evacuation simulation software can be used to verify the accuracy of the results.

The building was also not complying 100% with the Saudi building code as the egress width of the staircase should be a minimum of 1100mm according to the occupancy load.

Using open stairs at the edges of the buildings can be considered for high-rise buildings as smoke can be avoided by using this type of egress. But from the simulation results, the evacuation time was increased as occupants' had to travel longer distances. It is recommended to have at least 1 open stairways in case of smoke entering the stairways which will block the evacuation means.

Research in recent times has been pushing for the use of elevators during fire emergencies. This matter is difficult to implement in high-rise buildings as the lift will keep stopping frequently which might reduce the efficiency of the evacuation. It is recommended that after every 10 floors a refuge floor be labelled in order for elevators to be used only on these specific floors during emergencies and it will only stop on these certain floors. By doing this it can reduce the time wasted by opening and the closing of the door on each floor thus improving the evacuation efficiency.

Implementing a proper communication and notification systems can quickly and effectively alert occupants in the event of an emergency. This may include text message alerts, sirens, or other notification systems. This will help the occupants in making their decision faster weather they want to evacuate or not. This will assist in reducing the pre-evacuation time resulting in a faster evacuation.

Furthermore, to ensure the safety of occupants in high-rise buildings, it is important to have a comprehensive evacuation plan in place that includes clear evacuation routes, adequate signage, and regular training and evacuation drills. The facility manager must also ensure that the building's fire safety systems, such as smoke detectors, alarms, and sprinklers, are regularly maintained and tested. A well-designed and well-executed evacuation plan, along with the use of simulation tools, can greatly enhance the safety and security of occupants in high-rise buildings.

Future work can focus on implementing a proper system and framework for utilizing elevators during emergency fire evacuations. Further study can be done on the impact of the building materials selection and it’s interaction with fire and smoke. New technologies are also present such as smart systems which can help occupants navigate during their evacuation by providing evacuation instructions on their phone devices helping in reducing the overall evacuation time.

Further research can be done on studying the impact of building materials selection and how fire can spread inside the buildings which can affect the occupant’s evacuation.

References

Adams, A. P. M. and Galea, E. R. (2011) ‘An Experimental Evaluation of Movement Devices Used to Assist People with Reduced Mobility in High-Rise Building Evacuations’, *Pedestrian and Evacuation Dynamics*, pp. 129–138. doi: 10.1007/978-1-4419-9725-8_12.

Akashah, F. W. *et al.* (2020) ‘Factors affecting adoption of emergency evacuation strategies in high-rise office buildings’, *Journal of Design and Built Environment*, 20(3), pp. 1–21. doi: 10.22452/jdbe.vol20no3.1.

Almeida, J. E., Rosseti, R. J. F. and Coelho, A. L. (2013) ‘Crowd Simulation Modeling Applied to Emergency and Evacuation Simulations using Multi-Agent Systems’. Available at: http://arxiv.org/abs/1303.4692.

Almejmaj, M. and Meacham, B. J. (2014) ‘The Effects of Culture-Specific Walking Speed and Pre-Movement Data on Egress Modeling in Shopping Malls- A Comparative Analysis’.

Atila, U. *et al.* (2018) ‘SmartEscape: A mobile smart individual fire evacuation system based on 3D spatial model’, *ISPRS International Journal of Geo-Information*, 7(6). doi: 10.3390/ijgi7060223.

Averill, J. D. *et al.* (2005) ‘World Trade Center Disaster Occupant Behavior , Egress , and Emergency Communications’, *Nist Ncstar 1-7*, 7, pp. 1–298.

Baddewithana, G. K. *et al.* (2013) ‘Smart and automated fire and power monitoring system’, *2013 IEEE 8th International Conference on Industrial and Information Systems, ICIIS 2013 - Conference Proceedings*, (December), pp. 542–547. doi: 10.1109/ICIInfS.2013.6732042.

Bernardini, G. *et al.* (2016) ‘characteristics’.

Birajdar, G. S. *et al.* (2021) ‘Realization of people density and smoke flow in buildings during fire accidents using raspberry and opencv’, *Sustainability (Switzerland)*, 13(19). doi: 10.3390/su131911082.

Brennan, P. (1997) ‘Timing Human Response In Real Fires’, *Fire Safety Science*, 5, pp. 807–818. doi: 10.3801/iafss.fss.5-807.

Bukowski, R. W. (2012) ‘Addressing the Needs of People Using Elevators for Emergency Evacuation’, *Fire Technology*, 48(1), pp. 127–136. doi: 10.1007/s10694-010-0180-y.

Chen, C. Y. (2009) ‘A fuzzy-based approach for smart building evacuation modeling’, *2009 4th International Conference on Innovative Computing, Information and Control, ICICIC 2009*, pp. 1200–1203. doi: 10.1109/ICICIC.2009.16.

Chen, T. *et al.* (2013) 'Experimental study of evacuation from a 4-storey building', *Procedia Engineering*, 62, pp. 538–547. doi: 10.1016/j.proeng.2013.08.098.

Cheng, M. Y. *et al.* (2017) 'BIM integrated smart monitoring technique for building fire prevention and disaster relief', *Automation in Construction*, 84(November 2016), pp. 14–30. doi: 10.1016/j.autcon.2017.08.027.

Chu, M. L. and Law, K. H. (2019) 'Incorporating Individual Behavior, Knowledge, and Roles in Simulating Evacuation', *Fire Technology*, 55(2), pp. 437–464. doi: 10.1007/s10694-018-0747-6.

Ding, N. *et al.* (2021) 'State-of-the-art high-rise building emergency evacuation behavior', *Physica A: Statistical Mechanics and its Applications*, 561, p. 125168. doi: 10.1016/j.physa.2020.125168.

Elbehiery, H. (2012) 'Developed Intelligent Fire alarm system', *Journal of American Science*, 8(8), pp. 1016–1025. Available at: http://dx.doi.org/10.1016/j.actamat.2015.12.003%0Ahttps://inis.iaea.org/collection/NCLCollectionStore/_Public/30/027/30027298.pdf?r=1&r=1%0Ahttp://dx.doi.org/10.1016/j.jmrt.2015.04.004.

Fang, H., Lo, S. and Lo, J. T. Y. (2021) 'Building fire evacuation: An IoT-aided perspective in the 5G era', *Buildings*, 11(12), pp. 1–24. doi: 10.3390/buildings11120643.

Fang, Z. *et al.* (2010) 'Experiment and modeling of exit-selecting behaviors during a building evacuation', *Physica A*, 389(4), pp. 815–824. doi: 10.1016/j.physa.2009.10.019.

Ferraro, V. and Settino, J. (2019) *Evacuation and smart exit sign system*, *Internet of Things*. Springer International Publishing. doi: 10.1007/978-3-319-96550-5_15.

Filippidis, L. *et al.* (2006) 'Representing the influence of signage on evacuation behavior within an evacuation model', *Journal of Fire Protection Engineering*, 16(1), pp. 37–73. doi: 10.1177/1042391506054298.

Garcia-Martin, R., González-Briones, A. and Corchado, J. M. (2019) 'Smartfire: Intelligent platform for monitoring fire extinguishers and their building environment', *Sensors (Switzerland)*, 19(10), pp. 1–19. doi: 10.3390/s19102390.

Gershon, R. R. M. *et al.* (2007) 'Factors associated with high-rise evacuation: Qualitative results from the world trade center evacuation study', *Prehospital and Disaster Medicine*, 22(3), pp. 165–173. doi: 10.1017/S1049023X0000460X.

Gholizadeh, P., Behzad, E. and Memarian, B. (2018) 'Construction Research Congress 2018 725', *Construction Research Congress 2018 Downloaded*, 2010(2012), pp. 725–735.

Groner, N. (2014) 'Human Factors Considerations in the Potential for Using Elevators in Building NIST-GCR-92-6 15 Human Factors Considerations in the Potential for Using Elevators in Building Emergency Evacuation Plans Office of Real Property Management and Safety', (September).

Gwynne, S. M. V *et al.* (2009) ‘Questioning the linear relationship between doorway width and achievable flow rate’, 44, pp. 80–87. doi: 10.1016/j.firesaf.2008.03.010.

Hsu, H. P. *et al.* (2014) ‘Emergency evacuation base on intelligent digital signage systems’, *Proceedings - 2014 7th International Conference on Ubi-Media Computing and Workshops, U-MEDIA 2014*, pp. 243–247. doi: 10.1109/U-MEDIA.2014.31.

Huang, J. and Fan, Z. (1989) ‘Analysis of Vivaldi antennas’, *IEE Conference Publication*, (301 pt 1), pp. 206–208.

Iftekharul, M. *et al.* (2016) ‘An Intelligent Fire Detection and Mitigation System Safe from Fire (SFF)’, *International Journal of Computer Applications*, 133(6), pp. 1–7. doi: 10.5120/ijca2016907858.

Johnsaida, N., Rahul, L. V and Shalini, T. (2018) ‘IOT Based Smart Fire Emergency Response System’, *2017 3rd International Conference on Applied and Theoretical Computing and Communication Technology (iCATccT)*, 3, pp. 194–199.

Johnson, N. R. and Feinberg, W. E. (1997) ‘The impact of exit instructions and number of exits in fire emergencies: A computer simulation investigation’, *Journal of Environmental Psychology*, 17(2), pp. 123–133. doi: 10.1006/jevp.1997.0047.

Joshi, G. *et al.* (2020) ‘Developing intelligent fire alarm system and need of UAV’, *Lecture Notes in Civil Engineering*, 51(March 2021), pp. 403–414. doi: 10.1007/978-3-030-37393-1_33.

Khan, A. *et al.* (2019) ‘An IoT Based Intelligent Fire Evacuation System’, *2018 21st International Conference of Computer and Information Technology, ICCIT 2018*, (February). doi: 10.1109/ICCITECHN.2018.8631945.

Khisty, C. J. (1985) ‘Pedestrian Flow Characteristics on Stairways During Disaster Evacuation.’, *Transportation Research Record*, pp. 97–102.

Kinateder, M. *et al.* (2014) ‘Social influence in a virtual tunnel fire - Influence of conflicting information on evacuation behavior’, *Applied Ergonomics*, 45(6), pp. 1649–1659. doi: 10.1016/j.apergo.2014.05.014.

Kinateder, M. T. and Kuligowski, E. D. (1825) ‘NIST Technical Note 1825 The Use of Elevators for Evacuation in Fire Emergencies in International Buildings NIST Technical Note 1825 The Use of Elevators for Evacuation in Fire Emergencies in International Buildings’.

Kodali, R. K. and Yerroju, S. (2018) ‘IoT based smart emergency response system for fire hazards’, *Proceedings of the 2017 3rd International Conference on Applied and Theoretical Computing and Communication Technology, iCATccT 2017*, 1(8), pp. 194–199. doi: 10.1109/ICATCCT.2017.8389132.

Koo, J. *et al.* (2013) ‘A comparative study of evacuation strategies for people with disabilities in high-rise building evacuation’, *Expert Systems with Applications*, 40(2), pp. 408–417. doi: 10.1016/j.eswa.2012.07.017.

Kuligowski, E. (2013) ‘Predicting Human Behavior During Fires’, *Fire Technology*, 49(1), pp. 101–120. doi: 10.1007/s10694-011-0245-6.

Kuligowski, E. D. and Mileti, D. S. (2009) ‘Modeling pre-evacuation delay by occupants in World Trade Center Towers 1 and 2 on September 11, 2001’, *Fire Safety Journal*, 44(4), pp. 487–496. doi: 10.1016/j.firesaf.2008.10.001.

Lin, J. *et al.* (2020) ‘How occupants respond to building emergencies: A systematic review of behavioral characteristics and behavioral theories’, *Safety Science*, 122(November 2019), p. 104540. doi: 10.1016/j.ssci.2019.104540.

Liu, Z. and Kim, A. K. (2003) ‘Review of recent developments in fire detection technologies’, *Journal of Fire Protection Engineering*, 13(2), pp. 129–151. doi: 10.1177/1042391503013002003.

Lo, S. M. and Fang, Z. (2000) ‘A Spatial-Grid Evacuation Model for Buildings’, *Journal of Fire Sciences*, 18(5), pp. 376–394. doi: 10.1177/073490410001800503.

Lovreglio, R. and Kinateder, M. (2020) ‘Augmented reality for pedestrian evacuation research: Promises and limitations’, *Safety Science*, 128, pp. 1–20. doi: 10.1016/j.ssci.2020.104750.

Lujak, M. *et al.* (2017) ‘A distributed architecture for real-time evacuation guidance in large smart buildings’, *Computer Science and Information Systems*, 14(1), pp. 257–282. doi: 10.2298/CSIS161014002L.

Luo, L. *et al.* (2008) ‘Agent-based human behavior modeling’, *Computer Animation And Virtual Worlds*, (August), pp. 271–281. doi: 10.1002/cav.

Maclennan, H. A. (1986) ‘Towards an Integrated Egress/Evacuation Model Using an Open Systems Approach.’, pp. 581–590. doi: 10.3801/iafss.fss.1-581.

Majumder, S., O’Neil, S. and Kennedy, R. (2018) ‘Smart apparatus for fire evacuation - An IoT based fire emergency monitoring and evacuation system’, *2017 IEEE MIT Undergraduate Research Technology Conference, URTC 2017*, 2018-Janua, pp. 1–4. doi: 10.1109/URTC.2017.8284186.

Meacham, B. J. (1999) ‘Integrating human behavior and response issues into fire safety management of facilities’, *Facilities*, 17(9), pp. 303–312. doi: 10.1108/02632779910278719.

Minegishi, Y. (2021) ‘Occupant evacuation elevators as a measure for crowd management and evacuation for people with mobility impairments in high-rise buildings’, *Japan Architectural Review*, 4(2), pp. 391–402. doi: 10.1002/2475-8876.12219.

Muhdi, R., Davis, J. and Blackburn, T. (2006) ‘Improving occupant characteristics in performance-based evacuation modeling’, *Proceedings of the Human Factors and Ergonomics Society*, pp. 1199–1203. doi: 10.1177/154193120605001118.

Nguyen, V. Q. *et al.* (2022) ‘A Smart Evacuation Guidance System for Large Buildings’, *Electronics (Switzerland)*, 11(18), pp. 1–16. doi: 10.3390/electronics11182938.

Ortakci, Y. *et al.* (2017) ‘Comparison of a smart mobile application-supported evacuation system and traditional evacuation systems’, *1st IAG Workshop on …*. Available at: https://web.karabuk.edu.tr/ismail.karas/files/4_3D_GeoInfo_2017_Manuscript_21.pdf.

Oven, V. A. and Cakici, N. (2009) ‘Modelling the evacuation of a high-rise office building in Istanbul’, *Fire Safety Journal*, 44(1), pp. 1–15. doi: 10.1016/j.firesaf.2008.02.005.

Owen, M., Galea, E. and Lawrence, P. (1997) ‘Advanced Occupant Behavioural Features Of The Building-exodus Evacuation Model’, *Fire Safety Science*, 5, pp. 795–806. doi: 10.3801/iafss.fss.5-795.

Pan, X. and Han, C. (2006) ‘A computational framework to simulate human and social behaviors for egress analysis’, *… on Computation and …*, pp. 1–10. Available at: http://www.australianscience.com.au/google/33425.pdf.

Park, H. *et al.* (2018) ‘BIM-based Virtual Reality and Human Behavior Simulation For Safety Design’, *Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe*, 2, pp. 823–832. doi: 10.52842/conf.ecaade.2018.2.823.

Pessiot, J. F. *et al.* (2010) ‘NRC Publications Archive (NPArC) Archives des publications du CNRC (NPArC)’, *Information Processing and Management*, 46(2), pp. 180–192.

Poon, L. (1994) ‘Evacsim: A Simulation Model Of Occupants With Behavioural Attributes In Emergency Evacuation Of High-rise Building Fires’, *Fire Safety Science*, 4, pp. 681–692. doi: 10.3801/iafss.fss.4-681.

Proulx, G. (1995) ‘Evacuation time and movement in apartment buildings’, *Fire Safety Journal*, 24(3), pp. 229–246. doi: 10.1016/0379-7112(95)00023-M.

Proulx, G. (1999) ‘Occupant response during a residential highrise fire’, *Fire and Materials*, 23(6), pp. 317–323. doi: 10.1002/(sici)1099-1018(199911/12)23:6<317::aid-fam705>3.3.co;2-q.

Proulx, G. and Pineau, J. (1996) ‘Differences in the evacuation behaviour of office and apartment building occupants’, *Proceedings of the Human Factors and Ergonomics Society*, 2, pp. 825–829. doi: 10.1177/154193129604001607.

Proulx, G. and Reid, I. M. A. (2006) ‘Occupant behavior and evacuation during the Chicago Cook County administration building fire’, *Journal of Fire Protection Engineering*, 16(4), pp. 283–309. doi: 10.1177/1042391506065951.

Purser, D. (2003) ‘ASET and RSET: Addressing some issues in relation to occupant behaviour and tenability’, *Fire Safety Science*, pp. 91–102. doi: 10.3801/IAFSS.FSS.7-91.

Ran, H., Sun, L. and Gao, X. (2014) ‘Influences of intelligent evacuation guidance system on crowd evacuation in building fire’, *Automation in Construction*, 41, pp. 78–82. doi: 10.1016/j.autcon.2013.10.022.

Ronchi, E. and Nilsson, D. (2013) ‘Fire evacuation in high-rise buildings: a review of human behaviour and modelling research’, *Fire Science Reviews*, 2(1), p. 7. doi: 10.1186/2193-0414-2-7.

Ryu, C. S. (2015) ‘IoT-based intelligent for fire emergency response systems’, *International Journal of Smart Home*, 9(3), pp. 161–168. doi: 10.14257/ijsh.2015.9.3.15.

Safayet, M. A., Rahman, M. and Anam, S. M. A. (2021) ‘Development of building information modeling (Bim)-based real-time fire alert system to reduce fire impact in bangladesh’, *Jordan Journal of Civil Engineering*, 15(3), pp. 421–434.

Saunders, W. (1997) ‘Occupant Decision Making In Office Building Fire Emergencies: Experimental Results’, *Fire Safety Science*, 5, pp. 771–782. doi: 10.3801/iafss.fss.5-771.

Shi, J., Ren, A. and Chen, C. (2009) ‘Agent-based evacuation model of large public buildings under fire conditions’, *Automation in Construction*, 18(3), pp. 338–347. doi: 10.1016/j.autcon.2008.09.009.

Shields, T. J. *et al.* (1999) ‘Evacuation behaviours of occupants with learning difficulties in residential homes’, *Disability and Rehabilitation*, 21(1), pp. 39–48. doi: 10.1080/096382899298089.

Shields, T. J. and Boyce, K. E. (2000) ‘Study of evacuation from large retail stores’, *Fire Safety Journal*, 35(1), pp. 25–49. doi: 10.1016/S0379-7112(00)00013-8.

Shields, T. J. and Proulx, G. (2000) ‘The science of human behaviour: Past research endeavours, current developments and fashioning a research agenda’, *Fire Safety Science*, (April), pp. 95–114. doi: 10.3801/iafss.fss.6-95.

Tien Doan, D. *et al.* (no date) ‘What is BIM? A Need for A Unique BIM Definition’. doi: 10.1051/matecconf/2019.

Wang, F. *et al.* (2021) ‘Simulation Research on Fire Evacuation of Large Public Buildings Based on Building Information Modeling’, *Complex System Modeling and Simulation*, 1(2), pp. 122–130. doi: 10.23919/csms.2021.0012.

Wang, Y., Kyriakidis, M. and Dang, V. N. (2021) ‘Incorporating human factors in emergency evacuation – An overview of behavioral factors and models’, *International Journal of Disaster Risk Reduction*, 60, p. 102254. doi: 10.1016/j.ijdrr.2021.102254.

Weinroth, J. (1989) ‘An adaptable microcomputer model for evacuation management’, *Fire Technology*, 25(4), pp. 291–307. doi: 10.1007/BF01040378.

Yan, F. *et al.* (2019) ‘Smart fire evacuation service based on internet of things computing for Web3D’, *Journal of Internet Technology*, 20(2), pp. 521–532. doi: 10.3966/160792642019032002019.

Yang, J., Shi, M. and Han, Z. (2015) ‘Research Intelligent Fire Evacuation System Based on Ant Colony Algorithm and MapX’, *Proceedings - 2014 7th International Symposium on Computational Intelligence and Design, ISCID 2014*, 2, pp. 100–103. doi: 10.1109/ISCID.2014.35.

Yang, L. *et al.* (2004) ‘A microcosmic discrete occupant evacuation model based on individual characteristics’, *Science in China, Series E: Technological Sciences*, 47(5), pp. 608–615. doi: 10.1360/03ye0292.

Yang, L., Fang, W. and Fan, W. (2003) ‘Modeling occupant evacuation using cellular automata - Effect of human behavior and building characteristics on evacuation’, *Journal of Fire Sciences*, 21(3), pp. 227–240. doi: 10.1177/0734904103021003004.

Yang, L. Z. *et al.* (2005) ‘Simulation of the kin behavior in building occupant evacuation based on Cellular Automaton’, *Building and Environment*, 40(3), pp. 411–415. doi: 10.1016/j.buildenv.2004.08.005.

Yasemin, A., Doğan, M. and Bayramlı, E. (2009) ‘The effect of red phosphorus on the fire properties of intumescent pine wood flour – LDPE composites Yasemin’, *Finnish-Swedish Flame Days 2009*, (August 2008), p. 4B. doi: 10.1002/fam.

Zhang, X., Li, X. and Hadjisophocleous, G. (2013) ‘A probabilistic occupant evacuation model for fire emergencies using Monte Carlo methods’, *Fire Safety Journal*, 58, pp. 15–24. doi: 10.1016/j.firesaf.2013.01.028.

Zhiming, F. *et al.* (no date) ‘Experimental study on determinants of the evacuation performance in the super-high-rise building’, *Arxiv.Org*. Available at: https://arxiv.org/abs/2004.04310.

Zhu, K. J. and Shi, Q. (2016) ‘Experimental Study on Choice Behavior of Pedestrians during Building Evacuation’, *Procedia Engineering*, 135, pp. 207–216. doi: 10.1016/j.proeng.2016.01.110.

Saudi building code (801) – 2018

Pathfinder - 2023.2.0816 retrieved from https://www.thunderheadeng.com/

PyroSim 2023.2.0816 retrieved from https://www.thunderheadeng.com/

Vitae

Name	:Abdullah Ehtesham Akbar
Nationality	:Indian
Date of Birth	:5/25/1998
Email	:abdullah98ehtesham@gmail.com
Address	:Flat 503 Marvel Mansion, Mehdipatnam, Hyderabad PIN:500028, Telangana, India
Academic Background	:Architectural Engineering

WORK EXPERIENCE

Architectural Engineer (Part Time) — **May. 2021 – Present**

Mazaya Althamina General Contracting — Dammam, KSA

Duties and Responsibilities:

- Designing Projects in 2D and Making 3D renders using AutoCAD, Revit and Enscape.
- Studying the project contract documents (Time schedule, project design drawings, BOQ, etc.).
- Analyzed project data to prepare quantity of materials and costs of works using AutoCAD, Revit and Excel.
- Assisting in preparing Commercial and Technical proposals for Tenders.
- Consulting with clients on building projects and solving technical issues.
- Working closely with the project manager to ensure the projects are going as planned.

EDUCATION

King Fahd University of Petroleum and Minerals (KFUPM)
Sep. 2021 – Present
Master of Science in Architectural Engineering (GPA 3.75/4.00)

Dhahran, KSA

- Specializing in Facilities Management

Imam Abdulrahman Bin Faisal University (IAU)

May 2016 – May 2021

Bachelor of Science in Building Engineering (GPA 4.21/5)

Dammam, KSA

- Senior Thesis Project on "Effectiveness of Implementing Green buildings in Saudi Arabia"
- Complete building design projects on (High School Building, Office building and Metro Station)

SKILLS & CERTIFICATIONS

Software Skills:

Proficient in: AutoCAD, Revit (BIM), Enscape, Microsoft (Word, Excel, PowerPoint)

Working Knowledge: Primavera P6, Design Builder, DIALux evo 9.1, STAAD.Pro and E-Quest

Certifications:

IELTS Academic Test Band - **(7.5)** – 2021

Registered in Saudi Council of Engineers **(SCE)** - 2021

Spoken English volunteer teacher – **(3 months)** – 2020