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FRAMEWORK FOR SENSOR BASED PHASED EVACUATION FROM A HIGH-RISE BUILDING

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International Master of Science in Fire Safety Engineering

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Abstract

Over the past years, many high-rise building fire incidents have highlighted the significance of evacuation strategies for such structures. In many of such incidents a clear failure of pre-planned evacuation strategy could be found. The failure of these strategies can be attributed to their dependence on multiple factors, including human behaviour, building dimensions and construction materials, and most importantly, the fire dynamics. Pre-planning an evacuation strategy that considers these complex factors poses a considerable challenge. It is equally challenging for the firefighters responding such fires. In the interviews conducted with the fire incident controllers, Klein reported the unavailability of any standard procedure to fight a high-rise building fire, because of that critical decisions are made relying on the previous experiences and the limited visual information from the building's exterior. Gauging the extent of fire from outside the building is firstly inappropriate and increases the chance of human error.

One of the most effective way to evacuate a high-rise building is utilizing the phased evacuation strategy. A case study is performed to compare two commonly used evacuation strategies (simultaneous & phased evacuation) using the Pathfinder program. The results clearly depict that using phased evacuation algorithm proposed by Gravit prioritize those who were immediate risk of fire. This significantly reduces the evacuation time for those occupants & the overall density in the evacuation pathways also remains less. This will ensure their safety and an overall streamline evacuation without any congestion. However, the main problem lies in the implementation of strategy and static nature of the algorithm.

The advancement in the technology and development of AI and machine learning has resulted in installation of sensors in the modern-day buildings. Till now, the sensors data is used majorly for comfort, energy management and security applications as pointed out by Hamins. The same data could be utilized for the fire safety applications & specifically for strategizing an evacuation in this case. A framework for a smart phased evacuation system is therefore provided in this thesis.

The proposed smart phased evacuation system will take its input from the sensors to detect a fire and to analyse the number of occupants present in real time. The system will run the algorithm using these inputs and will formulate an evacuation strategy. The implementation of the strategy

would be done by using an evacuation fire alarm for the floors which need to evacuate immediately, and voice alarms will be used to instruct the remaining floor occupants. With that, the system will continue the monitoring of the building and will update the strategy in case the fire spread is detected in a manner different from what is described in the proposed algorithm. In this way the system will provide a real-time and a dynamic evacuation strategy.

For the future scope, the major task would be developing a system based on the proposed framework and its implementation in a real building. When implemented, the system would be another big step towards the overall smart firefighting framework proposed by Hamins.

Contents

Chapter – 1 Introduction **1**
1.1 Objective.. 2
1.2 Thesis outline 3
1.2 Thesis delimitations... 4
1.4 Thesis limitations 5
Chapter -2 Literature Review **6**
2.1 Smart Evacuation & Navigation System... 11
2.1.1 History.. 11
2.2 Existing evacuation system 13
Chapter 3 Model Case Study **17**
3.1 Phased evacuation from iGent building... 17
3.2 Limitations of case study 18
3.3 Model Setup 18
3.4 Pathfinder... 19
3.4.1 Occupant modelling.. 19
3.4.2 Merging effect in Pathfinder 20
3.4.3 Route choice in Pathfinder... 21
3.5 Test cases.. 22
3.6 Phased evacuation delays 23
3.7 Model Validation.. 24
3.8 Results and discussion for simulation 25
3.8.1 Comparison of evacuation time 30
3.8.2 Average congestion time 32
Chapter 4 – Framework for smart phased evacuation system **35**
4.1 Architecture for smart phased evacuation from high rise building 36

4.2 Hardware required for the system 39
4.3 System Working 42
Chapter 5 Conclusion 44
Chapter 6 Future scope 46
Acknowledgements..47
References 48
Appendix 51
Case studies of some infamous incidents 51

List of figures

Figure 1 Thesis Outline

Figure 2 Examples where trench effect was observed. Left: Fire in residential high-rise building in Shenyang, China (Huge fire rips through two 25-storey tower blocks in seconds in China | Daily Mail Online)
Right: Hospital fire in Istanbul, Turkey (A hospital is on fire in Istanbul: photos, videos (unian.ua))

Figure 3 Rotational fire spread observed in a building fire (Taken from Peacock et al., n.d.)

Figure 4 Left: Variation of flame speed with the angle (taken from Zhang et al., 2022)
Right: Fire in building of inclined surface (taken from Peacock et al., n.d.)

Figure 5 Left: Applications of smart firefighting system (Hamins et al., 2015) ; Right : Analogy of a smart firefighting system

Figure 6 Scheme for phased evacuation proposed by Gravit et al., 2018

Figure 7 Human flow density results from Gravit et al., 2018

Figure 8 Left: Relation between density and movement speed; Right: density and specific flow (right) (from Gwynne & Rosenbaum, 2016)

Figure 9 iGent Building actual and revit model representation

Figure 10 iGent Building sample floor plan representation

Figure 11 Model setup flow

Figure 12 Pathfinder merging behaviour representation

Figure 13 Case 1: Simultaneous evacuation

Figure 14 Case 2: Phased evacuation - Fire on floor 7th of the building

Figure 15 Case 3: Phased evacuation - Fire on floor 3rd of the building

Figure 16 Initial time delay settings to mimic phased evacuation in Pathfinder

Figure 17 Case 1: Simultaneous evacuation occupant density at time 50 seconds (right loop showing assumed fire floor in case 2)

Figure 18 Case 1: Simultaneous evacuation occupant density at time 200 seconds

Figure 19 Case 2: Phased evacuation – Fire on floor 7 occupant flow at time 50 seconds (Green representing occupants of fire floor and red as occupants of floor above location
Figure 20 Case 2: Phased evacuation – Fire on floor 7 occupant flow at time 160 seconds
Figure 21 Case 2: Phased evacuation – Fire on floor 7 occupant flow at time 540 seconds
Figure 22 Case 2: Phased evacuation – Fire on floor 7 occupant density at time 50 sec
Figure 23 Case 3: Phased evacuation – Fire on 2nd floor occupant density at time 20 sec
Figure 24 Case 3: Phased evacuation – Fire on 2nd floor occupant density at time 170 sec
Figure 25 Case 3: Phased evacuation – Fire on 2nd floor occupant density at time 370 sec
Figure 26 Floor evacuation timing graph (case 1 & case 2)
Figure 27 Floor evacuation timing graph (case 1 & case 3)
Figure 28 Average congestion time graph: Case 1
Figure 29 Average congestion time graph: Case 2
Figure 30 Average congestion time graph: Case 3
Figure 31 Architecture for smart phased evacuation from a high-rise building
Figure 32 Smart phased evacuation system working in an online mode
Figure 33 Smart phased evacuation system working in an offline mode
Figure 35 One Meridian Plaza fire (Source: https://en.wikipedia.org/wiki/One_Meridian_Plaza)
Figure 36 Caracas tower fire, Dubai (Source: https://en.wikipedia.org/wiki/Caracas_tower)
Figure 37 Torch tower fire, Dubai (Source: https://en.wikipedia.org/wiki/Fire_torch_tower)
Figure 38 Grenfell tower fire, London (Source: https://en.wikipedia.org/wiki/Grenfell_tower)

List of tables

Table 1 Constants for Eq. 1 evacuation speed

Table 2 Floorwise initial delay times to simulate phased evacuation

Table 3 Typical list of sensors present in a building

Table 4 Commonly available single board computers

Table 5 Differences between cloud computing and edge computing

List of abbreviations

1. **ANN** – Artificial Neural Network
2. **BIM** – Building Information Modelling
3. **BLE** – Bluetooth Low Energy
4. **CCTV** – Closed Circuit Television
5. **CPS** – Cyber Physical System
6. **IFC** – Industry Foundation Classes
7. **IoT** – Internet of Things
8. **NFPA** – National Fire Protection Association
9. **NIST** – National Institute of Standards and Technology
10. **SFPE** – Society of Fire Protection Engineers

Chapter – 1 Introduction

In an event of a fire, the priority is always to save the life on the occupants and then comes saving the property. Therefore, evacuation is a critical topic that pertains to safety of the occupants in an emergency. With the growth in population, more and more cities are growing in multi direction (especially vertically), meaning that the number of occupants in each building would be much higher. Now, while evacuating from a single-story building might not sound like a difficult task, a high rise multi story building evacuation offers many additional challenges. In an emergency situation, it is not uncommon that occupants are unaware of the available evacuation routes, loses their direction and fails to find a way to the exit or gets trapped in a bottleneck situation. A bottleneck situation occurs when many occupants use the same evacuation route elements and at the same time, this directly results in more evacuation time and serious injuries or casualties (Choi et al., 2021).

The other factor which provides a challenge for the firefighter during an evacuation from a high rise building is limited amount of information available to the firefighters. (*Evacuation from Fire in High-Rise Residential Buildings*, n.d.) reports that there is a significant lack of published academic peer reviewed evidence on how firefighters make decisions on evacuating occupants from high-rise residential buildings in the event of a fire. Still, based on the interview with 26 experienced fire incident commanders, (Klein et al., 2010) found that there is no standard procedure for evacuation or firefighting in a high rise building fire. The decision made by the Incident commander is based on their previous experiences and the limited amount of information they are getting from the fire. This is in line with findings of (Kinsey et al., 2018) & (Cohen-Hatton et al., 2015). This could sometimes have poor implication as seen in case of a Grenfell tower fire incident, where a complete failure of Stay-put evacuation strategy was observed (*GTI - Phase 1 Full Report - Volume 1.Pdf*, n.d.).

In a high-rise building fire, it could be really hard to predict the spread because of very limited information & complex fire nature. Firstly, the construction material/insulation & cladding varies from building to building and so are the passive fire protection measures present inside. Secondly, the weather, wind condition and the origin of fire also plays a major role in fire growth. The fire growth rate may also vary due to factors such as trench effect, corner influence or floor inclination. Therefore, relying completely on past experience may not be the most efficient way of responding to a fire. In providing a framework for smart firefighting, NIST proposes a solution to this problem by developing a system which could provide real time indoor conditions that could assist a fire incident commander in deciding the line of action.

A dynamic system can be built by utilizing real-time data from various sensors present inside a building. In modern day buildings, sensors installed for majorly comfort, energy management and security applications are not utilized for fire safety as pointed out by (Hamins et al., 2015) & (Chevin, 2020). The input from the same sensors could be used to determine whether it is safe for the occupants to stay inside the building or initiate an evacuation. As described previously, an evacuation from a high-rise building offers different challenges. A smart evacuation system can ensure a streamlined evacuation by preparing a strategy according to the fire location and its spread to prevent any bottleneck situation. Also, input from the occupants and firefighters before and during an emergency event could also provide critical information about the availability of exits. Therefore, a fusion of all data can be done that can be useful for safe & timely evacuation of those who are in immediate vicinity of fire and reduce the chances of fatalities.

1.1 Objective

In the previous section, the need for a smart evacuation system which could provide real time information about the fire location and its spread is identified. This could help in facilitating the evacuation for those who are in immediate vicinity of fire thus facilitating a more effective phased evacuation and could also assist the firefighters to prepare their line of action. Therefore, the final goal of this thesis is to provide a framework for a device that could be used for creating a smart evacuation strategy based on the real time conditions in the building.

In order to do that, the following objectives are identified -

1. Firstly, brief information about existing evacuation strategies will be provided along with case studies of some infamous high rise building fire incidents (in appendix -1).
2. Secondly, a comparison will be made between the full simultaneous evacuation and phased evacuation taking the iGent tower as the subject. The results will be helpful in

understanding the effectiveness of a phased evacuation from a high rise building over simultaneous evacuation

3. Thirdly, a discussion on the already existing smart evacuation models will be presented. This will be done based on the literature review.
4. Lastly, a framework for implementation of smart phased evacuation methods from a high-rise building will be presented along with its usability and limitations.

1.2 Thesis outline

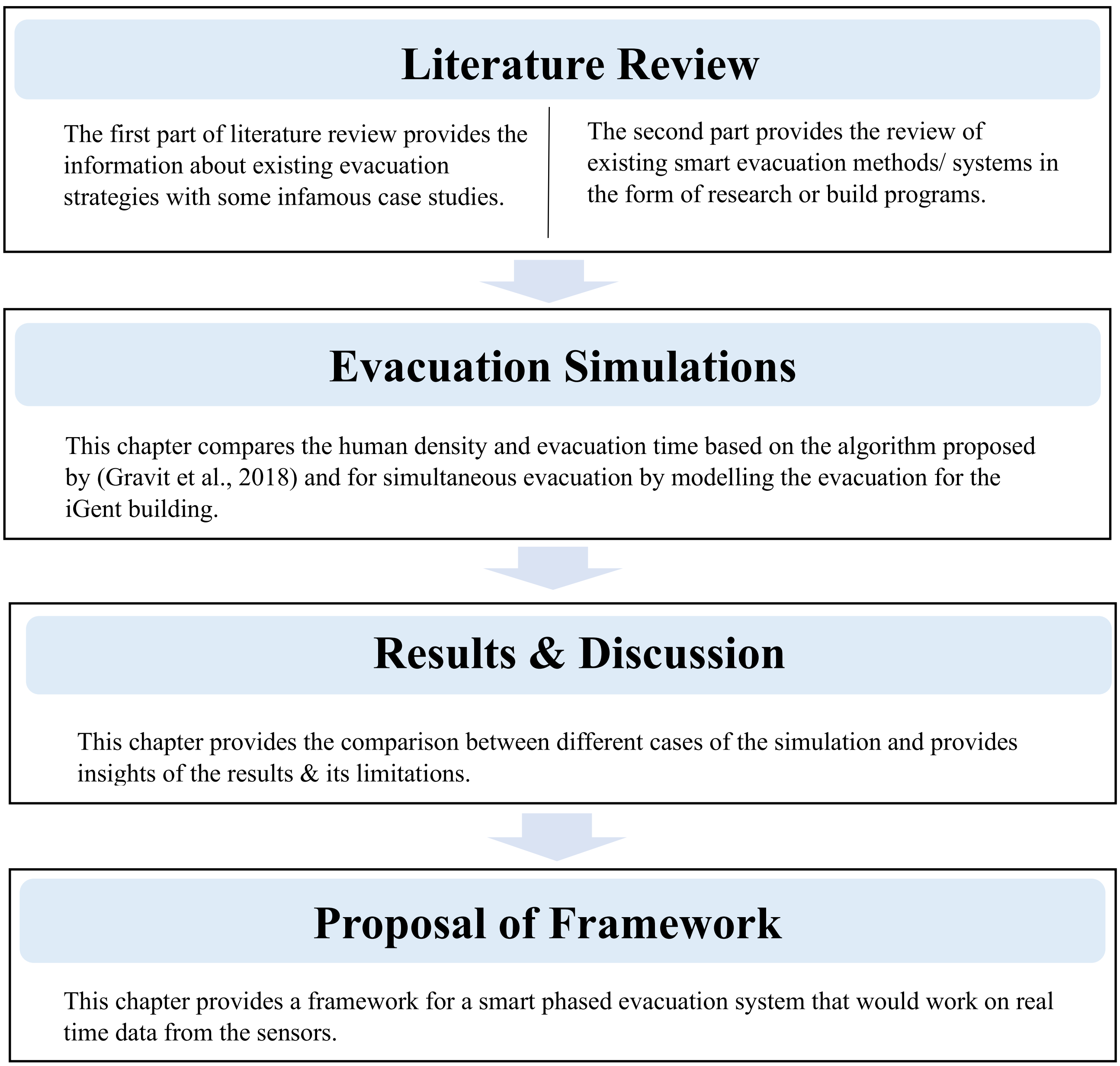


Figure 1 Thesis Outline

1.2 Thesis delimitations

The main focus of this thesis is to understand the existing evacuation strategies for high-rise buildings, their limitations and based on that providing a new framework for smart phased evacuation. Evacuation is a very wide topic therefore it is important to delimit the scope of this thesis. The main delimitations are: -

- Study of human behaviour: This work relies on modelling of evacuation done by the Pathfinder application developed by the thunderhead engineering. The modelling is done by using the steering model which attempts to simulate the human behaviour and movements as closely as possible by using a steering system to move and interact with other occupants (*Pathfinder*, n.d.). No separate study of human behaviour has been done or included in this work.
- Study of occupant characteristics: For performing the evacuation simulations, this work relies on the default human characteristics present in the pathfinder application (details present further in chapter 3). People with disabilities, children and old aged occupants are not counted for the evacuation simulation exercise.
- Study of fire behaviour: Effectiveness of an evacuation is relative to the ASET, which inherently depends on the fire behaviour. It is not possible to include each aspect of fire behaviour in this work. However, some key aspects are touched upon in the literature review. The proposed framework works by detecting various fire signatures which are directly related to the fire growth & its behaviour.
- A high-rise building is typically more than 18m and practically could go up to any height. Based on factors such as building material & passive fire protection measure present in the building, the most suitable strategy may not be phased evacuation but stay put. Therefore, generalising that proposed framework for every building may not be suitable. The suitability of the framework is further discussed in the later chapter of the thesis.

These delimitations are crucial for obtaining more accurate results that correspond to reality. The human behaviour and characteristics may vary from the simulated model and the system may not be able to provide most effective evacuation strategy in a sky scrapper building.

1.4 Thesis limitations

Below are the identified limitations of this thesis: –

1. For the comparative study performed in Chapter -3 of this thesis, no actual evacuation exercise was performed. The comparison relies on the simulation done using the Pathfinder application. Therefore, the limitations valid for the application are valid here as well. These limitations are discussed further in the respective chapter.
2. While proposing the framework, an attempt has been made to address all the practical factors that may appear during the installation of the system. However, due to limited time and resources, the system is not actually installed. Therefore, it could be possible that some issues may arise during the actual installation & working of the system.
3. A major factor for efficient working of the system is the availability of various sensors effectively covering the building area. It is not appropriate to assume that all these sensors will be universally available in every building. Therefore, the effectiveness of the proposed system may vary.

   A list of typical sensors that could be utilised for the proposed system is provided in chapter- 4.
4. In the given limited amount of time, it was hard to do a code compliance study for a newly proposed system. Also, since many of such systems are in the development phase and continuously evolving, no particular system requirements were found in the UK or Bel building regulations.

Similar to the delimitations, the limitations have a direct impact on the usability and the effectiveness of the proposed system. It is suggested that before completely relying on the proposed system for an emergency evacuation, a separate study shall be conducted taking into account factors such as sensor availability, occupant characteristics and the building layout.

Chapter -2 Literature Review

According to The United Kingdom building regulations, a building with more than 7 storeys or height of 18m or above comes under a high-rise building. With time, the number of these high-rise buildings is continuously increasing, but research related to the efficiency of these strategies is very limited. There has been advancement in the technology but, not much advancement is seen in the field of building evacuation. Firstly, it is important to understand what the existing evacuation strategies are and what are their shortcomings.

Currently the evacuation strategy for high-rise buildings is based upon the pre-planning & these strategy generally remains unchanged even after any changes in the building. Broadly, there are 4 main evacuation strategies present (Lay, 2007) (Ronchi & Nilsson, 2013).

* **(**The evacuation strategies remain almost the same everywhere, the names could be different for e.g., Defend-in-place instead of Stay put in United States).

(1) **Simultaneous evacuation** – The approach when no occupants are not expected to remain inside the building for a prolonged time after the onset of a fire alarm. Therefore, all occupants start evacuating at once. (Wood, 1972) found that this is the natural instinctive behaviour of the occupants. But, according to (Lay, 2007), a simultaneous evacuation is not the most effective way to evacuate a high-rise building because the existing escape routes are not capable of accommodating all occupants at the same time. This could lead to congestion and delays in evacuation (Ronchi & Nilsson, 2013). Physically moving all occupants at once could create bottlenecks on the escape routes, further hindering the evacuation process.

(2) **Phased evacuation/Vertical Phased evacuation** - A phased evacuation is a method of evacuating people from an area in stages, rather than all at once. The purpose of a phased evacuation is to allow for a more orderly and controlled evacuation, which can help to minimize confusion and chaos, and ensure that people are able to safely leave the affected area. Phased evacuation is a useful strategy for managing the flow of evacuees and reducing congestion during an emergency such as a fire. However, it can be challenging to determine which floors should be

evacuated first, especially when the situation is rapidly evolving and the current occupancy of the building is unknown. (Lay, 2007) suggests in case of a high-rise building fire where phased evacuation strategy to be used, the fire floor and the floor above (and sometimes below) are evacuated first, but no clear information about how the rest of the building should be evacuated is present. A potential risk of the phased evacuation strategy is occupants becoming impatient and unwilling to wait, which can be addressed through effective communication. Therefore, communication plays a very important role during the phased evacuation. (Kodur et al., 2020) found evacuation time can be reduced by up to 35% when providing occupants with real-time information regarding the fire location, growth and spread, and information regarding available and blocked exits.

(3) **Stay Put** - A stay put evacuation strategy is often implemented in high rise flats or apartments. This strategy relies on effective passive fire protection systems and structural stability to ensure that occupants staying in place remains protected from the fire. For example, if the area is not affected by the fire, the 'Stay Put' strategy recommends remaining inside and not evacuating. This strategy seeks to minimize the number of occupants evacuating by instructing the occupants to stay in their homes and not to evacuate unless directed. (Ronchi & Nilsson, 2013) emphasize the significance of effective communication both before and during the defend-in-place strategy for fire emergencies and it relies on effectiveness of passive fire protection measures present in the building.

(4) **Delayed Evacuation –** Delayed evacuation is a method where the occupants wait at a designated/safer refuge area rather than evacuating to the final exit. This strategy is employed where either the occupants have a permanent disability and need assistance to evacuate or when certain conditions or circumstances make immediate evacuation impractical or hazardous.

Now, the limitation of all the existing evacuation strategies that are used is that they are static in nature. Once planned, the strategies don't generally change with any changes in the building (*Phase 1 Report | Grenfell Tower Inquiry*, n.d.). Fire is a very dynamic phenomenon which depends on different variables, therefore relying completely on a pre-planned strategy may not be the most effective way to handle the situation.

The second most widely used way to strategize a building evacuation is to rely on the instructions provided by the fire incident commander. As also described in Chapter 1, there is no standard operating procedure available for evacuation from a high-rise building (Klein et al., 2010) and then it all depends on the incident commanders past experiences and the limited amount of information he receives mostly from the visuals and information received from the occupants (Hamins et al., 2015). It is emphasized that this report does not intend to cast doubt on the proficiency of esteemed fire responders in any manner. But it is worth mentioning that the behaviour of fire could vary drastically based on various factors, which makes it problematic to just rely on past experience. Some of these factors are explained here

Example of factors that sometimes results in unnatural fire behaviour -

1. Trench effect – Studied after the fire at King's Cross, London, the trench effect occurs when a fire rapidly moves upward in close recess area. This happens because of Coandă effect when the flame lies very close to the surface. Due to the limited space, the fire becomes intense and rapidly moves in an upward direction.

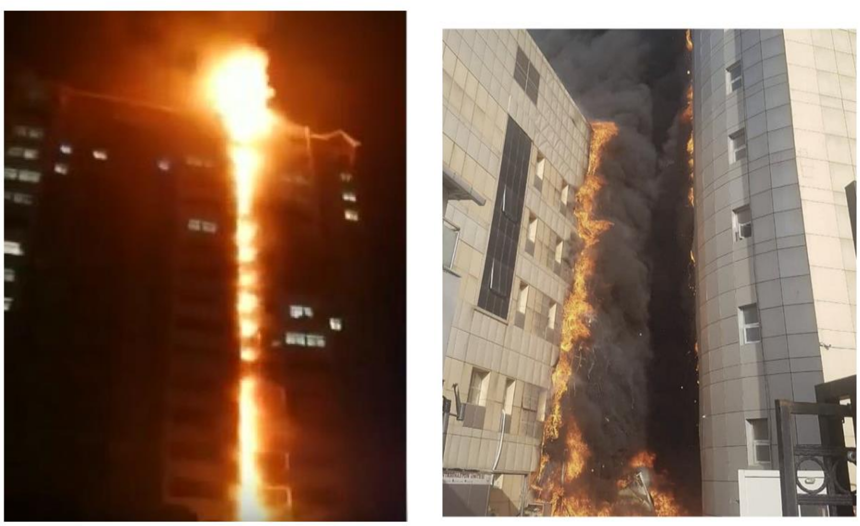


Figure 2 Examples where trench effect was observed. Left: Fire in residential high-rise building in Shenyang, China (Huge fire rips through two 25-storey tower blocks in seconds in China | Daily Mail Online)

Right: Hospital fire in Istanbul, Turkey (A hospital is on fire in Istanbul: photos, videos (unian.ua))

2. Rotational fire spread – In this case, the fire spread occurs at the building's corners without the assistance of the building roof. This typically takes place at lower levels and is impacted by the shape of building corners, as well as any other feature associated to or near the corners, such as string courses and cornices (Peacock, n.d.).

Figure 3 Rotational fire spread observed in a building fire (Taken from Peacock et al., n.d.)

3. Inclined surface – The behaviour of fire can be affected by the surface characteristic of a building. Similar to the trench effect, the Coandă effect becomes evident after a certain angle of inclination. (Zhang et al., 2022) concluded that beyond 20° inclination towards the ground, the flame velocity grows rapidly.

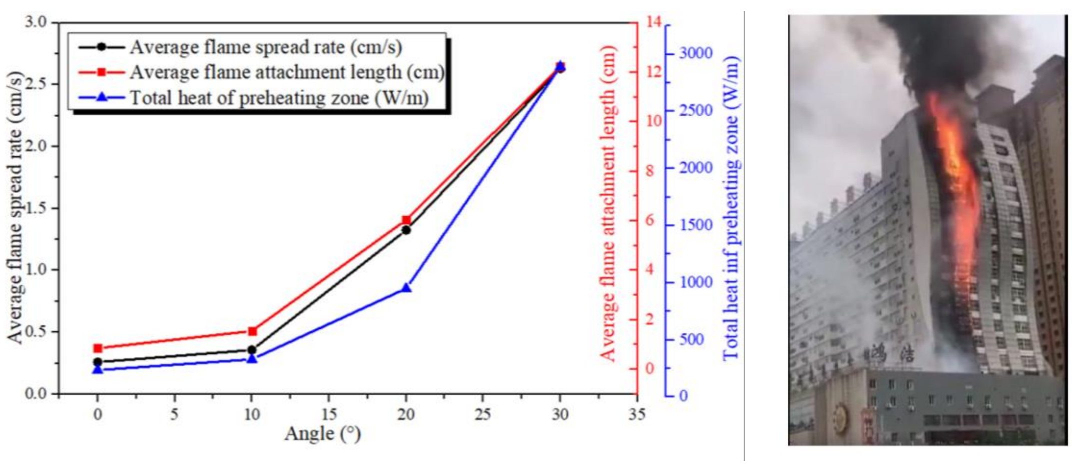


Figure 4 Left: Variation of flame speed with the angle (taken from Zhang et al., 2022)

Right: Fire in building of inclined surface (taken from Peacock et al., n.d.)

4. Insulation or cladding material – The material used for cladding of façade may have a serious impact in case a fire. While not all claddings possess a fire risk, a flammable cladding may produce a large amount of smoke and a rapid growth in fire spread. In

previous years, many unfortunate incidents have happened where due to flammable material or insulation, fire spread rapidly.

Effect of wind and weather condition may also affect the behaviour of fire. The list is not limited to only these factors. For a situation that depends on so many factors and variables, (Hamins et al., 2015) proposed a roadmap to rely on data from the sensors that could provide a real time picture to the occupants and the firefighters as well. The other major benefits of a smart system are as follows: -

1. **Improved situational awareness**: Real-time sensor data can provide building occupants and first responders with detailed information about the location and spread of a fire, helping them to make more informed decisions about evacuation routes and tactics.

2. **Increased safety**: The input from the various sensors can determine the areas with high occupant density and can provide an alternate route for the occupants.

3. **Better evacuation planning**: Real-time sensors can help to identify the location of fire and the system can provide the evacuation strategy based on the real time fire movement to the different floors.

4. **Reduced risk of human error**: Real-time sensor data can help to reduce the risk of human error by automating certain evacuation-related tasks, such as door unlocking and lighting activation.

5. **Increased efficiency and cost savings**: Real-time sensor data can help to improve the efficiency of evacuation procedures by providing accurate and up-to-date information about the building's occupancy and condition, which can reduce evacuation time and costs.

6. **Improved communication**: Real-time sensor data can be used to provide real-time updates and instructions to building occupants and first responders via mobile devices, social media, and other communication channels.

2.1 Smart Evacuation & Navigation System

2.1.1 History

The concept of smart firefighting came up in the early 2000's. A major phase change towards the use of internet for industrial uses was seen during that period. Hamins et al., 2015 called it *The Industrial internet revolution era*. In the pre-2000s era, basic technology such as two-way radios and thermal imaging cameras were used in firefighting operations to improve communication and enhance visibility in smoke-filled environments. However, these technologies were limited in their capabilities and were not widely adopted. In the early 2000s, advancements in sensor technology and communication networks began to be integrated into firefighting operations. Smoke detectors, gas sensors, and heat sensors became more sophisticated and were used to provide real-time data on fire conditions, improving situational awareness for firefighters. Additionally, communication systems, such as mobile radios and data networks, were improved to enable better communication among firefighting teams.

The next step to that advancement came with further development of internet of things. (Hamins et al., 2015) and (Wu et al., 2017) provided a concept for integration and utilization of various types of real-time sensor data from different sources, such as the community, buildings, fire fighters, equipment, and fire apparatus. The concept works by creating a Cyber Physical System (CPS). A CPS integrate the computing and communication capabilities of a system with physical components such as sensors and actuators. (For example - in self-driving cars, the sensors senses the road condition and provides this information to the system which based on machine learning and computation performs an action). Previously, CPS were used in domains such as transportation, manufacturing, healthcare, energy, and infrastructure, and examples include smart grid systems, autonomous vehicles, smart buildings, and wearable health monitoring devices (Patil et al., 2022).

The introduction of CPS for firefighting is very recent. Significant progress has been made in this field over the past few years, with ongoing research and exploration in various branches. Almost every aspect of CPS for firefighting is witnessing the advancements and discoveries.

Few of the domains for a smart firefighting are described here –

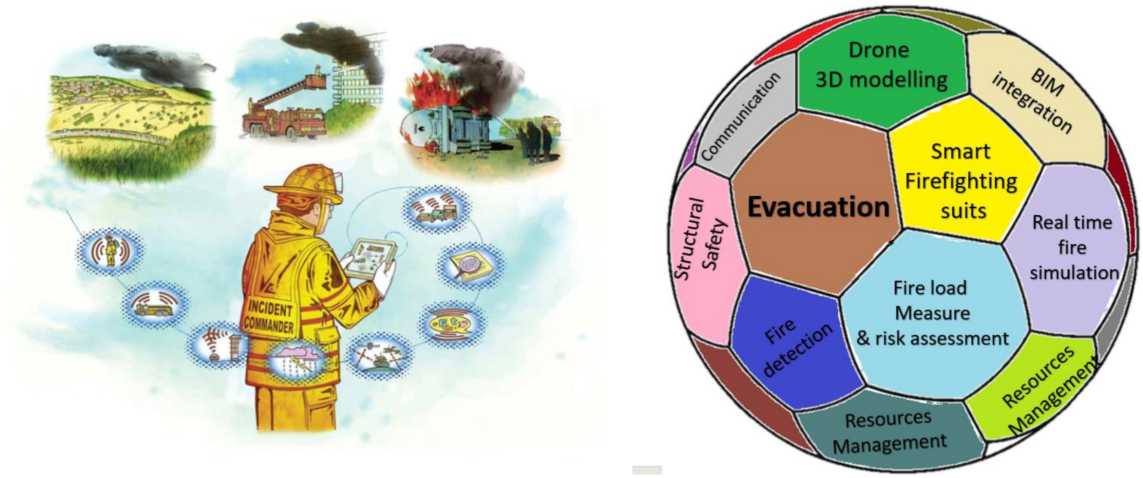


Figure 5 Left: Applications of smart fire fighting system (Hamins et al., 2015) ; Right : Analogy of a smart firefighting system

As an analogy, one could conceptualize the smart firefighting system as a structure resembling a soccer ball, as depicted in Fig – 5 (right). This structure is composed of various modules arranged in the shape of pentagons and hexagons. When integrated, these modules culminate in an efficacious and comprehensive intelligent firefighting solution. It should be noted that this field is presently evolving and developing. Currently, attempts are being made to address individual structures and this report could be taken as an attempt to address one.

Some possible domains with ongoing research are as followed: -

(1) Information about the building – The firefighters and the incident commander can get valuable information related to the accident on the go (for e.g. type of building, location of fire, fuel on fire, number of occupants at risk, evacuation paths available etc.) An early demonstration of it was conducted in 2005 by NIST, Wilson and the North Carolina Fire Department (Reneke, 2013) (Davis et al., 2007).

(2) Smart firefighting suits – Using the smart technology, it could be made sure that firefighters responding are safe by analysing their vitals in real time. (Soukup et al., 2014)

(3) Structural Safety – The stability of a structure is always a major concern during a fire emergency. With the use of sensors placed at strategic location in the building, the structure could be monitored in real time.

(4) Fire load and risk measurement –Constantly changing fire loads can be monitored with the use of AI and Machine learning. When connected with BIM, a real time simulation of a fire can be done. This could help firefighters to understand the growth of fire and take necessary actions in advance.

(5) Evacuation - With the structure becoming more complex, a smart evacuation has been of interest for many researchers around the word. A smart evacuation system could provide an optimum evacuation route by taking into account the predicted fire growth, occupant health conditions and the building layout.

2.2 Existing evacuation system

Significant research has been conducted on safe path prediction in the event of an emergency using various pathfinding methods. However, no work specifically provides a way to evacuate in a phased evacuation manner. Some of the leading studies related to the topic are presented here: -

(Barnes et al., 2007) worked in a similar way as (Li et al., n.d.) & (Tseng et al., 2006) to navigate the occupants to an exit using a 2D plane. A distributed algorithm is used to direct evacuees to exits through complex building layouts in emergency situations. The algorithm uses wireless sensor networks to find the safest paths for evacuees, taking into account the relative movements of hazards, such as fires, and evacuees. But the hazard-based numbering was pre-defined based on the simulation or conservative estimates of emergency engineers.

Shortcoming- Hazards are assigned highest values which can be too conservative, and people would be taking longer routes.

- Does not take into account human factors (their speed/ health condition)
- No human density / flow density is considered.

(Zualkernan et al., 2019) suggested the use IoT technologies to track the location of the fire and building occupants, and then directs the occupants smartly towards a safe exit. The system uses Bluetooth Low Energy (BLE) beacons for indoor localization using the occupant's mobile phones. The system also tracks areas of danger using smoke and temperature sensors. Real-time information gathered from sensors and occupants is also provided to emergency response services.

Shortcomings –

- Does not provide take into account human factors (their speed/ health condition)

- No human density / flow density is considered.

- Vertical evacuation strategy not present

One of the most advanced path predicting mobile application was developed by (Atila et al., 2018). The application was named Smart escape. The real-time, dynamic, Intelligent, and user-specific evacuation system was developed by using a mobile interface for emergency cases such as fire. The application works by collecting various environmental sensory data and takes evacuees' individual features into account, uses an artificial neural network (ANN) to calculate personal usage risk of each link in the building, eliminates the risky ones, and calculates an optimum escape route under existing circumstances.

These technologies provides an excellent medium to predict the path in an emergency but none of this research addresses the question of smart evacuation from a high rise building or simply how a phased evacuation could be strategized based on the real time information from the sensors. (Gravit et al., 2018) provided an algorithm for phased evacuation from a high-rise building. The algorithm is based on the separation of the evacuating people flows and the prevention of their crossing. It describes the process of dividing a section into stages and determining the sequence of evacuation floors. Concepts on which algorithm is based upon –

1. Prioritizing the evacuation of those occupants present on the floor where the fire originated & subsequent floors above and below. This is represented as zone 1 (red) in the Figure 6.
2. Since the fire is more likely to spread upward faster, therefore, consecutive evacuation of floors well above the fire origin. Represented as zone 2 (green)
3. Evacuation of occupants who are present well below the fire origin could be evacuated in a manner to prevent congestion in the staircase. Since these floors are comparatively safer than the above floors therefore these can be treated as 3rd priority. Represented as zone 3 (blue)

Evacuation scheme –

Figure 6 represents floors on the Y-axis and unit time on the X-axis. It is assumed that the fire occurs on the floor-n. (Gravit et al., 2018) came up with the following evacuation scheme –

1. Evacuation from the floors in immediate vicinity (Red zone)
   - 1.1 Evacuate the fire origin floor without any delay.
   - 1.2 n+1 floor (overlaying floor) has to be evacuated such that no interaction occurs with occupants of floor below.
   - 1.3 n+2 floor follows a similar strategy with no interaction with the below floor occupants.

1.4 n-1 floor occupants should start evacuating when all the occupants from the floors above cross through level n-1.
1.5 n+3 floor should start moving after a certain time delay such that a continuous flow could be maintained without any congestion.
1.6 n+4 should evacuate in similar manner as point 1.3
1.7 n-2 should evacuate in similar manner as point 1.4
1.8 n+5, n+6, n-3 and n+7 should evacuate in the same manner as defined in (1.2 – 1.4)

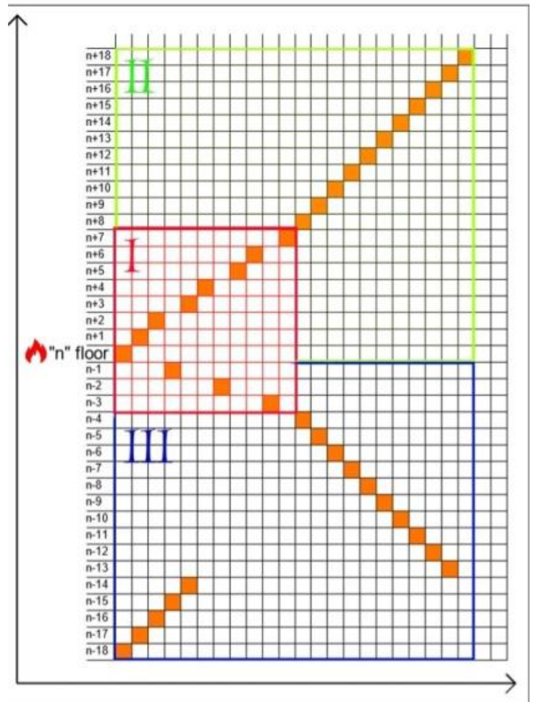


Figure 6 Scheme for phased evacuation proposed by Gravit et al., 2018

2. Second stage evacuation (Zone – 2) – from the floor n+8 onwards consecutive linear floor evacuation shall be commenced such that the flow of occupants remains continuous and without any congestion. This shall be done up to the top floor of the building.
3. Third stage evacuation (Zone – 3) – Evacuation for the floors n-4 and below, the priority is in reverse order as of point 2, that is, n-4 should evacuate first than n-5, n-6 and so on in a continuous linear manner.
4. The floors which are well beyond the fire location and close to the ground level should evacuate in such a manner that no interaction occurs with the occupants coming from the above floors.

Before the simulation results, an important aspect that (Gravit et al., 2018) pointed is that the phased evacuation does not necessarily means an accelerated evacuation, this was evident especially when evacuation timings of simultaneous and phased evacuation were compared. Similar results were presented by (Rahouti et al., 2018) while comparing evacuation strategy for a 12 floor dormitory building. Nevertheless, a phased evacuation focuses on early evacuation of those who are in immediate vicinity of fire. It can be concluded that if implemented correctly, the time an occupant would come in contact with smoke or high temperature during a phased evacuation & the overall density would be lesser as compared to situation where everyone evacuates at the same time. Also, a less occupant density could directly be linked with a lower risk of injury and potential overlapping of paths during the evacuation (Thompson et al., 2018).

For implementing the algorithm (Gravit et al., 2018) simulated the evacuation in a 20 floor building (G+19). The time units were determined by running the Pathfinder simulations. The result of the evacuation simulation showed that in case of a simultaneous evacuation, the density of people in stair reached upto 7-8 people/m^2 and incase of phased evacuation simulation using the algorithm, density remained around 3 people/m^2 (Figure 6).

This algorithm has further been implemented in the next chapter to simulate the evacuation from the iGent building.

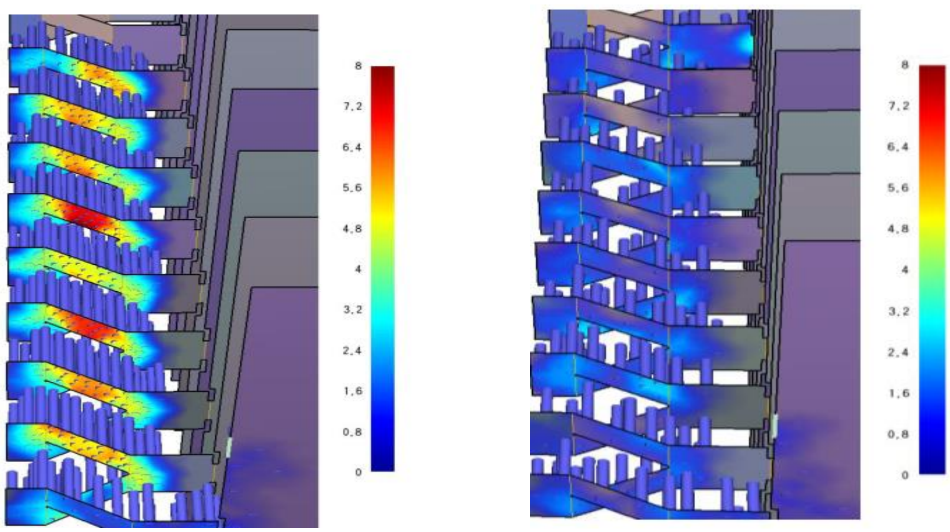


Figure 7 Human flow density results Left: Simultaneous evacuation; Right: Phased evacuation (from Gravit et al., 2018)

The occupant density is also an important factor which directly links with the speed of occupants during evacuation. (Gwynne & Rosenbaum, 2016) presented the graphs shown in Fig. 8 below. They concluded that the movement speed decreases with the increase in density and beyond the value of 3.5 person/m^2, the movement ceases to exist or the speed becomes almost negligible.

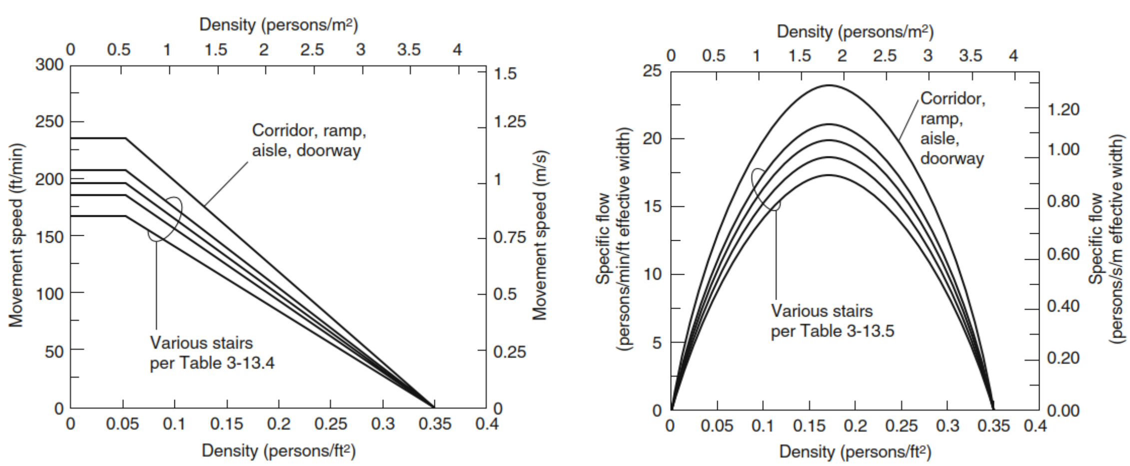


Figure 8 Left: Relation between density and movement speed; Right: density and specific flow (from Gwynne & Rosenbaum, 2016)

Chapter 3 Model Case Study

3.1 Phased evacuation from iGent building

The model case study is performed for the iGent building*. The high-rise building consists of 13 floors (Ground+12). The height of each floor is assumed here as 3m, hence the total height of 39 meters. The building is used for business i.e., mostly office layout and work related to research. The building is a part of the Tech Lane Ghent Science Park which hosts 11 university labs and 12 public research centers.

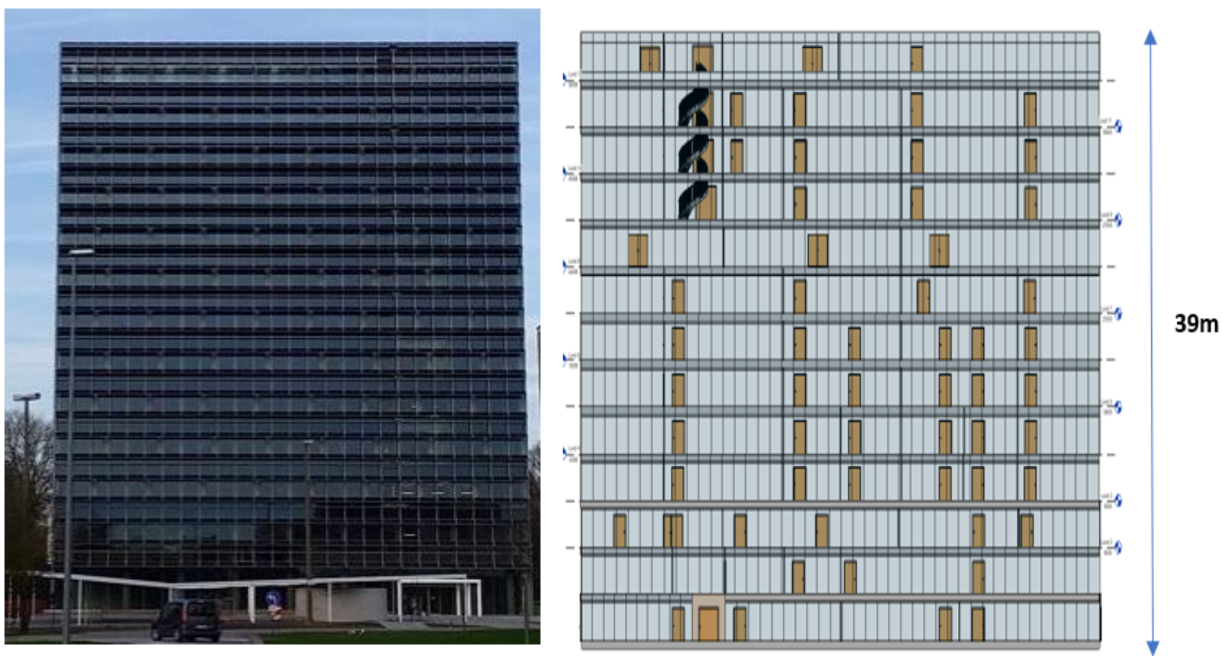


Figure 9 iGent Building actual and revit model representation.

Figure 10 iGent Building sample floor plan representation.

* iGent (UGent Campus Ardoyen)
Technologiepark-Zwijnaarde 126, 9052 Gent

The building has a typical floor length of 66m and width of 41m. Hence, the total gross area for each floor is 2706 m^2. It consists of majorly two staircases running from top to the ground floor. One other staircase is present from the first floor to the ground floor. Apart from that the building has some internal helical stairs and 2 lift shafts. For the evacuation modeling, the helical stairs are not considered. The width of staircases are as follows -

Staircase 1	Level 0 to Level 12	180 cm wide
Staircase 2	Level 0 to Level 12	170 cm wide
Staircase 3	Level 0 to level 1	300 cm wide

3.2 Limitations of case study

This study focuses on comparing a simultaneous evacuation modelling with a phased evacuation modelling following the algorithm proposed by (Gravit et al., 2018). For verifying & validating the results obtained by Gravit and to establish consistency, Pathfinder has been used here. Obviously, this model does not represent all possible high-rise buildings as they can be different in dimensions, egress components, building material etc. The selection of the building has been done because of the various sensors that are already present inside the buildings. This would help in further development of this project and the related projects. It should be made clear that certain attributes may require building specific calculations and the results of this simulation may not apply to the other building (e.g., number of floors in building, travel distance from stair, size of egress components, occupant characteristic may very). Therefore, it is recommended that specific building evacuation study shall be done. The evacuation simulation results provided in this report doesn't take into account the less mobile population. The thesis is limited to study & provide a smart solution for phased evacuation using the stairs only, therefore evacuation using the elevator has not been considered and addressed.

3.3 Model Setup

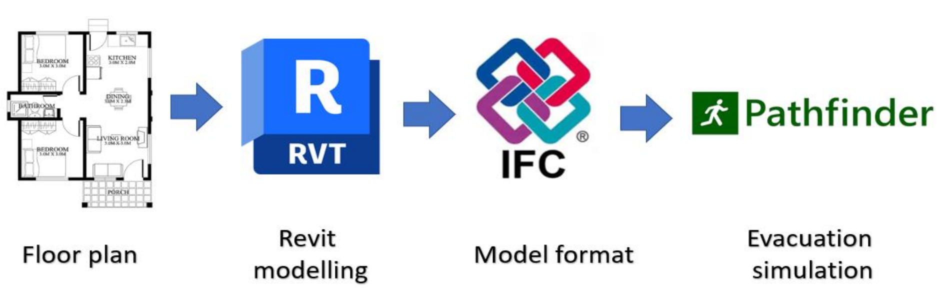


Figure 11 Model setup flow

Firstly, a building model of the iGent building was prepared using Autodesk Revit software (*Revit-software)* using the floor plans of the building. Revit provides a platform to construct a BIM model which could contain functional and physical characteristics of the building. Revit could also be used to document and visualize the projects in 4D.

The second step was to export the building model into IFC format. IFC is a universal file format which contains information about various building components that can be shared with various stakeholders. The format can be imported into various software programs.

For the final step the model was imported into the Pathfinder. An IFC format file can easily be imported to the Pathfinder, and it automatically detects various building components with sufficient accuracy.

3.4 Pathfinder

Pathfinder 2022 (version 2022.3.1207) is a commercially available software developed by Thunderhead Engineering. Presently, Pathfinder has two simulation modes – steering model and hydraulic model. The steering model attempts to simulate the human behaviour and movements as closely as possible by using a steering system to move and interact with other occupants. The hydraulic model on other hand works on hand calculations method provided under the SFPE Engineering Guide to Human Behaviour. For this mode, the speed of occupants does not vary while coming in close proximity to other occupants, and they can interpenetrate. However, the speed & flow is controlled by the density of people and the dimension of the evacuation components respectively.

When compared together, the steering model provided more conservative results than the SFPE hand calculations & resembled more closely to actual human behaviour. Therefore, for the present simulations, the steering mode has been incorporated.

3.4.1 Occupant modelling

It is assumed that on each floor 100 occupants are present, therefore the total number is 1300 occupants. This assumption is based on the upper limit of number of occupants present in the building on a typical day. The spread of occupants on each floor is done in a random way (in-built function in Pathfinder). Pathfinder does not have a specific method to perform a phased evacuation therefore the function of initial delay is used to perform the evacuation in the phased manner – more explained in the section below. The walking speed of the occupants is taken as default values. The walking speed varies based on the various factors such as proximity to structural component or any other occupants, density of occupants or any attraction/repulsion components. But the average maximum default speed in Pathfinder is 1.19 m/s with a standard deviation of 1 m/s, the values are based on SFPE handbook guidelines (Gwynne & Rosenbaum, 2016) .

The size of the staircase is an important variable for calculating the speed of descent during the evacuation (Gwynne & Rosenbaum, 2016)**.** The speed is calculated using equation 1

$$S = k - akD \qquad (1)$$

where

S = Speed along the line of travel

D = Population density ([person/m^2)

k = Constant from table 1

= k1; & a = 2.86 when speed is in ft/min and density in person/ft^2

= k2; & a = 0.266 when speed is in m/sec and density in person/m^2

Table 1 Constants for Eq. 1 evacuation speed

Exit route element		k1	k2
Corridor, aisle, ramp, doorway		275	1.40
Stairs			
Riser (in.)	Tread (in.)		
7.5	10	196	1.0
7	11	212	1.08
6.5	12	229	1.16
6.5	13	242	1.23

For the simulation staircases of riser 7.5in and tread 10in has been used.

3.4.2 Merging effect in Pathfinder

Merging is observed when the occupants of any floor adds up with the occupants coming from the above floor in the staircase area. This happens at the point where the floor exit merges with the staircase (as seen in Fig 12). The yellow zone and the white arrows represent the movement of occupants coming from the floor above and the red zone represents the area where the occupants of this floor are merging.

While (Kobes et al., 2008) argues that occupants on upper floors tend to avoid allowing occupants from the current floor to enter the stairwell during an evacuation, Pathfinder maintains his merging ratio as 50:50 (*Pathfinder User Manual*, n.d.). For the performed simulations, this value is taken as default i.e., 50:50.

Figure 12 Pathfinder merging behaviour representation

3.4.3 Route choice in Pathfinder

For deciding the route for the evacuation, Pathfinder works on the locally quickest algorithm. In this, the occupant is assumed to have a knowledge of complete exit route (including all door widths, queues at the exit doors, distance from the doors to the exit). Based on the that information, costs are assigned for the each exit door and the door with the least cost is selected (*Pathfinder User Manual*, n.d.).

3.5 Test cases

A fire could occur practically anywhere in a building. To validate the usability of the algorithm in any possible fire scenario, 3 cases have been selected here: -

(1) Case 1: Simultaneous evacuation

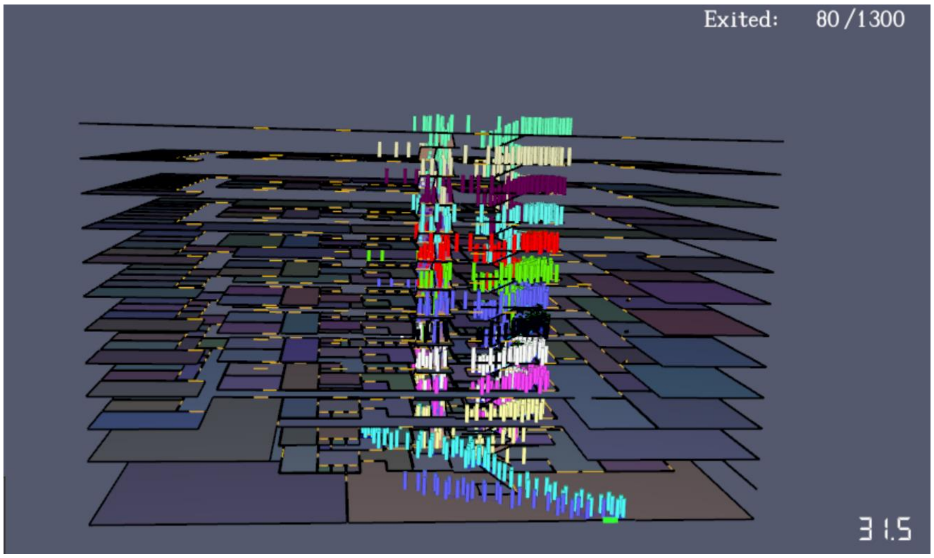


Figure 13 Case 1: Simultaneous evacuation

(2) Case 2 : Phased evacuation - Fire on 7th floor of the building

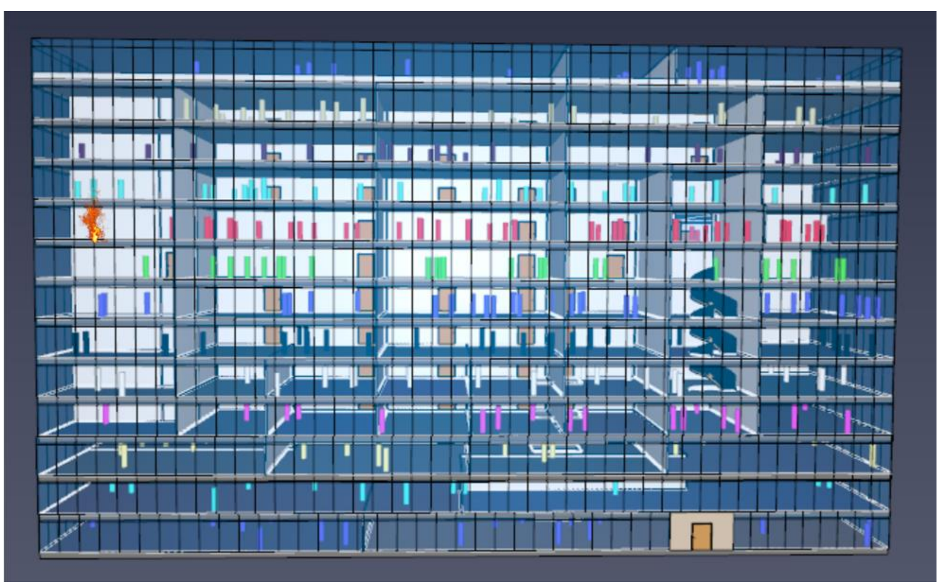


Figure 14 Case 2: Phased evacuation - Fire on floor 7th of the building

(3) Case 3: Phased evacuation - Fire on 2nd floor of the building

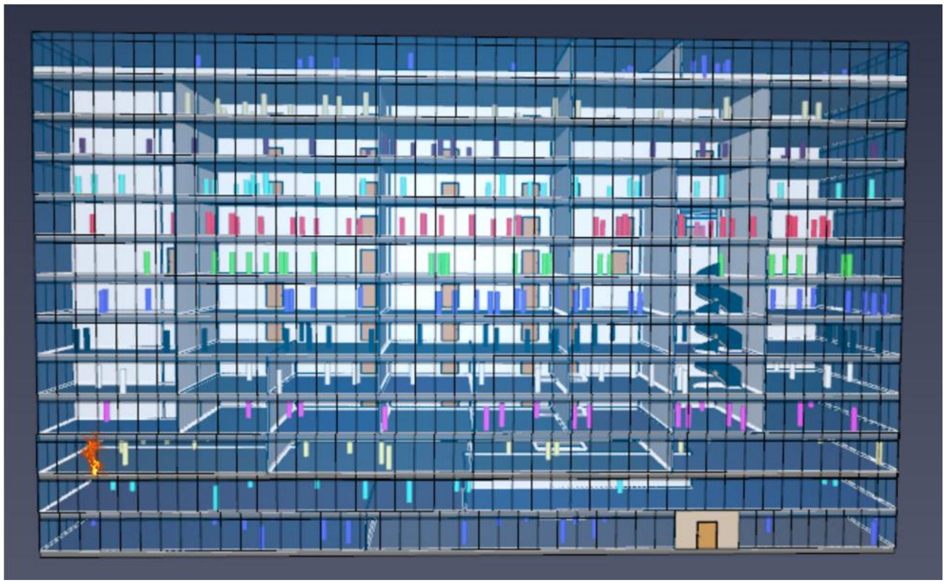


Figure 15 Case 3: Phased evacuation - Fire on floor 3rd of the building

Note: The above images are for representational purposes only, no actual fire was simulated.

3.6 Phased evacuation delays

Pathfinder does not have a direct or specific function to perform a phased evacuation. Nevertheless, the function of initial delay is used to emulate the phased evacuation. The initial delay function makes the occupant wait for the specified time, before starting to evacuate.

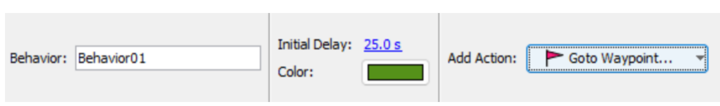


Figure 16 Initial time delay settings to mimic phased evacuation in Pathfinder

The time step calculated by Gravit in her modelling was taken as 25 seconds and all the sequencing of the evacuation was performed based on that time step. By sequencing here means the time gap between the movement of consecutive floor. In the present case, the time step is calculated by test running the simulations & measuring the time taken by the farthest located occupant on each floor to reach the staircase & to travel to the lower floor. This time step came as 30 sec. which simply signifies that the time step depends directly on the layout of a floor plan. The larger distance an occupant has to travel to reach the staircase, the more this time step will be. Therefore, it is safer to mention that for every individual building, a separate evacuation calculation study shall be done before applying the algorithm provided by (Gravit et al., 2018). As Figure-8 in the previous chapter depicts, beyond the density of 3.5 person/m^2 the movement ceases to exist, an attempt has been made to keep the density below this value. The measured delay times are presented for each test case below.

Table 2 Floorwise initial delay times to simulate phased evacuation

Case -2	Fire on 7th floor		Case -3	Fire on 2nd Floor
0	0 sec		0	0 sec
1	0 sec		1	130 sec
2	680 sec		2	0 sec
3	610 sec		3	30 sec
4	530 sec		4	60 sec
5	350 sec		5	150 sec
6	140 sec		6	180 sec
7	0 sec		7	210 sec
8	30 sec		8	240 sec
9	60 sec		9	270 sec
10	150 sec		10	300 sec
11	180 sec		11	330 sec
12	340 sec		12	360 sec

3.7 Model Validation

Just like all the evacuation models present, Pathfinder also incorporates stochastic variables to simulate specific aspects of the evacuation process, e.g., location of the occupants, unimpeded walking speed etc. To enhance the reliability of the results, it is crucial to run the simulation multiple times, incorporating variations in the randomized factors, and then compare the outcomes. In this case, the location of the occupants on each floor was selected as a random spread. This led to variations in travel time to the staircase and ultimately to the final exit. Therefore, to validate the model, the maximum travel time required by the farthest occupant was used as a time step. This maximum travel time was determined by carrying out the evacuation simulation with various random placements and comparing the results.

3.8 Results and discussion for simulation

Case 1: Simultaneous evacuation

As discussed in the definition, in case of simultaneous evacuation, all occupants start evacuating at the same time. The below figures provide occupant density at 2 different time frames during the simulation

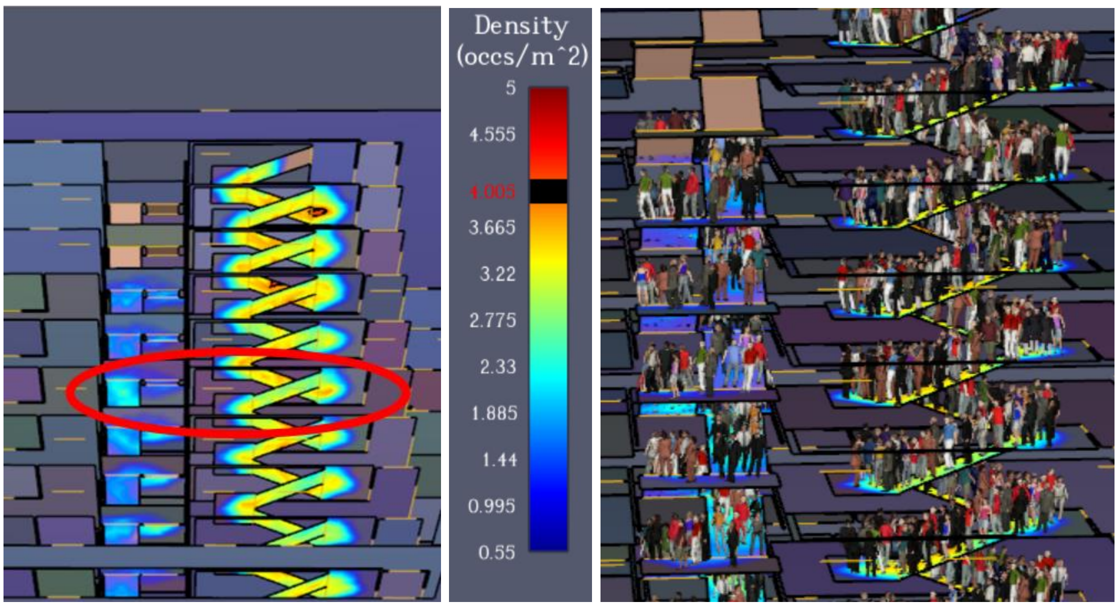


Figure 17 Case 1: Simultaneous evacuation occupant density at time 50 seconds (right loop showing assumed fire floor in case 2)

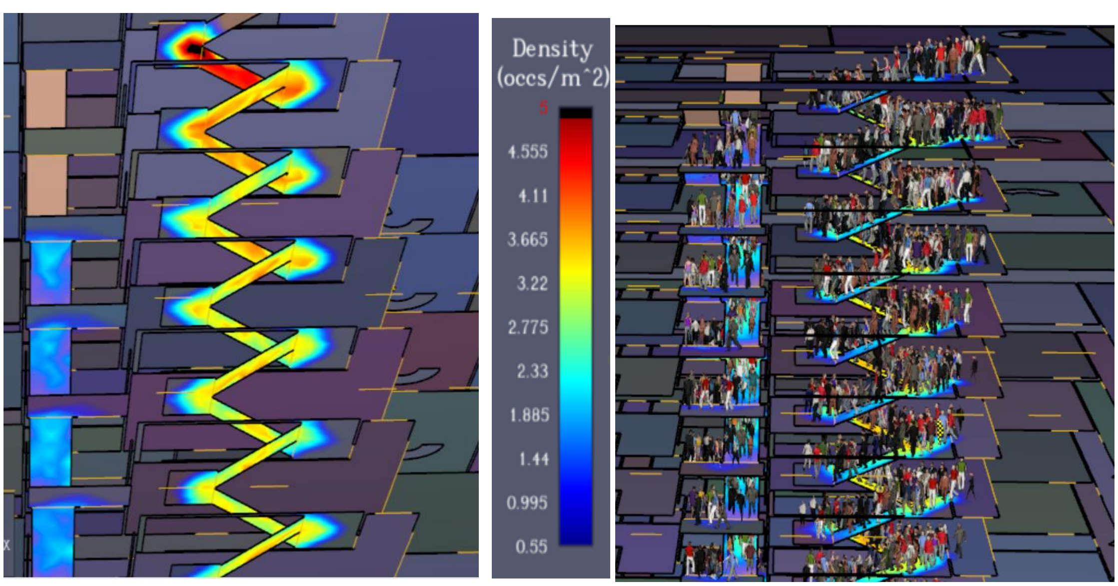


Figure 18 Case 1: Simultaneous evacuation occupant density at time 200 seconds

From the figures it is evident that the occupant density goes well beyond 3.5 person/m^2 . This value reaches 5 person/m^2 in the staircase area. According to (Gwynne & Rosenbaum, 2016) this will lead to 0 movement condition and a congestion situation can be observed. From the Pathfinder results also, it is very clear that, in such conditions the flow of occupants tends to 0. Although, this occupant density is still lower when compared with the results obtained by (Gravit et al., 2018) and as discussed by (Huang et al., 2022) , where the maximum density could go upto 7-8 person/m^2.

In the case where fire is assumed on the 7th floor, the simulation run signifies that due to congestion of people in the staircase, the occupants of the 7th floor who are at immediate risk of fire have to queue around the staircase area. In a situation where the fire occurs just around the staircase, the impact could be really high on the queuing occupants because of the smoke and other combustion products.

Case 2: Phased evacuation – Fire on floor 7th of the building

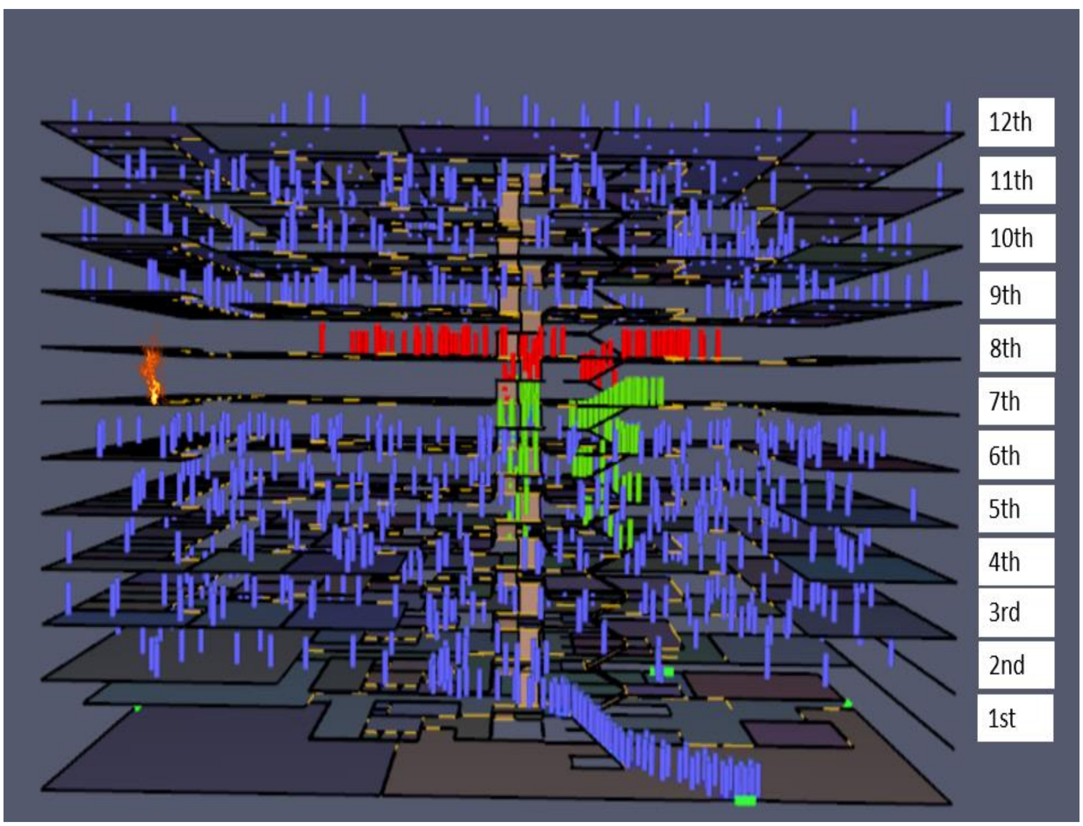


Figure 19 Case 2: Phased evacuation – Fire on floor 7 occupant flow at time 50 seconds (Green representing occupants of fire floor and red as occupants of floor above location

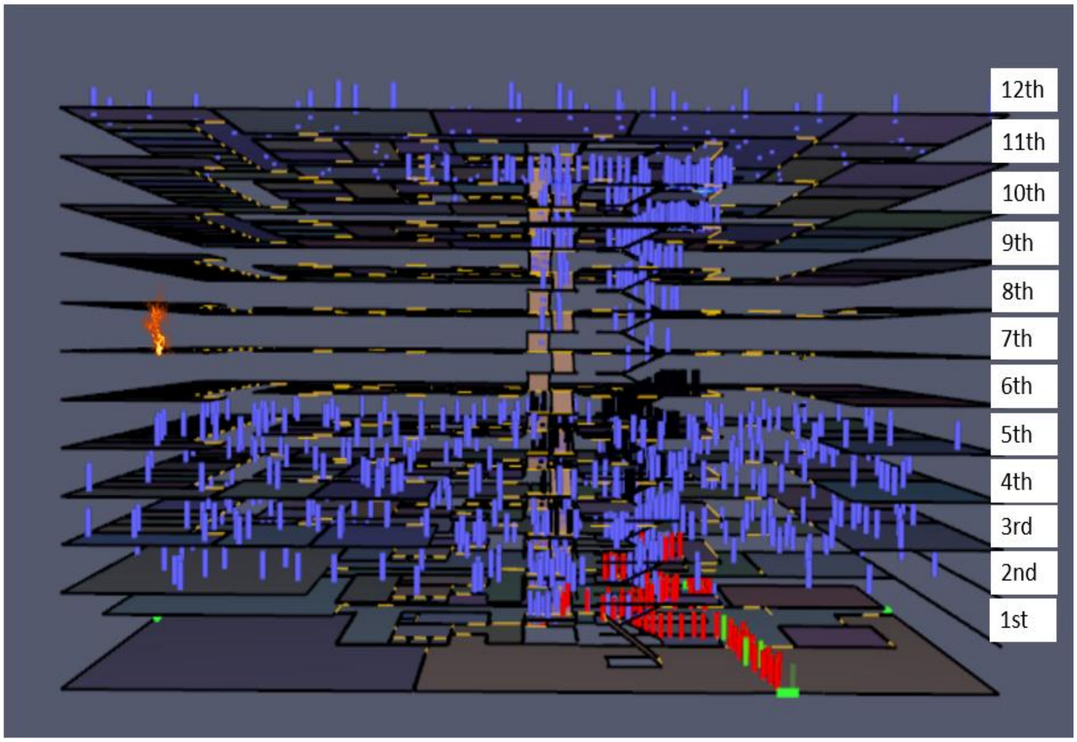


Figure 20 Case 2: Phased evacuation – Fire on floor 7 occupant flow at time 160 seconds

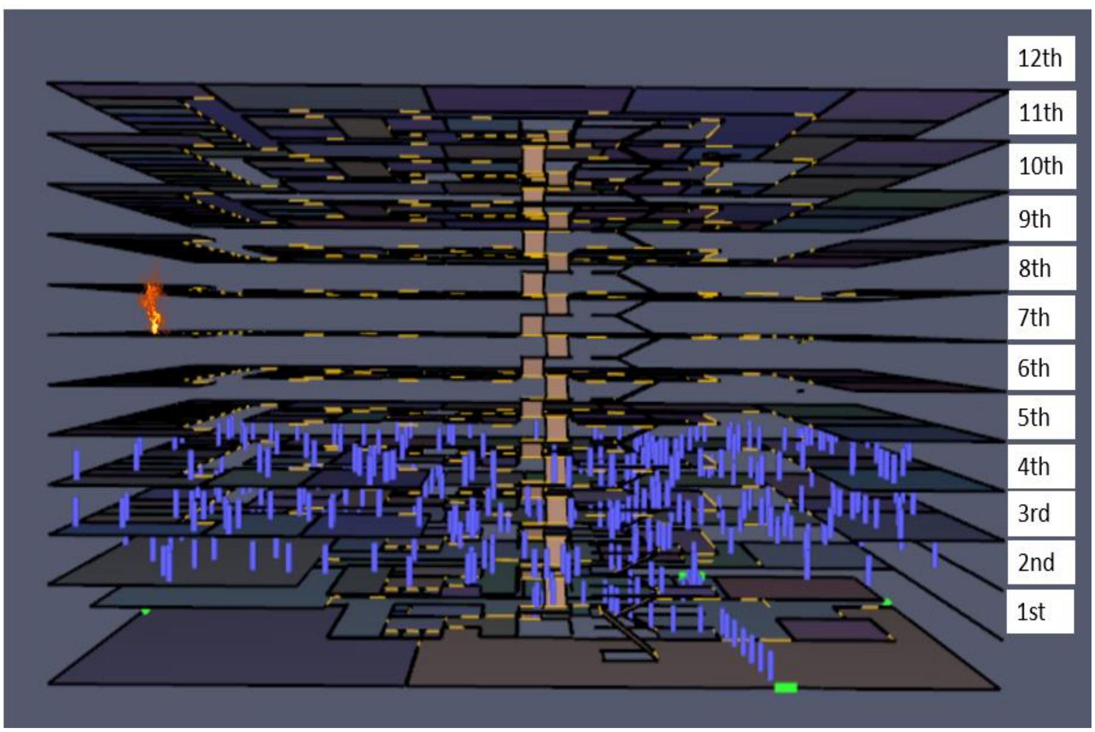


Figure 21 Case 2: Phased evacuation – Fire on floor 7 occupant flow at time 540 seconds

The effectiveness of the phased evacuation model aligns with the findings of (Lay, 2007) and (Gravit et al., 2018). In this case, priority was given to the floor where the fire originated, which was the 7th floor. As depicted in the preceding figures, the evacuation process commenced with the evacuation of the seventh floor, followed by the eighth and ninth floors. Subsequently, the floor directly below the fire location, which was the sixth floor, was evacuated.

Considering the typical behavior of fires, there is a higher likelihood of flames spreading to the upper floors of a building. Thus, the evacuation algorithm gave priority to the above floors to ensure the safety of occupants. This prioritization is demonstrated in Figure 21, where the evacuation process first focuses on evacuating occupants from the floors above the fire before attending to the floors which were well below the fire location and were in a relatively less hazardous situation.

It is noteworthy that occupants on the ground floor were also among the first to be evacuated. This decision is based on the understanding that, during an evacuation, these individuals are less likely to rely on the staircase for exiting the building. Consequently, their evacuation can be carried out smoothly without causing any obstruction or congestion on the stairs.

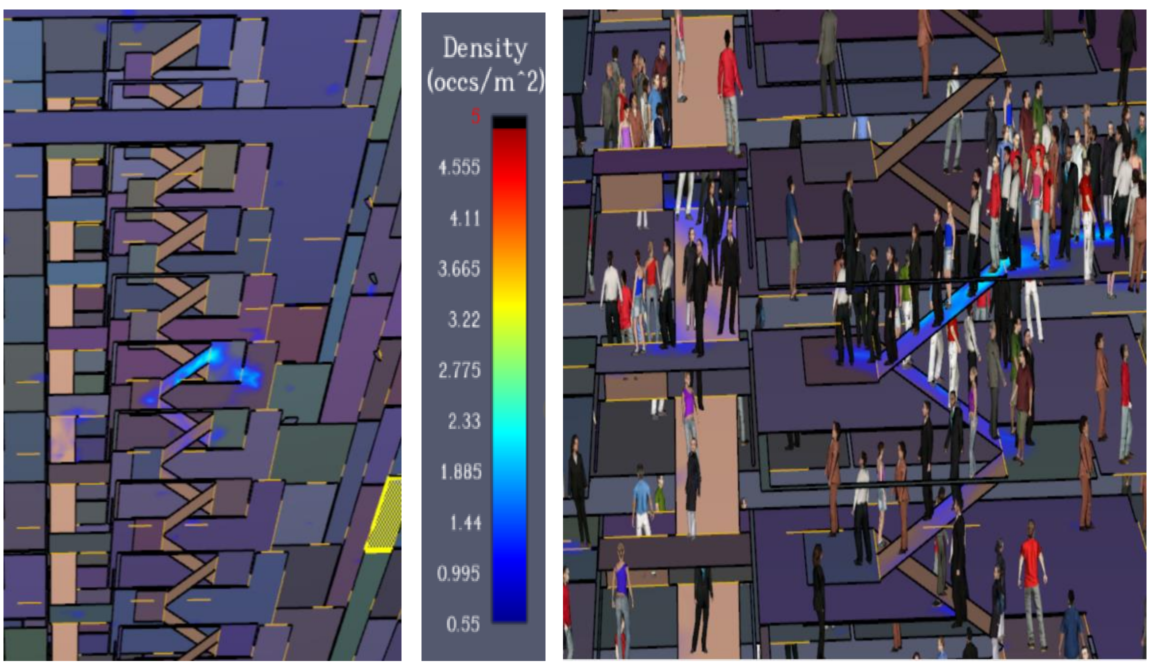


Figure 22 Case 2: Phased evacuation – Fire on floor 7 occupant density at time 50 sec

The analysis of the model's density study presents compelling evidence that implementing a phased evacuation strategy based on the algorithm ensures that the density of occupants in the staircase never exceeds 3.1 persons/m^2 at any given time. The density consistently hovers around 2.7 persons/m^2, indicating minimal congestion and facilitating a smooth and efficient evacuation process.

Case 3 : Phased evacuation – Fire on floor 2^nd^ of the building

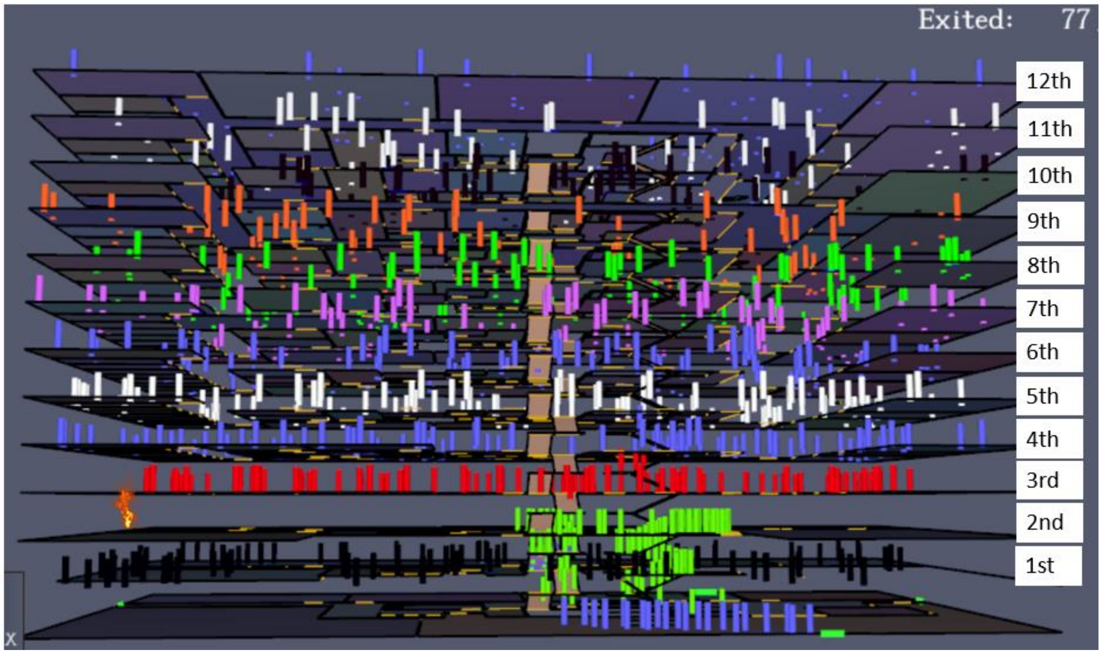


Figure 23 Case 3: Phased evacuation – Fire on 2nd floor occupant density at time 20 sec

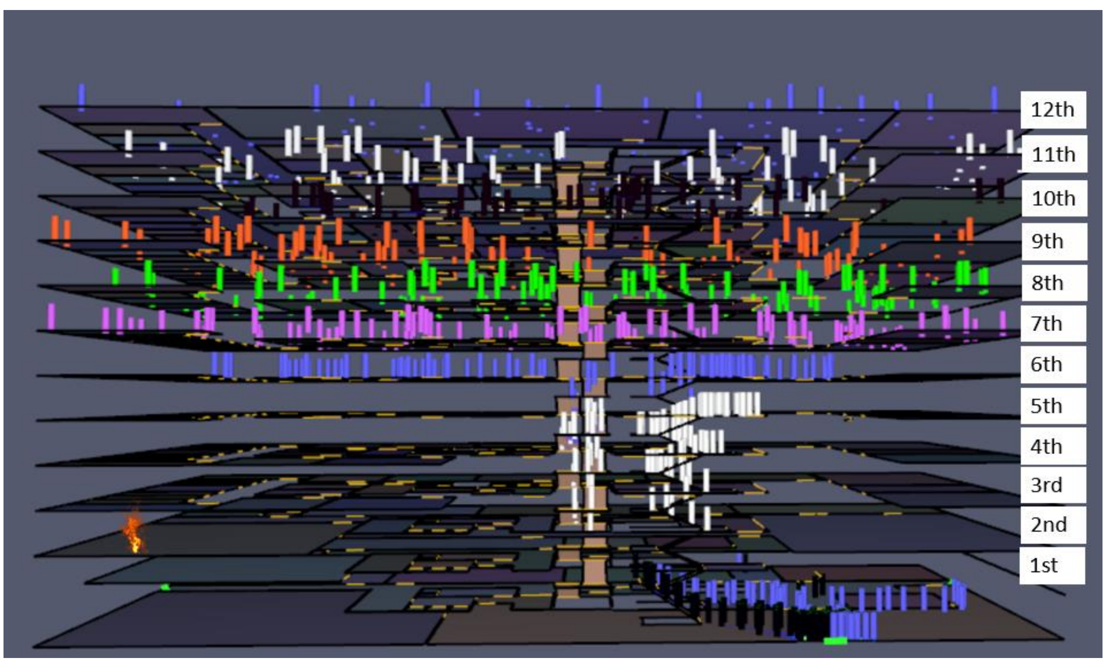


Figure 24 Case 3: Phased evacuation – Fire on 2nd floor occupant density at time 170 sec

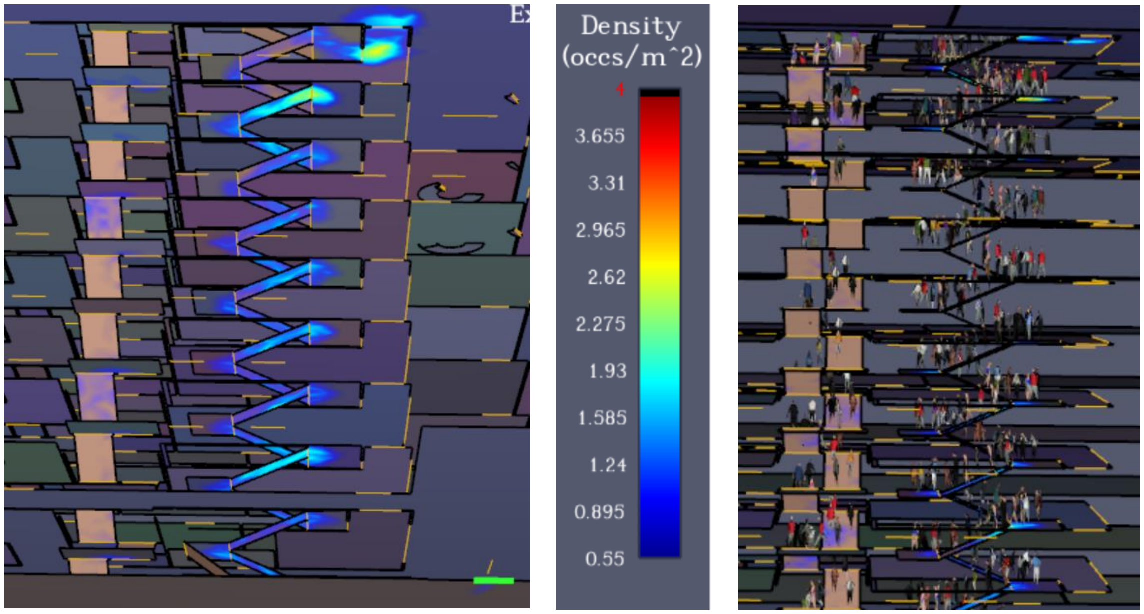


Figure 25 Case 3: Phased evacuation – Fire on 2nd floor occupant density at time 370 sec

Similar to the 2nd case, here also the priority for evacuation is given to the occupants of the floor where fire is located and then the nearby floors. The density remains well below a 3.5 occupants/m^2 and a streamline evacuation was observed.

3.8.1 Comparison of evacuation time

(1) Total evacuation time

Simultaneous evacuation	Phased evacuation (fire on 7th floor)	Phased evacuation (fire on 3rd floor)
556 sec	780 sec	673 sec

The total evacuation time suggests that the fastest way of evacuation is still simultaneous evacuation. But as earlier mentioned by (Ronchi & Nilsson, 2013) , (*Evacuation from Fire in High-Rise Residential Buildings*, n.d.) and (Gravit et al., 2018) the purpose of phased evacuation is to provide an evacuation strategy prioritizing the occupants who are at immediate risk. Additionally, (Huang et al., 2022) raised concerns about the risk of injuries during stairway evacuations. According to Huang, the continuous increase in density within a human cluster because of simultaneous evacuation significantly elevates the chances of injuries and compression asphyxia during the evacuation process. As demonstrated earlier, cluster formation was observed throughout in the case of simultaneous evacuation.

(2) Floor evacuation time

In this section, a comparison will be done based on the maximum time occupants took from the start of evacuation to reach the point of final exit in the building

(a) Case 2: Fire on the 7th floor

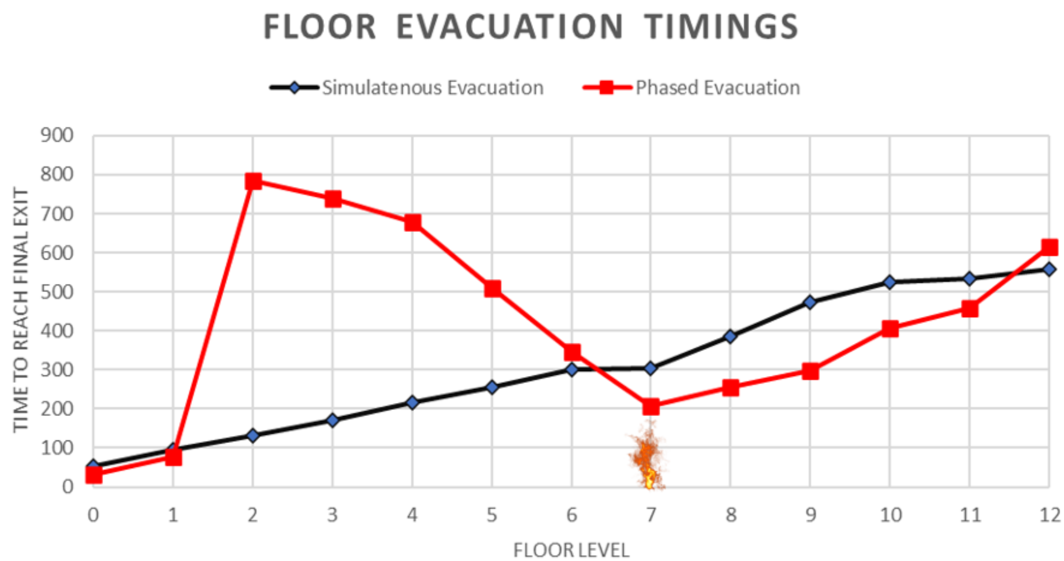


Figure 26 Floor evacuation timing graph (case 1 & case 2)

(b) Case 3: Fire on the 3rd floor

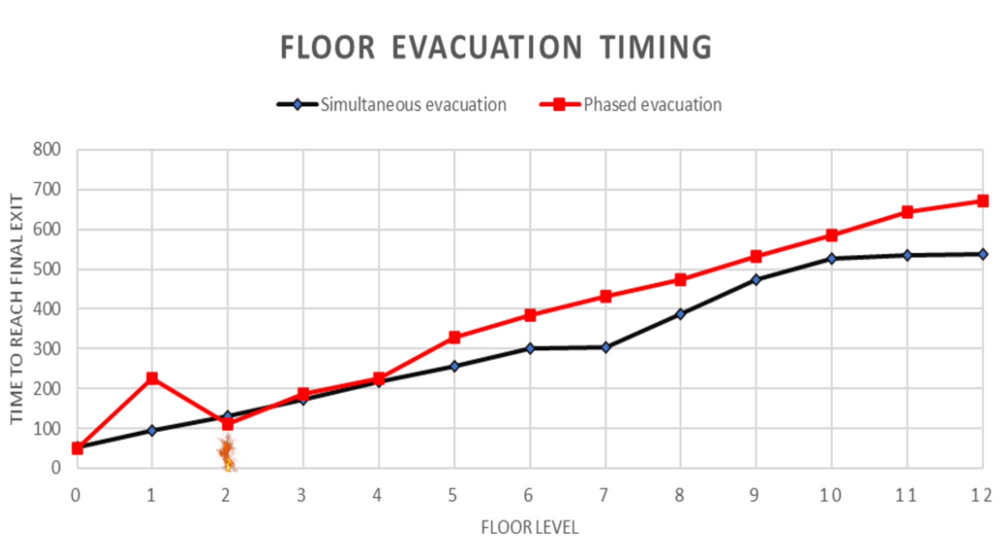


Figure 27 Floor evacuation timing graph (case 1 & case 3)

When looked at the simultaneous evacuation curve, the occupants of upper floors required a longer time as expected to reach the final exit point of the building, regardless of the fire location. The time taken for evacuation was found to be nearly proportional to the floor level. However, when compared with phased evacuation for case 2, where the fire occurred on the 7th floor of the building, priority was given to the occupants of that floor and the surrounding floors. The data visualization clearly indicates that individuals residing on the 7th floor and above took almost 100 seconds less to reach the final exit point. For the floors which are well below the fire location, the time taken to reach the final exit point is greater high as compared with the timing for simultaneous evacuation, this is because these floors were deemed safe in comparison to the floors nearby the fire location.

Based on the second graph, which illustrates the evacuation timings for both simultaneous and phased evacuation scenarios in the event of a fire on the second floor of the building, it is apparent that the time taken for occupants to reach the exit point is similar for the floor on fire and at least two floors above, in both cases. However, for the floors above this range, for phased evacuation the time required is greater and the evacuation time follows a pattern similar to that of the simultaneous evacuation scenario, where the time to evacuate is directly proportional to the floor level. Notably, in this particular case, occupants on the first floor required an additional 100 seconds to evacuate to the final exit, as priority was given to the floor on fire and the floors above, which were deemed to be at a higher risk.

3.8.2 Average congestion time

This section provides the comparison of average congestion time occupants of each floor have to face during evacuation in all 3 cases. According to the (*Pathfinder User Manual*, n.d.), an individual is deemed to be in a state of congestion if their travel velocity falls below a specific threshold velocity. The total duration of congestion can be quantified as the amount of time that the occupant spends travelling at this velocity.

1. Simultaneous evacuation

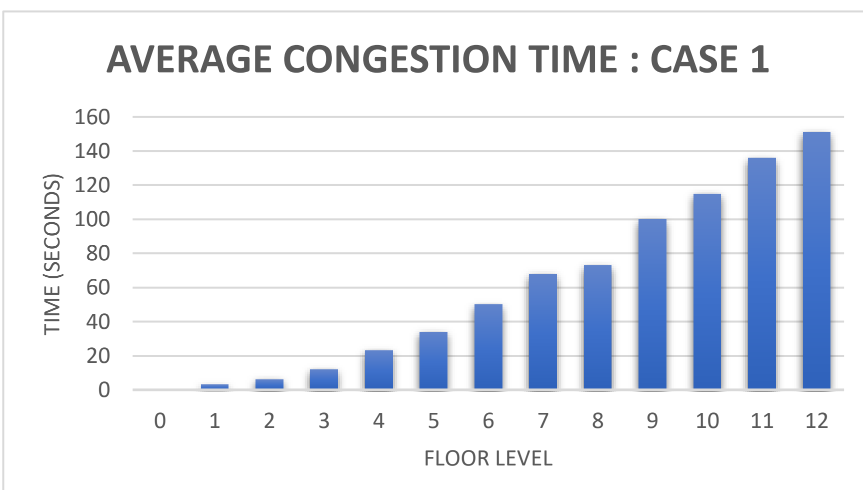


Figure 28 Average congestion time graph: Case 1

2. Phased evacuation - Fire on floor 7th of the building

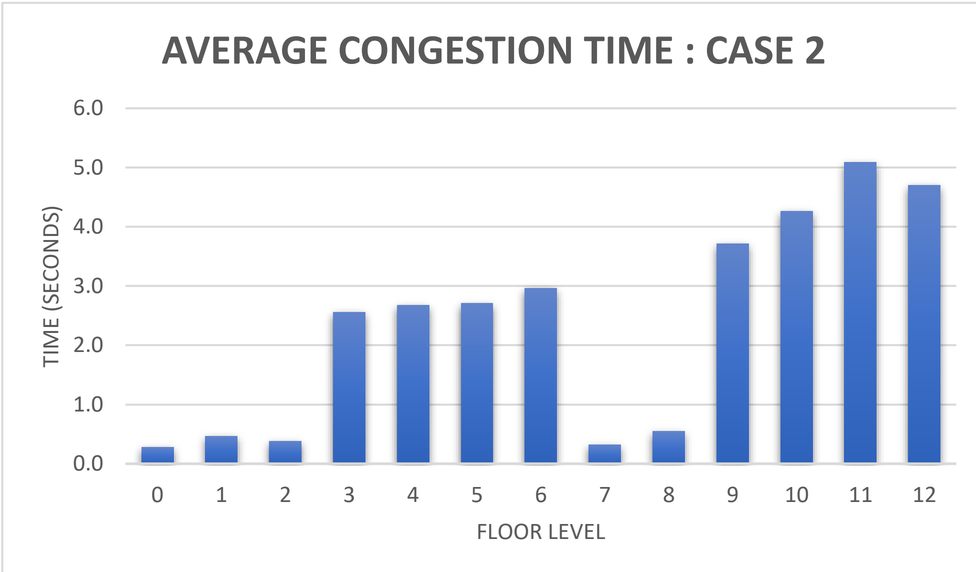


Figure 29 Average congestion time graph: Case 2

3. Phased evacuation - Fire on floor 3rd of the building

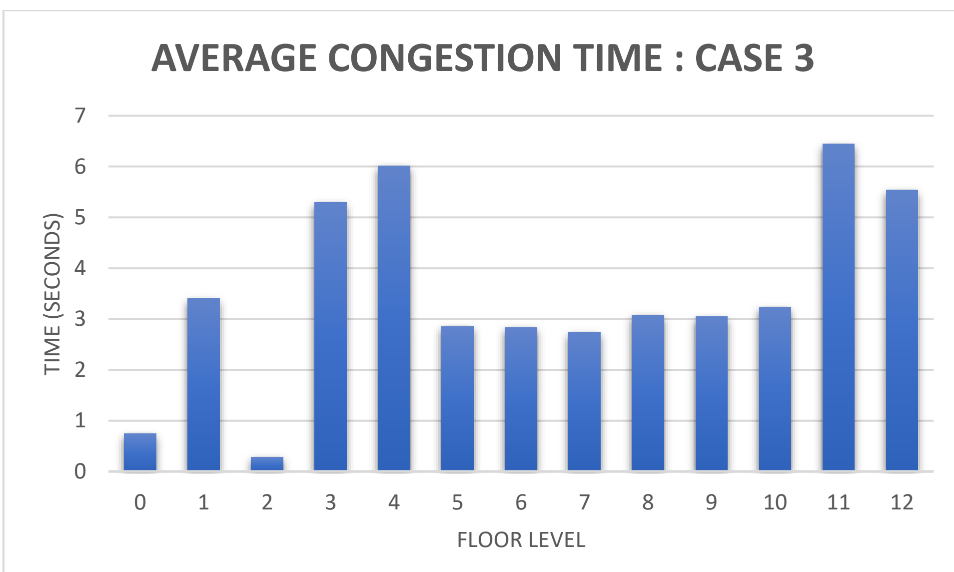


Figure 30 Average congestion time graph: Case 3

For the simultaneous evacuation, the congestion time is directly proportional to the floor level. This could be explained by the fact that the occupants from the above floors have to travel a greater distance and stay in the staircase area for a longer period of time. The

magnitude of congestion time for the above floors is of the value 80-140 seconds. This value is very high when compared with the other two graphs.
The graphs for congestion time for case 2 and case 3 provide almost similar results and the congestion time value is well below the timing in simultaneous evacuation. The magnitude of congestion time is few seconds. From this, it could be concluded that a streamlined evacuation could be performed when a phased evacuation strategy is applied for evacuation from a high-rise building.

In reality the phased evacuation method will only be useful & optimum when implemented effectively. As (Lay, 2007) mentions, the key risk behind this strategy is the occupant reluctance. (Proulx, n.d.) also concluded that occupants are more likely to evacuate immediately rather than waiting and following a phased evacuation. As defined in the literature review, human behaviour depends on the various factors here. The implementation of this method may require proper training to the occupants. Also, (Ronchi & Nilsson, 2013) stresses the importance of clear communication, it is recommended that along with the fire alarm, a voice alarm providing the evacuation guidance related to waiting time and fire location should be present. Over the time, this was confirmed by many researchers such as (Nilsson, 2015), (Proulx & Sime, 1991), (Ramachandran, 1991) & (Powell & Booker, 1989).
Overall, the result obtained from the simulation supports the phased evacuation for the mentioned high-rise building.

Chapter 4 – Framework for smart phased evacuation system

The results obtained for the phased evacuation simulation for the iGent building provides some promising results and a comparatively safer & planned way of evacuation. The algorithm provides a faster escape for the people who are in immediate danger of fire rather than everybody evacuating at once.

The 3 major drawbacks of the algorithm that needs to be addressed are

1. Factor of human behaviour for implementation of a phased evacuation
2. The system provides strategy based on fixed number of occupants on each floor
3. The static nature of the algorithm

As described in the discussion of the previous chapter, human behaviour plays the most important role in effectiveness of a phased alarm strategy. A voice alarm providing necessary details as (Nilsson, 2015) found, would be more effective. Therefore, a system that could provide necessary real time information about the fire and guidance is required.

An important limitation of the evacuation modelling in the previous chapter is that a fixed number of occupants are assumed on each floor based on the maximum typical value. But, in reality the number of occupants present on each floor may highly vary. For example, the number of occupants could be higher in case of a gathering or an event on any floor, whereas the number could be low during the vacations. Therefore, providing a fixed time for the occupants of a floor to evacuate may not provide the most optimum solution. Instead, a smart system should take that into account automatically and provide an evacuation strategy based on that.

As also described in the previous chapters, the spread of fire depends on the various factors such as the location of fire, cladding material, wind effects, trench effects, corner influences, inclined surfaces etc. (described in more details in the previous chapter). The algorithm provides a clear way to evacuate the building, but a fire may not follow the expected path of spread. As described in the case study sections, the spread of fire happened at an unexpected speed in various cases. Therefore, a smart phased evacuation system algorithm should present an evacuation sequencing based on the real time conditions.

It is suggested that the system should follow the proposed algorithm in-general. But, if the fire spreads to the floors above or below at an expected rate and the sensors detect this spread, an advance system should be able to prepare an evacuation strategy based on that. This could be done by constant monitoring of the building even after the fire happened.

This chapter proposes a framework to rectify these three drawbacks.

4.1 Architecture for smart phased evacuation from high rise building

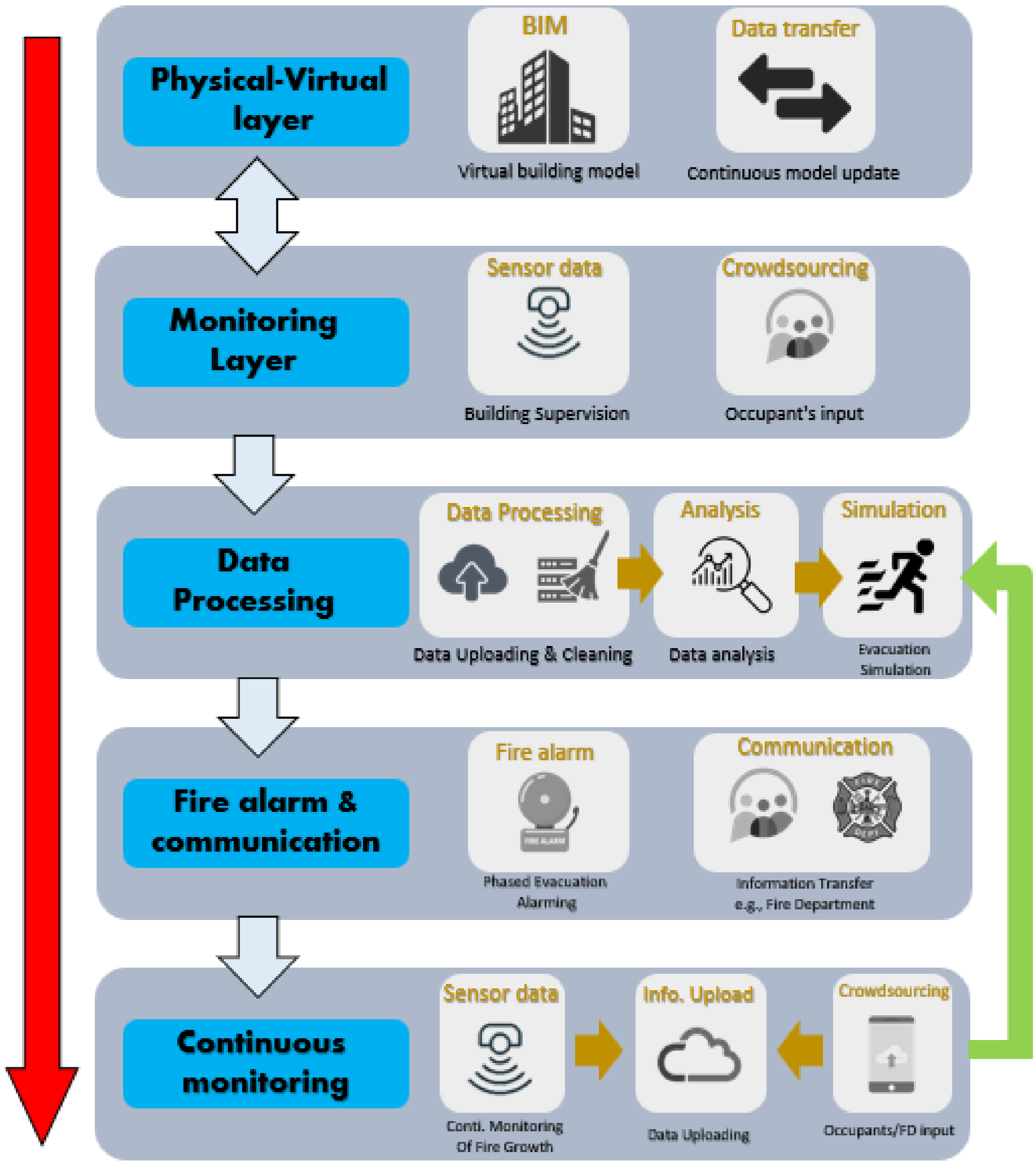


Figure 31 Architecture for smart phased evacuation from a high-rise building

1. Physical virtual layer

The architectural design of the building plays a crucial role during an evacuation. Factors such as the building layout, obstructions, and the type of building material used are vital in determining the rate at which a fire can spread. The size of staircase, doors and corridor are the key components for calculating or simulating the evacuation. Information about the locations and availability of firefighting equipment such as extinguishers/hose reels could also assist during firefighting and evacuation. All this information, along with others, is part of the building management system. Therefore, the first step is to create a building model with all relevant information. This model will provide sufficient information to the system to perform calculations and simulations in order to provide the most efficient evacuation strategy.

Since the use of a building or its layout or dimensions of its component may change during the life cycle of the building, updating the building model is as important as preparing a new model. Therefore, the systems should be regularly updated with information regarding the changes in the building.

2. Monitoring Layer

For a smart system to work, the building needs to be monitored 24x7. This could be possible by incorporating the sensors inside the building. A typical list of sensors that may be present inside a building is provided here –

Table 3 Typical list of sensors present in a building

Serial no.	Sensor type	Typical example	Usage/Remark
1.	Fire Detectors	Heat/smoke/flame detectors	As per the regulations, fire detectors are installed in the high-rise buildings based on its occupancy.
2.	Water Sprinklers	Vary based on temperature ratings	If present, the water sprinklers could also be used detect a fire.
3.	CO_2 & CO Monitors		These are installed in modern day buildings to measure the indoor air quality (IAQ) and are recommended under (US EPA, 2019). This could help in sensing a fire at an early stage
4.	Temperature sensors	Thermostats	Inputs from the thermostats/automatic HVAC system could provide a real time temperature information in various parts of the building.
5.	Humidity sensor	Generally present in HVAC systems	Sudden changes in the environmental condition such as humidity can also be a result of a fire.
6.	CCTV or Thermal imaging cameras		Commonly installed these days in buildings. Input could be utilized to detect the fire as well as number of occupants present in the area.
7.	Human counter sensor	Installed at doorway/entrances to keep the track	The sensor provides number of occupants present in a building/floor at any point of time.

*(the use of sensors defined above is not just limited to the evacuation only)

- Typical sensors installed to detect fire
- Sensors installed to measure the indoor air quality & comfort
- Sensors installed for surveillance and security purposes

For a system to be advanced and dynamic, the time required for evacuation of occupants on each floor shall be determined based on the head count. This could be done by human counter sensors or CCTV/Infrared cameras present in the area. This information could also be used to make sure everybody has evacuated.

Another key aspect is to use the input from the occupants in case any sensor fails to detect a fire, or a fire occurs in an area where sensors are not present. Although since the system relies on multiple sensors, it is unlikely to happen but nevertheless, the system should have an option to manually update about the fire and its location. In that case, the rest of the system works in a similar manner.

Data management

Data Processing – The step includes firstly uploading the data, storage and cleaning it. While storage of data is done to analyse and would help to view the records in future, data cleaning is process of removing irrelevant/poorly formatted data.

Data Analysis – In order to determine the occurrence of fire, the cleaned data is analysed based on the set limits by the user. If the threshold limit of any parameter is breached, a fire occurrence can be confirmed in the area where breach is detected.

Evacuation Simulation – Based on the location where the fire is detected and the number of occupants present on the different floors, a phased evacuation strategy will be formed. The floor on which the fire is detected will receive an alarm to evacuate to a place of safety without any time delay. The consecutive floors will receive an evacuation alarm based on simulated time for evacuation of occupants present in real time on each floor. This will be done to ensure a streamline evacuation without any congestion.

Fire alarm & communication

Based on the analysis of the data done by the system, the next step is to raise a fire alarm. The fire alarm will provide a signal to initiate the evacuation. Since it is phased evacuation, the fire alarm will be given in a sequenced manner – first to those who are more at risk. The remaining floors where the evacuation is yet to be commenced/not required, a voice message providing the instructions shall be used. This is in line with findings of (Kodur et al., 2020).

Another important aspect of this step in providing the information related to evacuation strategy to the fire department. And this will also provide additional information about the spread of fire & availability of the evacuation components.

Continuous Monitoring

When the fire condition is detected, the system will provide phased evacuation alarms based on the analysis. Even after initiating an evacuation, the system will continue monitoring the building or it can take input from the occupants. In case the fire develops in a manner which is different from the algorithm provided by the system, then the analysis will be done again, and the evacuation strategy will be modified so that people who are in immediate risk of fire are prioritize for the evacuation.

Example – If the fire is detected on n^{th} floor, as per the base algorithm, the occupants of that floor would be first to evacuate followed by n+1; n+2 and n-1 floor respectively with the simulated time gap to avoid congestion. But in case the fire/fire signatures are detected before the simulated time on n+3 floor (example scenario), in that case the system will re-analyze the evacuation strategy and will prioritize evacuating the occupants of that floor. Same will be the case if the fire is detected on the lower floors before the simulated time.

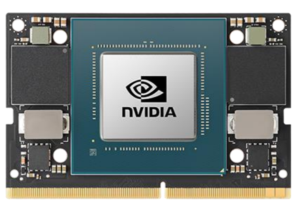
4.2 Hardware required for the system

1. **Sensors:** As explained in the previous section, the sensors are required for monitoring purposes in the building. The sensors will gather spatial and temporal data related to fire and to estimate the number of occupants in the building. For the purpose of fire detection, input from sensors such as heat detectors, smoke detectors, flame detectors, CO monitor, CO_2 monitor will be utilized. Based on the building occupancy and use, a threshold limit could be set for estimating a fire and non-fire condition.

   Human sensors: Equipment such as a CCTV, human counter sensor or footpads could be used to estimate the number of occupants present on each floor. Generally, human counter sensors are installed at the doorways.

2. Single board computer: A single board computer could perform functions of a normal computer in limited capacity based on the model and make of the system. These computers are built using microprocessors assembled on a single board. The major benefit of this system is the compact size of it and overall cost. A few examples of most commonly used single board computers are presented: -

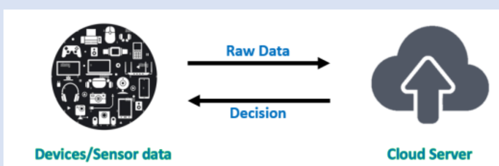
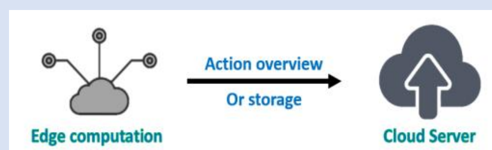
Table 4 Commonly available single board computers

Model Name	**Image**	**Features**	**Limitations**
Raspberry Pi 4		Raspberry pi 4 offers an affordable compact system which has a set of General-Purpose Input/Output (GPIO) pins. This allows users to connect it to external components such as LEDs, sensors, and motors. It also offers connectivity to the Ethernet and Wi-Fi.	Raspberry Pi is designed for low-power applications and has limited processing power, RAM & storage. This means that the system may fail to provide poor performance while running multiple applications. Due to its limited capacity, it could not perform a real time video analysis.
Arduino MKR WiFi 1010		This is powered by a 32-bit ARM Cortex-M0+ processor and provides a clock speed of 32 MHz. It has an in-built connectivity option to Wi-Fi and BLE. Other features include headers for connecting sensors such as temperature and gas detectors (such as CO and CO_2)	The system is powered by a low-power processor, this limits the performance of the system and therefore fails to perform tasks such as real time video analysis which may involve image processing and complex algorithms.
NVIDIA Jetson		NVIDIA Jetson is designed to handle high-performance computing tasks related to artificial intelligence (AI), computer vision, and deep learning. It offers high processing power, multiple connectivity options, and supports various sensors such as cameras and microphones.	The main limitation of this system is the cost and high-power consumption as compared to the other similar systems.

Based on the requirements for a real time phased evacuation system and the features offered by different single board computers, NVIDIA Jetson can be assumed as the best option for the purpose. An important reason for choosing this system is that in case of an unavailability of internet connection (which could happen in case of a fire), the system can perform the analysis in a stand-alone condition and provide output to the fire alarm panel.

3. **Analysis & computation** – Overall, there are two ways in which the analysis & computation of the data received from the sensors could be performed. These two ways are
    a. **Cloud Computing**
    b. **Edge Computing**

Table 5 Comparison between cloud computing and edge computing

Cloud Computing	Edge computing
Cloud computing relies on centralized data center, therefore all the sensor data needs to be first uploaded to an online server after that the analysis would be performed. 	Edge computing relies on distributed computing resources that are closer to the devices. This means that the computation would be done closer to the location where data is gathered (in this case – by NVIDIA Jetson system. 
The average response time could vary from minutes to days	The average response time is milliseconds.
The uploading of data requires huge amount of bandwidth.	Since no data is directly uploaded on the cloud, the required bandwidth is significantly reduced.
In case of no connectivity, the system could not perform any analysis or computation.	Analysis and computation could still be performed in case of no connectivity to the internet. The storage of the data and action overview could be hampered.

In case of a fire, it is likely that the internet may fail or may not be present, this could result in total failure of the system in case cloud computing is used. Therefore, edge computation shall be used here. This is one of another reason why a single board computer like Nvidia Jetson is required for this application as it is designed to perform edge computation using powerful GPUs and dedicated hardware accelerators that can handle complex computations in real-time.

4. **Fire alarm panel:** The fire alarm panel will receive spatial and temporal information about the fire. The fire alarm panel would be connected to a fire alarm and the voice alarm devices present in the building.

5. **Voice alarm devices:** The voice alarm panels were deemed important for an effective phased evacuation strategy. In this case, the voice alarm will provide the information about the fire location and the guidance related to movement.

4.3 System Working

Based on the described architecture and the hardware in the previous section. The working of the system could be possible in 2 modes

Mode 1: When internet connectivity is available

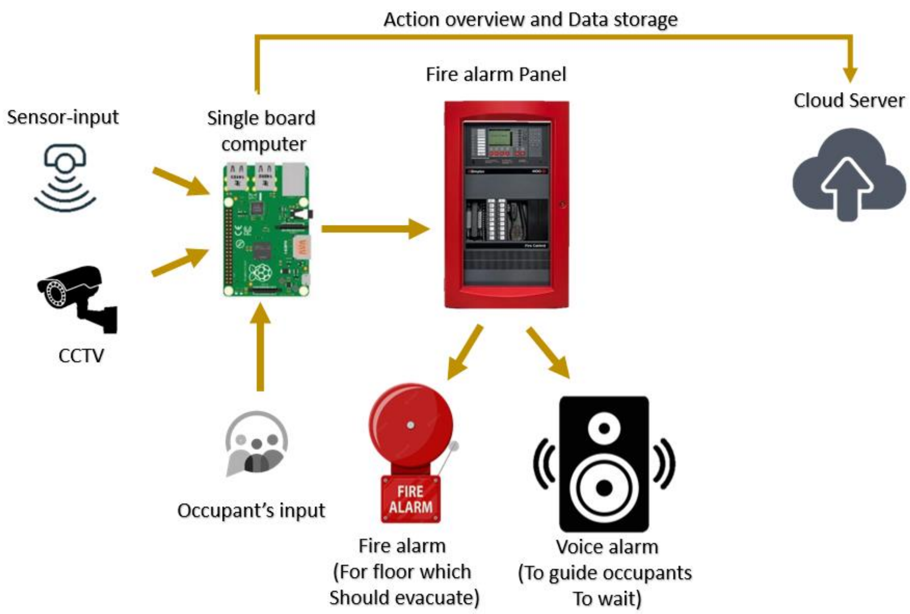


Figure 32 Smart phased evacuation system working in an online mode

Mode 2: Stand-alone mode

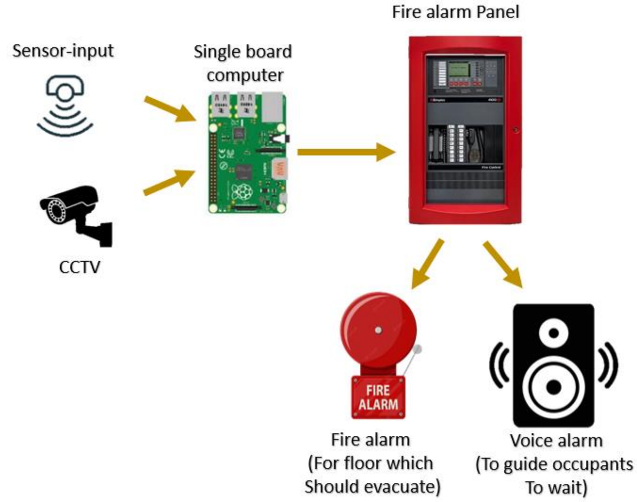


Figure 33 Smart phased evacuation system working in an offline mode

Working

The building's sensors will collect fire detection data, while CCTV's or similar devices will collect information on the number of occupants. This data will be fed as input to the Nvidia Jetson single board computer, which will determine if a fire condition exists by comparing the data to stored threshold values and the number of occupants will be determined using computer vision algorithms and image processing. If a fire is detected, the fire alarm panel will be triggered based on the output from the single board computer. At the same time, a phased evacuation algorithm will be simulated, and a voice alarm will be broadcasted to the remaining floors providing guidance on evacuation based on the location of the fire and the evacuation strategy determined by the algorithm.

If the single board computer is connected to the internet, occupants can use a system UI to provide information about a fire and its location, in case the sensors fail to detect the fire or occupants detect the fire earlier than the sensors. This input from the system UI will be used to initiate a fire condition, and the computation will be done in the same manner as described above. However, this feature will not be available if the single board computer is not connected to the internet.

If the system is in online mode, the data will be transmitted to a web server for storage. This data can be used to maintain records and analyze the system's performance. However, in offline mode, the single board computer's limited storage capacity means that only a small amount of data can be stored on the device. Except that, the system will perform as programmed.

A significant operational aspect of the system is the continuous real-time monitoring, even when the evacuation is in progress. As described in the architecture section, if a fire is detected on a floor that is scheduled for evacuation later according to the algorithm, the system will provide a fire alarm and voice signal based on an updated evacuation plan that prioritizes the occupants of the fire floor first.

Chapter 5 Conclusion

In this thesis, a study of existing evacuation strategies is done. It is identified that the existing evacuation strategies rely completely on pre-planning. During the course of building many changes may occur in the building design, its use, and the construction material and in event of fire, the spread of fire may not happen as expected. This was confirmed by case studies of some infamous fire incidents. It was also highlighted that the current on-scene decision making by the responders related to evacuation strategy is not standardized and is mostly based on previous experiences and limited information visible from the outside of the building. Therefore, a need for a smart evacuation system which could provide an evacuation strategy based on the real time condition inside the building is identified.

It is noteworthy to mention that research regarding the efficiency of evacuation algorithms is scarce. Specifically, studies concerning the phased evacuation strategy are even more limited. Therefore this could be taken as limitation of this thesis that it only relied on algorithm proposed by (Gravit et al., 2018). But nevertheless, the proposed algorithm was tested in chapter 3.

A comparative study of simultaneous evacuation and phased evacuation was done. For that the iGent building was modeled and Pathfinder was used to simulate the evacuation. For that, 3 different cases were considered:

1) Full simultaneous evacuation
2) Phased evacuation: Fire on floor 7
3) Phased evacuation: Fire on floor 2

The results were in-line with the results obtained by (Gravit et al., 2018). Key findings are mentioned here –

1) Less occupant density in the staircase was observed for phased evacuation making it a safer alternative. This directly links with less changes of injury and compression asphyxia during the evacuation.
2) Floors in close proximity to the fire were evacuated the earliest. Priority is given to the floors where the fire is more likely to spread, this ensures the safety of occupants present on these floors.
3) Almost no congestion time was observed during the phased evacuation simulation resulting in a streamline evacuation.

In chapter 4, the framework for a smart phased evacuation system was provided. The system would work based on the inputs obtained from the fire detection sensors and human counter sensors. The fire sensors would provide spatial & temporal information about the fire and the human counter sensor could help in determining the occupant load on each floor. Based on the current occupancy, the timing required for each floor to reach the exit point can be estimated. The proposed smart system will not just rely on the predefined algorithm, but it will constantly monitor the fire situation in the building. And in case the spread of fire is detected on a different floor as expected, the system will update the algorithm in real time and will come up with a new strategy.

Chapter 6 Future scope

1. **1.** The main task after this proposed framework for smart phased evacuation system would be to actually build a system and implement it in a high-rise building.
2. **2.** The proposed system is a part of the overall framework for smart firefighting. Therefore, it is highly recommended to discover the possibility of combining this system with the other related systems such as real-time fire simulation. That will help in predicting the spread of fire and preparing for a very early evacuation.
3. **3.** It could be important to explore this system's usability in skyscrapers because evacuation from a skyscraper may offer some additional challenges. Currently, this system is prepared focusing on evacuation using the staircase only, but this could be improved by taking into account the lifts as well.
4. **4.** The proposed system could be further developed to include the Bi-directional flow of the firefighters during the emergency, or the system should be further developed to check the real time availability of the staircases. In case a staircase may not be suitable to use, the system should be smart enough to provide an evacuation strategy based on the remaining means of escape.

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Appendix

Case studies of some infamous incidents

Case studies of some infamous incidents characterized by rapid fire growth have been highlighted here. These incidents serve as valuable examples for understanding the dynamics and challenges associated with quickly spreading fires, which may be hard to predict.

1. **The One Meridian Plaza fire in 1991, Philadelphia** – The fire ignited on the 22nd floor of the building. As reported, only three people were present, who were involved in the job of refinishing wood work. The fire was started in the pile of rags which were soaked in the linseed oil (Chubb, Jennings and Routley 1991).

   The building's construction materials also contributed to the severity of the fire. The building was constructed with a curtain wall, which is a non-load-bearing exterior wall made of glass and metal. This type of construction allowed the fire to travel vertically up the building's exterior and spread quickly through the floors. In this unfortunate incident, 3 firefighters lost their life after being trapped in the building's stairwell during the fire. The firefighters were exposed to high levels of smoke and heat during their attempts to extinguish the fire and evacuate occupants from the building.

Figure 34 One Meridian Plaza fire

(Source: https://en.wikipedia.org/wiki/One_Meridian_Plaza)

2. **The Caracas Tower fire in 2004, Venezuela** – The Caracas Tower fire occurred on October 17, 2004, in Caracas, Venezuela, and resulted in the deaths of at least 17 people. The fire started in the building's electrical room and quickly spread to the upper floors due to the lack of fire-resistant materials in the building's construction. (Moncada March/April 2005)

   One of the primary reasons for the evacuation failure here was the lack of an effective evacuation plan and proper training for building occupants. The fire alarm system in the building did not function properly, and the public address system was inadequate, which made it difficult to notify building occupants of the fire and give them instructions for evacuation. Additionally, the stairwells in the building were not clearly marked, and some were obstructed, which hindered evacuation efforts. Another factor that contributed to the evacuation failure was the building's design, which had limited escape routes. The building had only three stairwells, and they were narrow, making it difficult for occupants to evacuate quickly and safely.

Figure 35 Caracas tower fire, Dubai

(Source: https://en.wikipedia.org/wiki/Caracas_tower)

3. **The Torch Tower fire in 2017, Dubai** – The reported cause of the fire was a faulty electrical wiring in one of the apartments on the ninth floor. The fire quickly spread up the building's exterior cladding due to the strong winds and combustible cladding material, which contributed to the severity of the fire. A delay in the evacuation was observed in this case because a proper emergency evacuation plan was not in place and a communication gap was observed between the firefighting team and the occupants.

Figure 36 Torch tower fire, Dubai

(Source: https://en.wikipedia.org/wiki/Fire_torch_tower)

4. **The Grenfell Tower fire in London, England in 2017**- The infamous Grenfell tower fire incident occurred on June 14, 2017, in London, England. The fire broke out in the 24-story building, causing the deaths of 74 occupants. The fire reportedly began in a refrigerator-freezer in one of the flats on the fourth floor and rapidly spread up the outside of the building due to the building's cladding system. The cladding, which was installed during a recent refurbishment of the tower, was made of flammable material.

Figure 37 Grenfell tower fire, London

(Source: https://en.wikipedia.org/wiki/Grenfell_tower)

The other main reason of such large number of casualties was to have the "Stay Put" strategy. The "stay put" strategy instructed by the firefighting team to occupants to remain in their apartments unless they were directly affected by the fire, but in this case the strategy totally failed. The fire spread rapidly throughout the building, largely due to the combustible cladding. The fire spread between apartments and compartments, and the building's design and construction did not contain the fire as intended.

"Five years on, "stay put" remains the policy for fires in most high-rise buildings" – BBC News