STUDY OF CRITICAL FIRE SAFETY PARAMETERS AND DEVELOPMENT OF AN EVACUATION STRATEGY FOR HIGH RISE BUILDINGS

A thesis submitted to the
University of Petroleum & Energy Studies

For the award of
Doctor of Philosophy
in
Health, Safety & Environment

BY
Suvek Salankar

July, 2021

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DECLARATION

I declare that the thesis entitled **"STUDY OF CRITICAL FIRE SAFETY PARAMETERS AND DEVELOPMENT OF AN EVACUATION STRATEGY FOR HIGH RISE BUILDINGS"** has been prepared by me under the guidance of Dr. S. M. Tauseef (Internal Supervisor), Professor and Assistant Dean (R&D) - Department of HSE and Civil Engineering, UPES, Dehradun and Dr. R. K. Sharma (External Supervisor), Head – Sustainability, India Glycol Ltd, Kashipur.

No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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CERTIFICATE

I certify that **Suvek Salankar** has prepared his thesis entitled **"STUDY OF CRITICAL FIRE SAFETY PARAMETERS AND DEVELOPMENT OF AN EVACUATION STRATEGY FOR HIGH RISE BUILDINGS"**, for the award of Ph.D. Degree of the University of Petroleum & Energy Studies, under my guidance.

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ABSTARCT

Population is growing in large cities due to rapid urbanization leading to increased demand for housing and work space for people. But at the same time, such major cities face a shortage of land. To alleviate this contradiction, higher rise buildings are being constructed to have more people on a small piece of land. As high-rise buildings grow and these cities become more modern and complex, the risk of fire has become a primary concern. This makes fire fighting and evacuation very challenging. Furthermore, as timely safe evacuation is a major challenge for building designers and occupants, emergency preparedness plays an essential role in the overall management of fire safety. An important feature of emergency preparedness is the timely evacuation protection of building inhabitants from the fire.

For evacuation, there is a simple, universally accepted method, which is to evacuate the entire building through a staircase. But, in the case of high-rise buildings, it is very difficult to vacate the entire building within the required timeframe. This is because of the long distance traveled and the very high number of occupants. In the past, a few incidents have occurred in which occupants lost their lives in the stairs while evacuating the building. Therefore, a systematic approach to building evacuation is required to ensure that all occupants are evacuated in a safe and time-limited manner during a fire emergency. Consequently, managing the evacuation is an essential aspect of life safety. Its success depends on the systematic use of all egress components and their proper management. Few evacuation strategies are available such as phased evacuation, total evacuation, defend-in-place, and delayed evacuation. But all these strategies have their advantages, disadvantages and suitability

Evacuation management is also influenced by a variety of important factors associated with fire and smoke dynamics and building performance. All these parameters are discussed in detail in the present study. Scenario building models are considered to represent a realistic configuration of large commercial buildings is commonly used and has a high occupant and fire load. The scenario building is complex enough to represent the worst-case evacuation scenario for the study purposes. The parameters taken into account for the sample building models conform to national and international codes.

To study the concept of evacuation further, a computer simulation is used, which is a better alternative compared to actual physical simulation. Computer simulations are cost-effective, flexible, interactive and reliable. There are several evacuation models available and each has unique features with specialties and limitations and is discussed in detail in this study. Of the different models available, we have very limited models that can be used for this study. Pathfinder, an agent-based evacuation simulator, designed to study complex buildings fits into every aspect of this study. Also, there is a strong validation process for this simulation that makes it more reliable to capture more complex scenarios. It monitors the travel of different type of occupants with different mobility, according to needs, and the calculation of the speed of the occupants via emergency exits. The output visualization of this model allows the user to find the path through the models and modify the view adjustment to better analyze complex structures.

As time is the most important criterion in the safe evacuation of occupants, the basic purpose of this study is to optimize the evacuation time. This is necessary, so that people reach the required safe place in the shortest possible time. The first part of this study explains the optimization of evacuation time by various means related to the building infrastructure and the behaviour of the occupants. The first section of this study discusses a systematic and comprehensive approach to the various optimization methods available in the literature. These approaches fall into three broad areas. One deal with the design and infrastructure of the building, the second is setting the path and departure of the occupants and the third is a change in the behaviour of the occupants. In the second section, a simulation-based method is applied to different staircase designs w.r.t. the placement of exit doors. This involves studying its impact on the optimization of the evacuation time. Accordingly, the best possible configuration of the staircase is proposed.

In managing the evacuation, the anticipated evacuation time is always a critical consideration. This is necessary for deciding the design of the building parameters and also the evacuation strategy. If the evacuation time is known, from a design perspective, the geometry of the staircase can be decided, and also we can decide the evacuation strategy. Although there are few studies available to calculate the evacuation time that suggest a relationship between occupant discharges rates, occupant flow and occupant density. To further simplify, in the second part of this study, a fresh approach of estimating the evacuation time of stairs in high-rise buildings is suggested. This is calculated using various building parameters such as the stair width, the height of the building and the number of occupants. In this study, 120 building models are examined. The impact of all these parameters on the overall building evacuation process is also investigated.

During an evacuation, the most important requirement is to evacuate the occupant from the most affected area well before the tenability is reached rather than evacuate the entire building. This prevents occupants who are far from the fire hazard from being exposed to the fire hazard and may prioritize the evacuation of occupants who are at immediate risk. With this concept, using a well-known concept of available safe evacuation time (ASET) and required safe evacuation time (RSET), the safe evacuation strategy is suggested in the third part of this study. The tenability limit is one of the determining factors used in this study in deciding on a safe evacuation, suggesting the amount of safe evacuation time

available during an incident. In addition to tenability, other factors influence the evacuation, such as the time required for the remaining building evacuation, the time required for the total evacuation, occupant speed, population density, and flow rate are also studied and analyzed. A 50 storey office building model is considered as a case study and studied for its evacuation time. Different options of evacuation strategies like total evacuation, phased evacuation (progressive) with different zones are considered. A pathfinder evacuation model is applied to analyze various determinants and determine the best possible evacuation strategy.

All the suggestions put forward in this study provide a theoretical basis and technical support for the architectural design, the building management team and the relevant authorities. It helps to prioritize the evacuation of people who are at immediate risk and to determine the strategy according to the situation. The proposed mathematical model can be used to estimate the egress time for all building types. The main benefit of the model is its short computation time and easy computation method. It is useful in determining the RSET, which is useful to the designer for the safe design of the building. In addition, the maximum permissible load for occupants may be determined once we have estimated the required safe exit time. The proposed stair configuration to maximize egress will achieve the ultimate goal of occupant safety. The strategy proposed in this study will also be helpful in making a decision for the safe building evacuation.

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CHAPTER 5 OPTIMIZATION OF EVACUATION TIME DURING BUILDING EVACUATION

LIST OF SYMBOLS

η : Combustion efficiency

$: US dollars

ΔH_C : Calorific value of the combustible material

C : Centigrade

D : Population density (p/m^2)

K : Standard movement speed

M : Mass of combustible material in the compartment (kg)

N : Number of people entering the staircase

S : Practical movement speed (m/s)

T : Time of burning (s)

Q : Heat release rate (kJ/s) or (kW)

W : Enclosure width (m)

Y : Stoichiometric air fuel mass ratio.

d : Travel distance in the staircase between the two floors

k : Constant (value around Unity)

m : Mass loss rate (Kg/s)

n : Number of floors in a building

o : Number of occupants per floor per exit

t : Maximum time in seconds

u : Number of unit width

w : Width of the door (m)

A_t : Total compartment surface area (m^2)

A_o : Area of opening in the enclosure (m^2)

A_T : Total surface area of the compartment excluding opening (m^2)

A_O : Area of opening (m^2)

D_1 : Enclosure depth (m)

H_o : Height of the opening (m)

T_s : Time equivalent for fire severity (min.)

Q_t : Fire Load density (MJ /m^2)

Q_{fo} : Maximum HRR for flashover (MW)

Q_{max} : Maximum heat release during fully developed fire phase (kW)

Q_v : Peak heat release rate – Ventilated controlled (kW)

h_k : Effective heat transfer coefficient (kW/mK)

h_w : Averaged height of the ventilation openings (m)

m_a : Mass of air flow (kg/s)

t_1 : Time the last person entered in the staircase

t_2 : Time the first person entered in the staircase

t_s : Duration fully developed fire (s)

t_d : Time of onset of the decay phase(s)

$Q^{''}$: Fire load in compartment (Kg)

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LIST OF ABBREVIATIONS

AC : Air Conditioner
AMRI : Advanced Medical Research Institute
AHU : Air Handling Unit
ASCOS : Analysis of Smoke Control Systems
ASET-B : Available Safe Egress Time - BASIC
ASMET : Atria Smoke Management Engineering Tools
AS : American Standard
ASET : Available Safe Egress Time
BREAK1 : Berkeley Algorithm for Breaking Window Glass in a Compartment Fire (Computer model)
CAD : Computer Aided Design
CFD : Computational Fluid Dynamics
CFAST : Consolidated Model of Fire and Smoke Transport (Computer model)
CCFM : Consolidated Compartment Fire Model version VENTS (Computer model)
CO : Carbon Monoxide
CO_2 : Carbon Dioxide
CTBUH : Council on Tall Buildings and Urban Habitat
D : Dimensional
DETACT-QS : DETector ACTuation - Quasi Steady (Computer model)
DETACT-T2 : DETector ACTuation - Time squared (Computer model)
ELVAC : Elevator Evacuation
EN : European Norms
FDS : Fire Dynamics Simulator

FED : Fractional Effective Dose
FIRST : FIRe Simulation Technique (Computer model)
HVAC : Heating, ventilation, and air conditioning
HRR : Heat Release Rate
HRB : High-rise building
HCN : Hydrogen cyanide
IS : Indian Standard
IBC : International Building Code
kJ : Kilo Joule
LAVENT : Link-Actuated VENT (Computer model)
LPG : Liquefied Petroleum Gas
m : Meter
NBC : National Building Code of India- 2016
NFPA : National Fire Protection Associations
NIST : National Institute of Standards and Technology
NO_x : Nitrogen Oxide
PUC : Polyurethane
PVC : Polyvinyl chloride
RSET : Required Safe Egress Time
SO_x : Sulpher Oxides
W : Watt
WTC : World Trade Center
MW : Megawatts
kW : Kilowatt

CHAPTER 1

INTRODUCTION

1.1 High-rise Building

The population is increasing in the big cities due to rapid urbanization that increased the demand for lodging & working space for the people. But, at the same time, these big cities are also facing scarcity of land. To bridge this gap, there is more focus on the building of high-rise buildings due to its ability to accommodate more people on a small parcel of land. In our society, building infrastructure plays a very significant role & we spend the majority of our time inside the premises such as residences, shops, malls, workplaces, etc. In the U.S., people stay in the building 90 percent of their time [1]. Buildings are also the main infrastructure built and are needed for growth in any country. The building is designed to remain there for many years and help many people for their residential, professional, commercial, health care and much more throughout their lives. Modern-day construction technology aided by 3D modelling using sophisticated software is also supporting this concept to enable maximum occupancy per unit ground area.

Once those cities hit the sky with their large, growing buildings, they try to attract as many people as possible. Once they attract more people, more buildings and facilities are required, and that's going to continue. During the sixties and seventies, industrial trade in the US was flourishing, which resulted in a race for the tallest building in the world. It was considered as an indication of power and wealth and today everyone wants to build and stay in a large building.

It is also essential to be aware of the meaning of the high-rise buildings. Surprisingly, a high-rise building does not have a precise definition. Various standards have defined "high-rise buildings" in a number of ways: [2]

1. A building with "many stories" based on the Oxford English Dictionary.
2. Greater than 70 feet (21 m) as per US General Laws.
3. "75 feet or greater" measured from the lowest access level to the highest Floor in accordance with the International Building Code (IBC), the Building Construction and Safety Code, and 'National Fire Protection Associations' (NFPA) of the Life Safety Code-101.
4. India has different definitions based on different development control rules. According to the National Building Code of India-2016 (NBC), it is a building with a height of 15m and above [3].

In addition to tall buildings, there's a concept of large, very large, and mega-tall buildings. According to CTBUH i.e. Council on Tall Buildings and Urban Habitat [4], tall buildings are buildings with a height of 50 m or above, super-tall buildings are buildings with a height of 300 m or above, and Mega tall buildings are buildings with a height of 600 m or above.

When we look at the history of high-rise buildings, we see that humans have continually challenged the heights of the building. As a result, the concept of a high-rise building has evolved over the years. Vertical growth has traditionally symbolized supremacy and authority. The term "skyscraper" has been used to distinguish tall buildings from the late 19th century. By the 1920s and 1930s, few skyscrapers had been built. The United States is considered the cradle of the skyscraper. Tribune Tower, Chicago (141 m) was constructed in 1925, Chrysler Building, New York City (319 m) was constructed in 1930, Empire State Building, New York City (381 m) was constructed in 1932. In the sixties and seventies, two buildings were built. In 1972, the World Trade Centre in New York of height 417 m., which got destroyed in a terrorist attack on September 11, 2001. Another emblematic building is the Sears Tower, built in 1973 with the height of 442 m [5].

New financial centers were booming around the world, particularly in the big cities of developing countries such as Tokyo, Delhi, Mexico, Shanghai, Beijing, Mumbai, Dubai, etc. This began with a high demand for commercial and business buildings and further stimulated a vertical construction boom in these cities. At the same time, it is noted that countries such as Dubai and Abu Dhabi have rapidly changed their natural environment into large buildings composed of glasses. It was completely distant from their climatic requirements and they were not aware of the cost of the energy consumed and the damage to the environment. Today, this is a major concern for all of us and sustainable development is no longer a choice, but a necessity.

On the positive side, when it comes to population density, large buildings can be considered environmentally friendly, as they occupy minimal space, facilitate public transport and optimize the potential use of public facilities. They also have some challenges due to their features like deep plan, urban shadows, less use of natural ventilation, solar reflection, sealed glazed facades, glare, etc.

Up to the year 2000, there was not a single building constructed of height above 150 meters in India. But today there are 64 buildings of height more than 150 meters. Globally also, a similar trend is observed. Up to the year 2000, there were only 319 buildings above the height of 150 meters, but today there are 2809 buildings constructed across the globe. Similarly, there were only 4 buildings constructed above the height of 300 meters, but now there are 51 buildings available globally. This shows a tremendous rise in the number of such tall buildings [4].

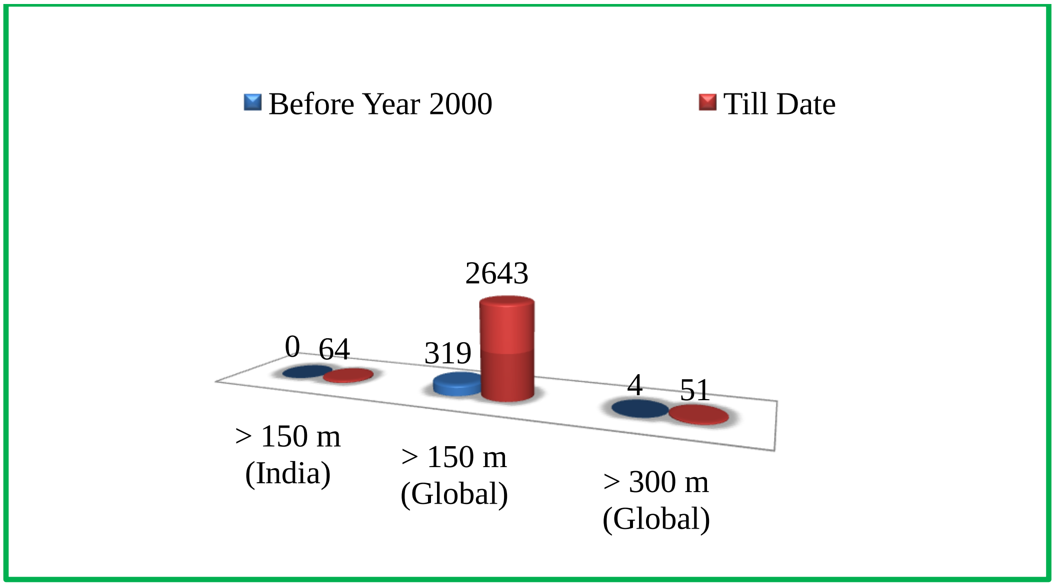


Fig. 1.1: Rise in construction of tall buildings in recent years

1.2 Challenges in a high-rise building

The rapid increase in construction of high-rise buildings raises various concerns because of its high population density, has exceeded the fire load, complex layouts and other complexities as well as its height. Currently, fire is a key concern and saving lives and property because of a fire is a significant challenge. These buildings are often iconic buildings and if there is a fire, the ‘landmark' reputation may deteriorate and impact the surrounding urban area. The functional diversification of these buildings also makes it difficult to carry out both the evacuation operations and firefighting. There are various vertical elements such as lift shafts, pipes, conduits, electric shafts, facades through which fire can spread very rapidly in the absence of appropriate fire separation. The result is a reduction in available escape time. This becomes even more complicated as regular elevators are not available during the fire as stairs are the only available and conventional channel for vertical egress. With over 100 floors and thousands of occupants, evacuation of the entire building can take over one hour. The result would be excessive queues, blocked evacuation points, prolonged evacuation, and possibly a stampede or death.

Another challenge is to have proper smoke management to support the firefighters in controlling the fire propagation and making sure the accessibility of the evacuation routes. It also leads to poor visibility.

There are various fire incidents in high-rise buildings which have resulted in catastrophic loss of human life and property, such as the World Trade Center (WTC) towers (2001), the CCTV/TVCC tower (2009), a fire in Shanghai (2010), AMRI Hospital (2011), etc. Compared to fires in low-rise buildings, fire behaviour in high-rise buildings has some unique features such as quick spread of fire and smoke, structural damage, and difficulty in evacuation. This is due to the high usage of the facade, complex building structures, fire and occupant load. In recent years, the facade industry has developed very quickly through advanced production techniques [6]. Because of the demand for energy savings, organic insulation such as polyurethane and polystyrene are usually used for the production of exterior walls in high-rise buildings. However, when these materials ignite, they can spread quickly and produce large toxic products. Therefore, the fire safety of façade materials is of paramount concern to high-rise buildings. The presence of a staircase, lift shaft or other structure leads to a chimney effect and a piston effect. It plays a main role in the spread of fires and smoke. Therefore, the study of smoke movement and the associated hazards to building inhabitants is very important [7][8].

During a fire, there is a potential break in the glass windows. The fire may go out of the broken window and is very difficult to control. To study this, Chen [9] carried out various experiments on float glass in a closed compartment with radiant heat. He studied the outcome of the shaded width on the rupture behaviour of window glass. Therefore, the fire resistance of glass is an important requirement because of the increasing usage of glass for curtain walls.

Human behaviour shows multi-directional intricacies in these scenarios. This relates to the behaviour of using the evacuation components, the relevance of their decisions and actions, their behavior with other occupants, etc. and consequently many problems must be solved when evacuating people. To study the behavioral aspect and the dependent problems, Ding et al. [10] carried out an extensive experiment using elevators.

It observed that the number of occupants influences their behavior. Also, the evacuees' queue with the shape of the line went slower than the shape of the arch. In high-rise buildings, these problems are more important due to their typical characteristics and therefore rescue, firefighting and evacuation are very difficult. At the initial stage of the fire, the horizontal spread of smoke is 0.3 m/s. In the fully developed stage, it can be up to 3-4 m/s vertically. To illustrate this, if there is a fire in the 100 m high building, smoke will travel to the top floor through the vertical shafts in just 30 seconds. The minimum evacuation time is therefore a key factor for a secure evacuation.

Due to the high occupant load and long vertical distance, we need more time to get out of the building. Additionally, once the building catches fire, it unblocks the airflow. It results in the rapid smoke/fire spread that increases the difficulty in evacuation. Further, from the exterior, fire fighting is not very effective because of its height and has to rely on an inbuilt fire protection system [11]. Identifying the origin of the fire is also very difficult due to the complexity of such buildings that leads to wastage of time and further spread of fire.

The piston effect is created by the movement of lifts in the shafts. In a single lift shaft, a duel effect may occur. It can create a pressure difference in the lift lobbies that move the smoke into the protected lobbies and finally into the lift shaft. It depends on the speed of the lift.

Heating, ventilation, and air conditioning (HVAC) is the basic requirement in high-rise building. Modern buildings have HVAC that contains air ducting, usually recycling air in the building. It mixes with the air of external atmosphere. These systems create a slightly positive pressure in the buildings, which means that the airflow continues to circulate. During a fire, smoke travels through these ducts and spreads further.

The stack effect, also known as the chimney effect, is a common occurrence during high-rise building fires. In a fire, buoyancy due to heat results in air displacement. Here, the warm air goes up and the cold air goes down. In staircases and elevator shafts, such effects are always very obvious.

1.3 Fire statistics

As per the world fire statistics 2020 [12], India suffers the most deaths due to fire per year across the world. In 2018, 4.5 million fire incidents caused 30812 deaths and 51351 injuries in developed and developing countries across the globe. It is very unfortunate that though the frequency of occurrence of a building fire is more as compared to other extreme events like earthquakes, floods, etc., the subject of fire safety has not received adequate importance in the overall fire safety vertical. According to NFPA [13], U.S. fire services responded to 1291500 fires in 2019. It caused an estimated annual average of 3704 deaths and 16600 injuries and $ 14.8 billion in direct property damage. This number is very high against 180 deaths caused by natural disasters in 2019 [14]. As per India Risk Survey [15], the risk of fire is third most dominant risk for business operations in 2018. From Aug 2018 till date, there were a significant number of incidents of fire in various occupancies in various cities in India. This indicates the risk continues to be a concern for all businesses. The National Crime Records Bureau [16] reported a total of 11037 fire accidents in 2019 with 441 injuries and 10915 deaths.

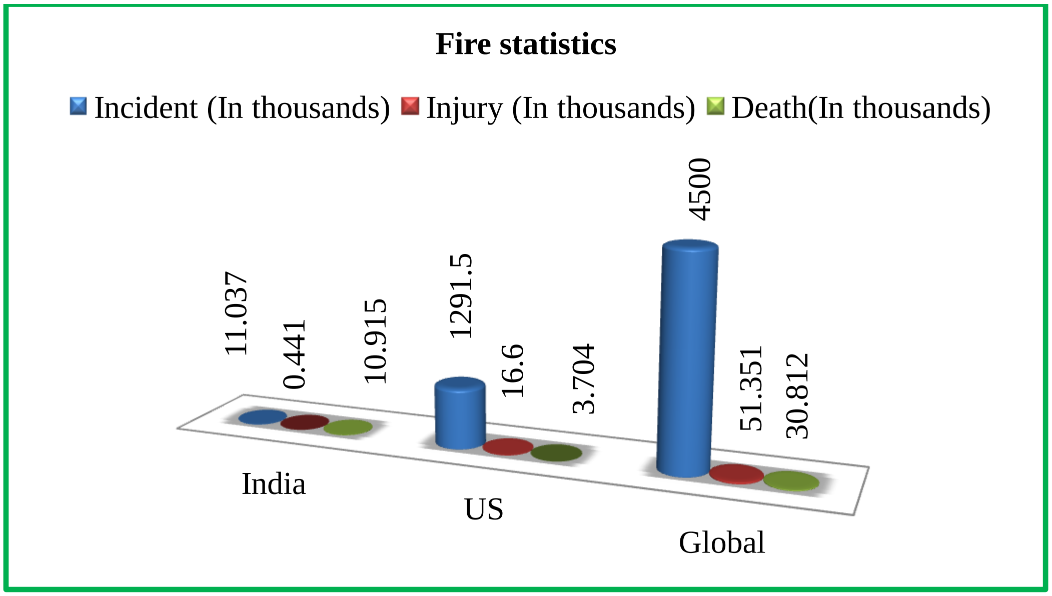


Fig. 1.2: Fire incidents and its consequences in recent years

This data is clearly showing the need for attention on fire incidents and the provision of necessary fire safety precautions along with the timely evacuation of the affected people to minimize adverse effects of fire hazards. In high-rise buildings, two leading factors affect the building evacuation, one is fire patterns and the other is the escape factor [17]. Evacuation factors are related to lack of familiarity with exits, longer evacuation distances, poor selection of exits, returns to affected area and catch fire on clothing. Fire pattern factors refer to the physical situation of the area, such as blocked exits by fire products, obstructed vision and trapped residents. In 79.6% of cases, contact with fire products was the main reason for the injury. This highlights the need for an appropriate system for safe evacuation.

1.4 Case studies of some of the major high-rise building fire incidents

Case Study 1: Jiaozhou Road, Jing'an District, Shanghai, China [18-24**]**

Date : 15th November, 2010

Time : 2.15 p.m. (Local time)

Building details : 28 storey residential building.

Brief Description :

The Shanghai building was being renovated as part of an energy conservation project. The scaffolding used in the construction project consisted of combustible wood platforms and nylon nets. The fire took place on the tenth level of the building. It began with building materials and propagated throughout the building. Firefighters were unable to carry water from the hose pipes to the upper floors from the ground floor. The building resided about 440 people with the majority of more than 50 years of age and the majority died as a result of asphyxiation caused by smoke inhalation.

Fig.1.3: Shanghai building fire with combustible scaffolding platforms used for renovation work

Loss : 58 people died and 70 others suffered injuries.

Probable reasons:

1. Sparks from welding work on the building ignited the timber scaffolding that covered the building.
2. It was surrounded by a steel scaffold. Wooden boards and bamboo were kept for workers to access and work. In addition, the scaffolding was surrounded by nylon net.
3. Ignition of polyurethane foam (PUC) provided outside the building for insulation and the flame retardants were not added. After burning, it has generated poisonous gases such as carbon monoxide and hydrogen cyanide.
4. Lack of fire sprinkler system and unavailability of water on the upper floors. Firefighting equipment could not reach the upper floors.
5. The fire spread rapidly because of a highly combustible material and good air flow.

Learning :

1. There should be an appropriate risk identification process for conducting such activities and action to be taken accordingly.
2. Whenever possible, avoid the use of combustible materials.
3. The work permit system should be strictly monitored, in particular for critical work such as hot work.
4. Ensure all occupants are aware of the emergency preparedness plan as well as their roles and responsibilities.
5. Emergency preparedness should be ensured at each corner of the building.
6. Adequate evacuation plans and strategies should be developed and evacuation drills conducted regularly.

Case Study II: Advanced Medical Research Institute (AMRI) Hospital, Kolkata, India [25-27]

Date : 9th December, 2011
Time : 2.15 a.m. (Local time)
Building details : 7 storey hospital building.
Brief Description:

There was a fire in the basement of the "annex" building of the AMRI Hospital early in the morning at 2:15 a.m. They called the fire department at 04:10 a.m.

The fire was primarily ignited and limited in the basement, but the smoke was transmitted through the air conditioning ducts and also to all the corridors. Soon the entire building was filled with heavy smoke. This resulted in serious suffocation of all available occupants inside. Ninety-three patients died while they were sleeping or were unable to escape.

Unfortunately, this was the second fire in an AMRI hospital in the last 3 years. The state authority had already informed the hospital administration earlier about the unacceptable and dangerous use of the basement.

Fig.1.4: AMRI Hospital fire

Fig.1.5: Firefighters evacuating a patient

Loss : Death of 93 people and many injured

Probable reasons:

1. The basement, designed for car parking, was used to store combustible materials such as LPG and oxygen cylinders, torn mattresses, wooden boxes and PVC tubing.
2. The fire probably resulted from an electrical short-circuit in the basement.
3. Smoke alarms were not activated, which reduced the response time and helped the fire spread further.
4. All of the fire protection system did not function during a fire. Staff was not trained to handle basic fire safety. This caused the fire to propagate rapidly.
5. The fire did not spread to the rest of the hospital except in the basement. Smoke was spread through AC ducts, which did not trip automatically and the fire/smoke dampers did not work/provide.
6. The central air-conditioned hospital did not have openable windows to the glass facade walls, which are mandatory. This resulted in smoke entrapment within the building.
7. Hospital management informed the local fire brigade of the incident after more than an hour and a half and lost the golden time of firefighting.
8. There was insufficient emergency lighting, which detracted from rescue and firefighting efforts.

Learning :

1. All compliance with the law and regulations must be strictly complied with and implemented to protect people's lives.
2. Emergency plans should be in place with clear guidelines for all concerns about their roles and responsibilities in various emergency scenarios and, accordingly, they should be trained. A suitable evacuation strategy should be decided for

different situations. Mock drills should be conducted to check overall preparedness.

3. All fire detection and protection systems shall be well maintained and always in good working order.
4. All staircases should be enclosed type with proper ventilation/pressurization.
5. At least one stairway shall open directly at ground level outside the building to allow for a safe evacuation.
6. Windows shall be capable of being opened for rescue and firefighting.
7. An appropriate ventilation and smoke exhaust arrangement should be installed in the basement to manage the smoke.
8. Do not store combustible materials in a building.

Case Study 3: Carlton Towers, near the old airport road, Bengaluru [26-27**]**

Date : 23rd February, 2010
Time : 4.30 p.m. (Local time)
Building type :

Commercial building with two parts.

Part-1: 27 m height, comprising common basement, ground, and 7 upper floors.

Part-2: 23.95 m height, comprising common basement, ground, and 6 upper floors.

The ground & 1st floors were designed for retail area and upper floors for office use.

Brief Description :

Fire started in the middle of the first two floors, in the electrical shaft of the building to the electrical cables. Few exits were locked and building management, even after observing smoke outside the building, did not open any exits.

Initially, the occupants of each floor of the building were ignorant of the smoke as they have not heard any alarm/warning communication and some people, who tried to get evacuated, were trapped due to locked fire exits.

Approximately 300 persons were rescued by firefighters.

Fig.1.6: Fire at Carlton Towers, Bengaluru

Fig.1.7: Firefighting operation during the Carlton Towers fire, Bengaluru

Loss : 2 deaths due to suffocation and 68 occupants were injured.

Probable reasons :

1. Along with the original cables, there were few extra cables from which the fire was caused due to electrical arcing, which may be due to a fracture in the internal conductor/ deterioration of conductor/abrasion.
2. To lay down extra cables, the floor seal was removed and was not provided again. This allowed the dense smoke to move upward, then horizontally resulting in a proliferation of smoke within the building.
3. The heat source appears to be the electricity-induced heating and ignition of the

power cord.

4. As the occupants were not aware that they should not use the elevators in the event of an emergency, a few occupants used the elevators and became trapped when the main power supply failed. The alternate supply did not function either.

5. The detection system provided in the building was not maintained and in some locations either covered with false ceilings or was removed.

6. On three staircases, one was in the center and one each on the two flanks with collapsible doors on the ground level. The exit route from the stairs on both flanks was locked. Also, fire doors provided at each staircase landing have been locked and the common passage between the staircases at 2nd, 3rd & 4th-floor levels have been modified and subsequently blocked with additional constructions/ alterations and shutters. This prevented the upper storey occupants from moving horizontally between smoke-filled and smoke-free areas. The doors to each stairwell, leading to the terrace, were also locked, preventing the occupants of the upper floors from escaping to the terrace. As a result of all of these factors, the occupants were trapped in the interior of the building.

7. The fire fighting system was not maintained and thus did not operate during the fire. The fire hydrant doors on each landing were latched.

8. The ground & first floor sprinkler system were removed and the underground system was not functional.

9. Most extinguishers were found missing and some available extinguishers were defective.

10. Most of the occupants were not aware of the topography of the building and the location of the exits. This impeded their movement and was stalled in the affected areas.

11. On the ground floor, the common passageway leading from the stairs to the exterior of the building was blocked when it was converted into a change room and storage space.

Learning :

1. All firefighting and life safety measures should always be healthy and operational.
2. Emergency exit doors must not be blocked and locked.
3. The means of egress from the building must be designed to accommodate the occupant load, but during this incident, only one-third egress was available impacted the evacuation process. This must be addressed and, if necessary, other arrangements made.
4. The electrical wiring shall be either armored type or should be through conduits.
5. Appropriate signage for evacuation plans should be placed in strategic locations.

1.5 Background and Significance of the study

As mentioned in section 1.3, thousands of fires occur each year and cause injury, loss of life and property damage worldwide. There are a number of reasons behind these incidents.

High-rise buildings have some basic complex features such as height, several vertical shafts, high occupant load, high fire load and high electrical load, etc. All these characteristics lead to the rapid spread of fire/smoke, difficulties in firefighting, and in rescue/evacuation operations. Here human losses are due to the products of fire, mainly carbon monoxide and other toxic byproducts depending on the burning material and also due to the effects of heat or the inhalation of hot gases. The effects of heat and smoke are usually faster than the effects of direct lesions caused by the flames. So the most important criteria next to fire prevention are to design the system of fire fighting and life safety in such a way that there will be minimum acceptable damage. This is normally associated with the design of appropriate evacuation components and the fire safety should be managed appropriately. The design of the evacuation components is important for the safe evacuation of the building, but its systematic use plays a crucial role in the building's evacuation systems to minimize loss of life. There are various egress components such as staircases, evacuation elevators, sky bridges, refuge floors, controlled descent devices, escape chute, etc. But each component has its advantages and its deficiencies. The traditional method to evacuate any building is by using a staircase. Although, there are a few limitations like behavioural aspects, ergonomics, group behaviour, gender, merging streams, fatigue of occupants, evacuation of disabled people, the counter flow of firefighters, long time required for tall building evacuation [28]. So we need a strategy to use a staircase for the best results of a safe evacuation. The evacuation strategy aims at the time required to safely evacuate all affected occupants along with other critical factors. It is thus generally very important that the building and its compartments remain integrated for a period that allows the planned evacuation. Therefore, the evacuation time is very important in the overall process to know the time needed to move from the affected area to a safe area.

There are few studies available for calculation of evacuation time for a high rise building. The methodology used for these studies is not very easy and the inputs required are also very complex. In some cases, it depends on population size and, in some cases, population density, and therefore the method of calculating evacuation time varies. In some cases, the determinants for calculating evacuation time are very complex.

In this study, a simple mathematical model is established to determine the egress time of a high-rise building. This is done using basic parameters such as the width of the stairs, the occupancy load and the number of floors. The study also proposes the best possible methods for an evacuation strategy based on the different determinants observed during the evacuation. The basic concept is to save people who are in immediate danger rather than evacuate the entire building. In addition, given the importance of minimal evacuation time, the study proposed the best staircase design for minimal evacuation time. It is hoped that this will guide all concerns such as designers, building management, trainers, occupants and other organizations that may be affected by a fire.

1.6 Chapter Scheme

The thesis comprises eight chapters followed by references and appendix.

Chapter 1: This is an introductory chapter that explains the details of the high-rise building and associated challenges from a fire and life safety perspective. Case studies to showcase the importance of fire safety in a high-rise building were also examined.

Chapter 2: Research objectives are defined in this chapter.

Chapter 3: A detail review of the literature for various significant factors related to fire & smoke dynamics and building performance like various fire hazards along with its consequences & their control, fire behaviour, tenability criteria, occupant load, and means of escape are presented in this chapter. The current trend of evacuation is also discussed with computer modelling available for fire safety.

Chapter 4: Details of the research and the methodology employed are described in this chapter. The assumptions made in this study are also given.

Chapter 5: Presents analysis of different methods of optimization for evacuation time. The optimization of different staircase designs is investigated and proposed the best possible design.

Chapter 6: A new methodology for calculating the evacuation time of a high-rise building, with examples and validation is presented in this chapter.

Chapter 7: In this chapter, various studies of evacuation strategies available for the buildings are referenced and the safest escape strategy is proposed based on a variety of determinants. It includes floor evacuation time, the time required to evacuate of the affected fire zone, occupant speed, population density, and flow rate during evacuation.

Chapter 8: This chapter provides an overview of the research and presents the limitations and scope of the new studies.

CHAPTER 2: OBJECTIVES OF THE STUDY

The safe evacuation of the affected area during an emergency is a major fire safety challenge in high-rise buildings. From a fire safety perspective, high-rise buildings are more difficult than other buildings in terms of occupant load, travel distance, and fire load, which leads to a longer and more complex evacuation process.

The intent of this study is to analyze and identify the factor that are responsible for building performance related to fire safety and suggest the best possible strategy for the safe evacuation of inhabitant with respect to the design of the staircase and priorities of the floor for safe evacuation.

As there is a variety of building elements like the height of the buildings, floor area, occupancy, and staircase width, the scope of this study is limited to high-rise buildings with business occupancy.

The goal of this study is to offer information to support all stakeholders in making appropriate decisions about the best method of evacuation and conduct a thorough assessment to further develop the fire safety plan framework based on the findings.

Accordingly, the following are the objectives of this study.

1. Identification of significant factors related to fire & smoke dynamics and building performance.
2. Identification of sample building characteristics and decide its zoning

3. Study and selection of suitable fire and evacuation models.
4. Identification and development of the best possible evacuation strategies for a building to minimize the loss of life.

CHAPTER 3: LITERATURE REVIEW

3.1 Significant factors related to fire & smoke dynamics and building performance.

Fire safety is about providing and maintaining a safe environment for all stakeholders to minimize the risk of human life, personal injury, damage of assets. and loss to the business. Consequently, the design of the building should be such that the possibility and impact of a fire is reduced. In addition to fire prevention, it is important to control the spread of fires at the initial stage while facilitating an appropriate evacuation process and quick communication with building occupants. With this aim, the overall objective would be to control fire in the early stage, smoke control, and toxic gases, facilitate the ways to allow people to escape, and provision of adequate structural strength. A number of fire protection measures are listed and classified under Hardware and Software. Hardware refers to physical structure that is integrated into the building and software means direct or indirect control of persons in relation to fire safety or dependability of hardware systems [29].

In this chapter, we mainly discuss hardware, related to the fire safety of the building performance. This can be grouped under three basic parameters: fire hazards in the building, the consequences of those hazards, and building interference to control those consequences along with different stage of the fire and different regime of burning which is useful for building evacuation

3.1.1 Fire hazards

Fire hazards are the fuel and ignition source available in the building. It includes everything in the premises that can be burned, aggravate the fire, disable the fire protection provisions of the building and hinder the firefighting function in some cases. Ignition sources include live flames, heating devices and hot surfaces, static electricity, chemical reactions, electrical short circuits, pyrotechnics and sabotage. Available information indicates that the primary reason for the fire in buildings is cooking [30].

After ignition, the fire may become more severe, depending on the ventilation available and the fire properties of the material. These include liquid petroleum gas, paints, ammunition, and natural gas. Combustible construction parts, such as composite panels and wood, also play an important role in generating toxic smoke. This also includes structural materials such as steel, wood, glass facade, false ceiling, glass partitions, and windows. Improper fire compartmentalization design can be a reason for quick fire growth and its propagation due to supply of a continuous oxygen supply to the fire. These issues directly affect or increase the severity of the ignition [29][31][32].

3.1.2 Consequences of fire Hazards

Fire hazards result in significant loss of life, property damage, environmental impacts and reputational damage.

Loss of human life: During the pre-flashover stage, combustion generates toxic gases like carbon monoxide, hydrogen cyanide, phosgene, which are extremely harmful and can be lethal within a few seconds even inhaled in little quantities [33][34]. The smoke produced by combustion also contains tiny particles of soot and toxic vapour that can irritate the eyes and digestive tract. Therefore, more deaths are caused by smoke than by the combustion itself [13]. Additionally, smoke and hot gases obstruct evacuation routes, further increasing the risk to people's lives.

Another fire threat is declining oxygen levels and hot air inhalation. When the oxygen level is below 17 %, humans exhibit poor judgment and loss of coordination. With the further drop of oxygen levels, human issues increases further such as 12 % occur headaches, dizziness and fatigue, at 9% the person may be unconsciousness and there may cardiac arrest when oxygen levels comes to 6% and person may die [13]. Moreover, inhalation of hot gases can burn the respiratory track and even can cause death [35].

Property damage: Another biggest risk to human life during the post-flashover phase is a collapse of a structure. This hampers the firefighting operation apart from the human loss. During a fully development phase, the fire temperature can exceed 1000°C, which can cause major deficit in the strength and rigidity of structural material such as steel, concrete, wood, etc. [36]. Material degradation can incapacitate structural elements and the building may collapse either during or following a fire. The material of construction also plays a crucial role in a fire to decide the stability of the building. Steel loses 2/3 of its strength at 600^{o}C which is known as its critical temperature [37].

Direct losses include property damage, loss of material due to fire. Also, there are few losses during firefighting such as damage to property caused by water, breaking of doors and windows, etc., structural harm, and cost of renovations. While indirect losses include time lost during the repair period, loss of relocation, loss of demolition of a constitution, higher insurance expenses, etc.

Environmental impact: Fires produce numerous environmental pollutants. Some of the pollutants include metals, particulates, hydrocarbons, chlorinated /

brominated dioxins and furans, etc. [38]. During a fire, the spread of these pollutants into the environment creates air pollution, from fire-fighting water runoff with fire products that cause water pollution and airflow, and water contaminants that cause soil pollution.

Loss of credibility: Credibility can be impacted as a result of the fire, depending on its severity. It can be a loss of stakeholder confidence, credibility, and regulatory enforcement.

3.1.3 Fire safety measures

Various building features contribute to the development of the fire and support vertical fire propagation. A large continuous window, open fire doors, ventilation compartment walls, extinguishing and ventilation conditions contribute to the horizontal spread of the fire. Vertical fire propagation is caused by flames through broken windows, lobbies or vertical wells [39] [40].

While various fire safety measures are necessary to achieve the intended objective, they can be categorized into three main sections.

1. Fire Prevention: Refers to the design and construction of the structure to prevent ignition by fire and the use of the material with the fire rating.
2. Life Safety: Includes items needed to limit the threat of fire, smoke or panic for life.
3. Fire Protection: These are the building's fire protection facilities and equipment to minimize fire damage.

Few elements may be part of more than one category mentioned above, as there is a very thin line between some of the categories.

3.1.3.1 Fire Prevention

Fire prevention is generally aimed at avoiding contact between the fuel and the ignition source and can be achieved through the following parameters.

A. Occupancy classification

A primary cause of fire is the failure to identify, recognize or foresee existing hazards. It is a very important component of any effective safety program. For this to happen, it is very imperative to understand the use of the building so that general hazards can be identified and restricted. All the codes classified the occupancy based on their use. NBC [3] classified as the business, residential, educational, industrial, institutional, assembly, mercantile, storage, and hazardous. On similar grounds, occupancies are classified in IBC and NFPA – 101 [41][42]. There are various aspects of fire safety related to occupancy, such as familiarity, occupant load, physical condition, occupant preparedness, resource availability, applicable codes and standards, fire load, etc. These parameters aid in deciding the future fire safety strategy.

B. Construction material

The materials used in the construction of any structure are an important factor in making that structure resistant to further combustion and in stopping the rapid spread of smoke, fire or fumes. As per NBC [3] and other Indian standards like IS - 1641 [43], the types of construction are categorized into four types, that is, Type 1, Type 2, Type 3 and Type 4 based on its fire-rated properties. Construction type 1 is with the highest fire resistant and type 4 is with the lowest fire resistant. Accordingly, type I construction is always suggested for high-rise buildings.

Currently, steel-framed structures are extensively used in high-rise buildings due to their qualities with respect to strength and seismic performance. On the other hand, from a fire perspective, the properties of its materials decrease considerably at elevated temperatures. To ensure the safe evacuation of inhabitants, the structures must be stable for at least some time, depending on the category of occupancy [44]. Several studies have been performed on the vertical and horizontal propagation of fires. The behaviour of a steel frame exposed to a variety of localized fire situations was studied by Rackauskaite and El-Rimawi [45]. He suggested that fire compartmentation in unprotected steel structures is essential for safe means of access and it also enhances the ability of a building to give occupants more time to escape. Kotsovinos et al. [46] studied the collapse mechanisms of large burning buildings and carried out a study using various fire propagation rates. It showed that travelling vertical fires had a major impact on buildings rather than simultaneous fires.

The impact of structural fire resistance on fire evacuation is also significant. It is therefore necessary that all structural and/or non-structural components have the required fire resistance rating. Moreover, the false ceiling, along with all the required luminaries must also be of non-combustible material. Cement is also widely used for building construction. At 300°C, it loses water, and it loses its strength. But the good part is, its absorption heat rate is low and therefore only prolonged intense fires can cause any weakening of concrete structures [47].

Fire resistance is important in both structural and non-structural elements. It is measured in three parameters as described in AS-1530 [48]. This is indicated in the minute/minute/minute model, for example 120/120/120. The first digit denotes the necessary stability of the element. It is a load-bearing component of the building. The second digit indicates the integrity of the substance. It is the ability to separate the fire and prevent flames and hot gases from penetrating the elements. The third digit is related to its ability to keep the temperature on the not-burned side below specific criteria. It is also referred to as material insulation.

C. Separate service ducts

There are various construction services such as cables, electrical wiring, telephone cables, plumbing hoses, etc., that have to be traversed throughout the building. It should be in the floor opening confined by the enclosure in the form of a duct. Since vertical service ducts allow vertical fire propagation, these ducts should be fire rated. Normally it is 120 minutes for the electrical shaft and 30 minutes for the plumbing shaft [3]. For the installation of electrical cables, medium and low voltage cables in the duct must be either protected or passed through metal conduits. The space between the supply cables and the walls shall be sealed with fire resistant material. Interphone cables, water lines, gas lines, telephone cables or any other service must not be placed near electrical cables. If gas lines are provided, the same must be maintained in a separate area only for this purpose, on the exterior walls, away from the stairs. The pipes must not be sealed and always visible as in the case of a false ceiling, it must be under the ceiling and must be as short as possible.

D. Electrical installations

These include sub-stations, diesel generators, etc. necessary for building the infrastructure. All of these facilities must be properly ventilated to prevent heating. A separate, ventilated or air-conditioned room for medium voltage panels should be equipped with fire-resistant walls and doors. For an oil substation, it should be located 7 m from adjacent buildings [3]. Areas designated for electrical installations should not be used to store combustible materials as they can be used as fuel and trigger a fire.

E. Glass Façade

Today, the glass façade is also a major cause of fire propagation [49], so it is always advisable to avoid using glass for exit and exit enclosures. According to regulations, it is allowed only in case the completely sprinklers installation with a fire separation of at least 9 m and tempered glass in a non-combustible assembly, with the capacity to grip the glass. There is always a potential for fire or smoke in the glass façade. The gaps between the slab and the facade must therefore be sealed at all levels. Open facade panels must be installed on each floor to help occupants and firefighters access the smoke evacuation during a fire.

3.1.3.2 Life safety

The ultimate goal of any fire safety measure is to save a life in case of an eventuality. Therefore, each building must be planned, constructed, prepared, supported, and managed to provide sufficient means of egress to protect the inhabitants from fire, smoke, gas, or fear during evacuation. It consists of the following key components.

A. Means of Egress

It is an uninterrupted means of moving anywhere from a building to a public road or safety area. It has three individual parts, exit access, exit and exit discharge that are discussed in depth in the next section. Its primary goal is the safe evacuation of any part of the affected building to a safe location.

B. Refuge area

This is a place where affected inhabitants, who are unable to use the stairs, can wait for instructions or support during an emergency evacuation for a short time. It is delivered to all high-rise buildings in accordance with their respective standards.

C. Fire Door

Fire doors perform two important roles from fire safety point of view. First, it ensures the instant evacuation of the occupant in case of emergency and can leave the danger zone quickly and enter the exit faster. Secondly, it performs the role of a fire barrier to ensure the safety of the unburned area for a certain time depending on its capacity.

D. Staircases

Stairs are an important component for the safe evacuation during a fire incident [50]. It plays a significant role during the evacuation since it is normally the only means of escape. In recent years, stairway accidents have occurred several times because of clogging during evacuation, which resulted in an enormous number of injuries, including loss of life. This shows that stairs are a hidden danger and can create tremendous social panic if not used properly [51].

The width and number of stairs vary as per the type of occupancy, the number of occupants and the travel distance [3]. High-risk buildings, such as tall buildings, should have a minimum of 2 stairs. The number of steps in a flight of stairs must be limited to 12 in accordance with ergonomics and fatigue. Stairs shall be made of non-combustible resources with a minimum fire resistance of 120 minutes. It should not be used for purposes such as exhaust system, vents, gas pipes, electrical boards, AC units or any mechanical equipment. For safe use of the stairs, a handrail is also required [52].

E. Smoke control

As stated earlier, smoke is the most risky element and a key factor in human loss. Hence smoke control is very important during fire incident. In the broad sense, it means managing the movement of smoke in the affected area either by using an active method or by passive method [53]. Installing fire and smoke barriers to the air conditioning ducts is a type of a passive control of smoke. Active method means directly control the smoke by using the pressurization and the exhaust system. Because evacuation can take a long time, smoke-free areas throughout the building are also required to accommodate virtually all occupants. This can be achieved in the following ways [54].

1. Control of Materials

The best approach to resolving the threat of smoke in buildings is to limit the amount of materials that can generate smoke and poisonous gases in a fire.

2. Use of sprinkler system

Smoke may also be restricted with the help of a sprinkler system because the absolute restriction of the amount of combustible material in a building is practically difficult. Water may decrease the smoke effect.

3. Dilution of smoke

In this case, the smoke is diluted to an acceptable degree. The flow rates necessary for adequate dilution may be determined from the knowledge of the flow of pollutants and the tenability criteria, normally of a value of 1 %.

4. Creation of pressure difference

This includes the creation of a favourable pressure differential inside a building, so that the smoke does not flow out of the already polluted compartment. It can be achieved either by natural ventilation or by mechanical pressurization. Here, air is injected into the required area such as stairs, lobbies, to create a pressure difference between the affected area and the unaffected area of the building. This prevents smoke or toxic gases from entering the safe area.

5. Smoke extraction system

When a fire erupts in a building, smoke extraction is required. This is typically a mechanical smoke extractor associated with smoke detection for activation. They use mechanical ventilators to quickly remove smoke and inject fresh air from the outside, allowing people to leave the building safely.

6. Natural Ventilation Systems

As its name indicates, natural ventilation systems do not operate with any mechanical machinery. During a fire, this system eliminates warm air and smoke and allows fresh natural air to enter the building to reduce the temperature of the building and assist occupants to evacuate by providing a safe escape.

F. Compartmentation

This is an area inside a building that is surrounded by a fire barrier or fire-resistant walls on all the sides. It is important,

- As smoke moves rapidly and can easily fill a room, compartmentation slows the spread of smoke and allows occupants to escape.
- Compartmentalization divides the building into smaller areas that are easy to manage for firefighters and emergency staff. If the building is compartmentalized very fast, fire fighters can enter the building quickly and start controlling the fire.

G. Display:

It is very important to have adequate signage for emergencies, especially egress. A fire at the Crowne Plaza Hotel in Denmark showed that firefighters needed nearly 8 minutes to get the firefighter's lift, which is located a distance not exceeding 30 meters. This happened only because of the lack of proper signage [55].

H. Detection system

It is designed to detect early-stage fires when sufficient time is available to safely evacuate occupants. Loss of assets can be minimized and operational downtime reduced through timely detection that helps to quickly control the fire. Various alarm systems also communicate to the emergency people about the details of the fire. Detectors are coupled with alarms that inform the people available in the building. Few systems also convey a signal to a control room. The detection system is coupled to various vital components such as AHU, smoke dampers, fire chutes, access controls, pressurization units, smoke management, fire doors, voice evacuation systems, etc.

3.1.3.3 Fire Protection System

This can be categorized as,

A. Active fire protection

These are systems that effectively respond to a fire emergency using an action that can be activated manually or automatically. It is used to extinguish the fire or slow down the fire. As its name implies, it actively participated in firefighting operations to put out the fire. It includes all the systems and equipment such as fire hydrants, fire extinguishers, sprinklers, etc. Normally, it is classed as follows:

1. **First aid fire fighting system:** As its name implies, it is used for fighting the initial stage of the fire. It must be used by persons trained before the arrival of external assistance. This includes fire extinguishers, hose reels, buckets or even sand, fire blankets, etc.

2. **Water-based fire fighting system**: It includes fire hydrants, sprinklers, high/medium velocity water spray system, water curtains, etc.

3. **Non-water-based fire fighting system**: It includes all the fire protection systems where water is not used such as CO_2 system, inert gas, dry chemical powder, etc.

B. Passive Fire protection

It controls the spread of fire without really involving fire fighting and without an external power system. This gives the inhabitants of the building sufficient time to escape well before the fire spreads. It includes fire resistant doors, fire-resistant walls, fire-resistance glazing, AC dampers, gap seals, fire retardant pants, etc.

Air handling Units (AHU)

The common cause of fire propagation is not to deactivate the AHU operation in the event of a fire. A separate AHU should be provided for each compartment and for each floor. It should be provided in such a way that it prevent smoke from circulating in the event of fire, which can be connected to smoke-sensitive devices for its actuation.

Fire/smoke dampers

Since the air duct is the primary source of fire/smoke propagation, dampers must be installed to control the spread of fire. The dampers must be installed in fresh air duct, supply air ducts and return air ducts of each compartment on every floor. It should be installed at the fire separation wall, before the vertical shaft, at each floor. The damper must be incorporated into the fire detection panel through a manual installation.

3.1.4 Fire Behaviour

The concept of fire behavior plays a key role in the overall design of fire protection system. It describes the development and propagation of fire. It is related to the chemical and physical properties of the fuel and its environment [56]. Fire is an oxidation process with the release of a great quantity of heat and light. There are three basic elements for burning: fuel, oxygen and heat, and the interaction of these three factors led to a concept of fire triangle. The fourth element is a chemical chain reaction and forms the tetrahedron of fire. It is the foundational principle of fire prevention and protection.

Once ignited, heat can be transferred according to three mechanisms [57],

- Convection – Heat transfer through the movement of hot liquid mass.
- Conduction – Heat transfer due to the displacement of adjacent molecules of solid material.
- Radiation – Heat transfer from hot surfaces to cooler environments via electromagnetic waves.

Fire behaviour refers to the various stages in the fire development, from the fuel ignition to the ignition of the flame, to the propagation of the fire to its stage of decay. It is divided into pre flashover and post flashover. Both these conditions affect the people and the property in different ways. The post-flashover fires influence the structural stability of the building. The pre flashover provides information regarding the rate of fire growth and the temperature of the fire in the compartment. This affects the safety of the occupants during their safe exit.

Following are some of the important elements of fire behaviour

3.1.4.1 Fire load

It is a significant variable necessary for the estimation of fire behaviour characteristics. It is a quantitative estimate of the fuel materials and how much energy can be released during complete combustion. It determines the fire severity. This is the thermal energy produced when the building contents burn down completely. Fire load density is the heat energy generated per square meter of the floor area after complete burning of the combustible material of a building. It is random and depends on the types of occupancy, such as residences, offices, libraries and hotels have different types of fire loads [58]. The unit of fire load density is MJ /m^2 [59] and can be calculated as follows,

$Q_t = M\Delta H_C / A_t$ ……………… Eqn. 3.1

Where,

Q_t = Fire Load density (MJ /m^2)
M = Mass of combustible material in the compartment (kg)
ΔH_C = Calorific value of the combustible material (MJ/kg)
A_t = Total surface area of the compartment (m^2)

3.1.4.2 Fire Initiation

It is the initiation and development of combustion response from a source of ignition that is self sustainable. The source of ignition is generally low and has little energy, but is often sufficient to initiate a fire. There is normally one of the following three ways of igniting: [60]

- Piloted ignition: The fire is started to the flammable mixture with the contact of a 'pilot' i.e. any naked flame or any electrical spark.

- Spontaneous or self-igniting: Here the flame creates spontaneously when the flammable mixture reaches to a required temperature. This is without pilot flame or spark.

- Spontaneous combustion of bulk fuels: This is a rare type of fire that is caused by self-heating in bulk solids due to chemical reactions, biological processes, or oxidation reactions.

3.1.4.3 Phases of fire (Fire propagation)

The fire propagation broadly falls under the pre-flashover and post-flashover categories. Pre flashover has incipient stage and growth stage and post flashover has fully developed stage and decay stage. So there are a total of four stages in fire propagation. Figure 3.1 shows a typical graphic depiction of typical fire development stages without fire suppression intervention.

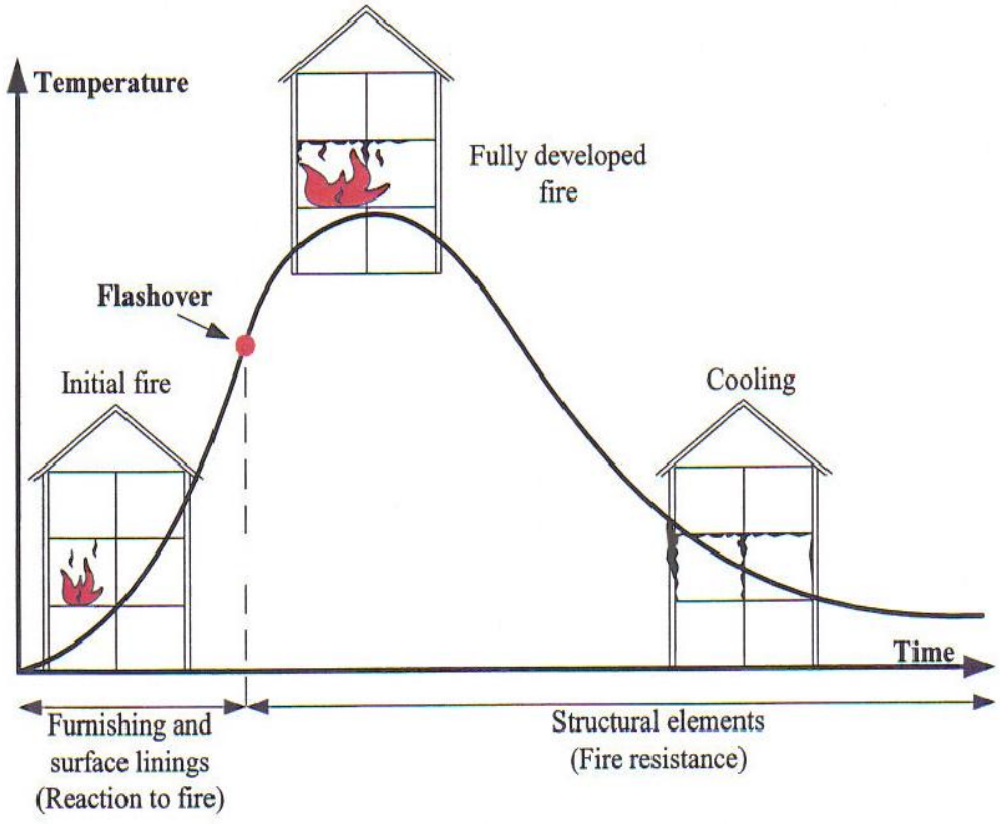


Fig. 3.1: Representation of typical stages of the fire development [61]

A. Incipient Stage

Fire is called to be in its early stages when it is very small and most heat transfer is not by radiation. At this point, quantitatively, a fire has a power of approximately 20 kW or less and a diameter of approximately 0.2 m. This is the thumb rule instead of firm separation lines [60]. At this stage, the material releases pyrolysis products which ignite as a result of various combustion processes, such as smoldering and flaming. Smoldering is a slow, low-temperature, flame-free combustion, supported by the heat that has been released when oxygen comes into direct contact with the fuel surface during the condensed phase [62]. If smoldering combustion occurs, the fire can spread until the fuel consumes or depletes oxygen, or it can lead to flaming combustion.

Smoke and/or other combustion products are normally generated during this stage. It may be detected by smell or activation of a detector and very simple to extinguish if someone is available. Here, heat detectors or a sprinkler system could not be used as the heat produced is not sufficient. Its duration can be from a few milliseconds (in case of the flammable liquids) to several days (in case of the coal stack). This depends on the primary combustible material involved, surrounding environment, and the ignition source. The threat is limited to occupants within the compartment who are not alert, asleep, or incapacitated.

In flaming combustion, there is always an increase in the speed of fire growth. It takes place when the fuel is a liquid, a gas that has evaporated or a solid that has pyrolysis to generate a mixture of air and flammable vapour. Once the flame ignites, there is generally enough heat in the flame to evaporate or paralyze the residual fuel to support combustion. The energy is generated by the combustion process called "heat release" which is useful for the size of the fire.

B. Fire Growth Stage

At this stage, a fire generates sufficient heat to promote the initial combustion reaction and also HRR (Heat Release rate) increases over time due to air availability and fuel. An accumulation of smoke and combustion products in a layer below the ceiling level forms a hotter upper layer in the room. The layer below is rather fresh and clean. and the smoke layer descends as it becomes thicker. Flashover occurs with the presence of radiant heat flux in the enclosure and is considered as a changeover period between the growth (pre-flashover) stage to the fully developed (post flashover) stage.

As the fire develops, the temperature rises and all surfaces are heated by the radiations of the flame, especially the top layer. When the radiation level reaches 15 to 20 kW/m2 and the top layer temperature reaches 500°C to 600°C, all exposed fuels catch fire quickly and burn severely [63]. This scenario is known as a flashover. This is a conversion of a small fire into a big fire where an entire compartment is on fire. Before ignition, fire growth is primarily restricted by the rate of pyrolysis of fuels. After flashover, the maximum size of the fire is usually controlled by the ventilation because the pyrolysed fuel can be burnt using the available air. At this stage, it is very difficult for occupants to survive due to high temperatures and elevated mixture of fire products and lack of oxygen. However, in large compartments, flashover will not always occur, even if the fire suppression system is not available. This is because, for large compartment sizes such as warehouses, it is difficult for the temperature of the hot layer to reach that high which is required for flashover and all the combustible objects to be ignited at the same time. Moreover, if the compartment is properly sealed, the temperature of the upper layer will be limited by a lack of oxygen.

Many mathematical models exist for predicting maximum HRR, [MW], for flashover namely,

i. McCaffrey et al. [64] suggested

$$Q_{fo} = 0.610\ (h_k\, A_t \sqrt{h_w})^{0.5} \qquad \text{……………… Eqn. 3.2}$$

ii. Babrauskas [65] suggested

$$Q_{fo} = 0.600\ A_w\sqrt{h_w} \qquad \text{……………… Eqn. 3.3}$$

iii. Thomas [66] suggested

$$Q_{fo} = 7.8\ A_{t+}\, 0.378 A_w\sqrt{h_w} \qquad \text{……………… Eqn. 3.4}$$

Where,

Q_{fo} : Maximum HRR for flashover (MW)
h_k : Effective heat transfer coefficient (kW/mK)
A_t : Total compartment surface area (m^2)
h_w : Averaged height of the ventilation openings (m)

Different techniques can be used for calculating the growth rate of a fire. The most common technique is t^2 (t squared). Here, the heat production of an ignited element increases with a squared function of time. It is also referenced in the NFPA-72 [67] standard with four classes of fire growth: slow, medium, fast and ultra-fast. EN.1991.1.2 [68] also defines the slow, medium and fast according to the time it takes for the fire to attain 1.05 MW. A slow fire takes 600 seconds, a medium fire takes 300 seconds, a fast fire takes 150 seconds and an ultra fast fire takes 75 seconds to reach 1.05 MW. It also depends on the combustion process, fuel type, ventilation and environmental interface [63]. In this way, combustion progresses with time and consequently alters the amount of smoke produced and the heat release rate.

The growth stage begins when the fire radiation regulates the burning rate. During this phase, the fire reaches the whole surface of the fuel, which increases the area of combustion and the resulting rate of heat release. Then start the ignition as the fire grows and propagates to the nearby fuel. Once started, the fire generally continues to grow unless it moves away from the adjoining fuel or causes an external firefighting operation. The flame then develops at a speed regulated by the size and combustibility of the fuel. This will continue until the fire is managed by the fuel surface or insufficient air supply. The initial stage of fire growth is called a "controlled fuel fire" because fire growth is managed by available fuel. If the fire is in a confined space, the growth of the fire can decrease because of short of oxygen. This is known as a "ventilation-controlled fire". But this is a very dynamic stage and can return to the fuel control for a while if there are changes in the ventilation as the doors are open or the windows are broken.

In this step, the room conditions can be defined by the two-layer setup. In the beginning, the air in the lower layer is the same as the room temperature. The upper layer, normally above the fire, contains smoke and hot gases. Its temperatures increase rapidly because of the heat available in the combustion products. When the plume comes in contact with the ceiling, the hot gases also move toward the ceiling. They leave the ignition source very quickly. This scenario is called the ceiling jet, which is enough to activate the heat detectors or sprinklers.

C. Fully-developed Fire

At this stage, all available fuels are burned and the fire burns at its highest intensity. This may be a fuel-controlled fire when limited fuel is available or a ventilation-controlled fire when air is available. At this stage, the heat flux can reach up to 150 kW/m^2 [69] and the temperature can be reached up to 1200ºC [70]. It may cause serious damage to the construction. Therefore, the fully developed stage remains a matter of concern for structural strength and the safety of emergency services, and therefore, taking into account property protection, structural stability, and fire propagation, this is the most important step. This phase is controlled by the fire load, compartment configuration, ventilation openings, thermal features and relative humidity of the atmosphere. In this stage, the fire is generally managed by the ventilation and the combustion rate is governed by the openings in the compartments. This means that the pyrolysis rate of the fuel is higher due to the availability of air. This results in the combustion of the fuel near the openings because the unburnt gases start to burn using outside air.

Typically, fire severity is the period during which the enclosure temperature remains above 600°C, i.e. flashover to the period of decay. Fire severity is important in determining the fire resistance requirements of the structural elements. The formula for determining the time equivalent for the severity of the fire is as follows [71].

$$T_s = K^* Q'' / (A_T{}^* A_O)^{1/2} \qquad \text{……………… Eqn. 3.5}$$

Where,

T_s : Time equivalent for fire severity (min.)
K : Constant (value around Unity)
Q'' : Fire load in compartment (Kg)
A_T : Total surface area of the compartment excluding opening (m^2)
A_O : Area of opening (m^2)

D. Decay Stage

At this stage, the HRR declines rapidly, despite the availability of sufficient air due to the reduction in fuel quantity and the inability to maintain the maximum combustion rate. In this phase, a ventilation-controlled fire is converted to a fuel-controlled fire. The combustion rate is regulated by the fuel supply, even if the available air is sufficient to burn off the remaining fuel.

The HRR during the decay stage can be estimated using the following equation [72].

$$Q(t) = \left\{1 - \frac{1.75(t - td)}{ts}\right\} Q_{\max} \qquad \text{……………… Eqn. 3.6}$$

Where,

t_s : Duration fully developed fire (s)

t_d : Time of onset of the decay phase(s)

Q_{max} : Maximum heat release during fully developed fire phase (kW)

3.1.4.4 Burning Regime estimates

The combustion regime of a fully developed fire is dependent upon the quantity of air available for complete combustion. There are two types of the regimes, one is a ventilation controlled regime and the other is a fuel controlled regime. If the surface area of the fuel in a compartment is large, the rate of combustion will be controlled by the dimensions of window openings. It's worse in terms of severity.

If the fuel surface is small, the combustion rate will be controlled by the fuel surface. In this case, the amount of air is unlimited due to large openings. Excessive air availability has a cooling effect. For these reasons, ventilation-controlled fires are more serious.

A. Mass loss rate

It basically rate of combustion of the fuel. If it is higher, the fire is considered to be quick. Kawagoe in 1958 [73] suggested that the ventilation controlled mass rate of wood is directly proportional to the vent parameters and suggested the following equation,

$$m = 0.092\ A_0 H_0^{1/2} \quad \text{……………… Eqn.3.7}$$

Where,

m : Mass loss rate

A_o : Area of opening in the enclosure (m^2)

H_o : Height of the opening (m)

After that, there were various studies conducted. In 1967, Thomas [74] observed that the above correlation did not apply to a very large opening. In 1972, Thomas et al. [75] investigated and correlated mass loss rate, vent parameters, enclosure dimensions and total enclosure area. In 1983, Law [76] provided a correlation known as Law correlation,

$$m = 0.18\ A_0 \sqrt{H_0}\ \{W/D\}^{1/2}\ (1\text{-}e^{-0.03.6\Omega}) \quad \text{……………… Eqn. 3.8}$$

Where,

$$\Omega = (A_t - A_0)/A_0\sqrt{H_o} \quad \text{……………… Eqn. 3.9}$$

A_t : Total surface area (m^2)

A_o : Area of opening (m^2)

H_o : Height of the opening (m)

W : Enclosure width (m)

D : Enclosure depth (m)

B. Heat release rate

HRR is a very vital metric for determining fire quantum. This is a critical feature in describing the magnitude of a fire. It is measured in kilowatts (kW). This is how quickly combustion reactions generate heat. This can indicate the HRR or the mass loss rate. The mass loss rate is expressed in kg/s. The relation between these two quantities can be expressed as,

$\mathrm{HRR} = \Delta\,\mathrm{Hc}^{*}\,\mathrm{m}$ ……………… Eqn. 3.10

Where,

m = Mass lost rate (Kg/s)

ΔH_c = Heat of combustion or calorific value kJ/ kg or kJ/ m^3

This equation indicates that the mass loss ratio and HRR are linked using the calorific value.

This depends upon the following parameters,

- Strength and position of the ignition source
- Nature, quantity, location, distance, orientation, and the surface of the fuel
- Compartment dimensions and geometry.
- Dimensions and position of openings.
- Thermal inertia of the compartment edges.

Theoretically, HRR is estimated as the multiplication of the mass loss rate and the heat of complete combustion. To simplify the calculations, we are assuming that the fuel burns at a steady pace.

$\mathrm{Q} = m\Delta\,\mathrm{Hc}$ ……………… Eqn. 3.11

$Q=m\ \Delta H_c$

Where,

Q : Heat release rate (kJ/s) or (kW)

m : Mass loss rate (kg/s)

ΔH_c : Heat of combustion or calorific value kJ/ kg or kJ/ m^3

Thomas [74], proposed the following equation to calculate HRR for ventilation controlled fire,

$Q_v = \eta\, m_a\, \Delta H_c / Y$ ……………… Eqn. 3.12

Where,

Q_v : Peak heat release rate – Ventilated controlled (kW)

η : Combustion efficiency (taken to be 0.65)

m_a : mass of air flow (kg/s)

ΔH_c : heat of combustion or calorific value kJ/ kg or kJ/ m^3

Y : Stoichiometric air fuel mass ratio.

This is a more specific form of the above equation

Fire Engineering guidelines [72], has given a more precise equation for peak HRR for ventilation controlled fully developed fire

$Q_v = 1260\, A_o \sqrt{H_o}$ ……………… Eqn. 3.13

C. Fire Enclosure Temperature

The thermal properties, nature, arrangement of the enclosure are important parameters for predicting the fire spread and intensity of the fire. The bigger exposed surface of the fuel causes a shorter but intense fire. Fuel with small exposed area gives a longer and less intense fire. Magnusson and thelandersson [77] decide on the shape of the HRR curve from the experiment carried out to estimate post-flashover temperatures. They suggested that the HRR increase from zero to maximum during the ignition phase controlled by the opening factor. It is stable during the flame phase influences by the ventilation controlled fire and further reduced to zero in the decay phase. Using the values of the opening factors and load densities, he generalized the shape of the HRR curve. This curve is known as a Swedish fire curve as mentioned in Figure 3.1.

D. Fire duration

The fire duration determines how the fire affects the structure that can be calculated using Law [76] and Lie [62]. The effective fire duration is calculated by dividing the total fire load within the enclosure by the fuel mass loss rate shown below,

$$T = Q'' / m \qquad \text{………………. Eqn. 3.14}$$

Where,

T = Time of burning (s)

Q'' = Fire load in the enclosure (kg)

m = Mass loss rate (kg/s)

Also, $m = 330\, A_O \sqrt{H_O}$

Therefore,

$$T = Q_t\, A_t / 330\, A_o \sqrt{H_o} \qquad \text{………………. Eqn. 3.15}$$

3.1.5 Tenability

Tenability is a limitation of the ability to escape from the affected area for persons exposed to a specific quantity of toxic product or any other product resulting from a particular incident. The building design emphasizes the survivability of occupants in case of fire [78]. It includes visibility limit, temperature (heat flux), carbon monoxide dosage and a high concentration of combustion products such as CO^2, HCN, SOx, and NOx. This gas can cause burns, eye irritation and respiratory problems. It can also lead to death, even if one is not directly exposed to the fire.

Tenability depends on various parameters such as quantity of combustible materials, surface area of combustible materials and type of combustible materials. This also depends on the fire intensity, the duration of the fire and the ventilation. But all these factors are very unpredictable as they change normally over time and are very difficult to estimate during the design stage of the building. So, in the first instance, it is difficult to know how a fire will behave in the future, as the details of the fuel material that will be available in the future are unknown. Few guidelines, such as EN 1991-1-2, suggest a limit for the maximum allowable fire load under occupancy [68] that must be met for the entire life of the building. However, there are no specific means of controlling it over its lifetime. The fire load is directly related to the tenability criteria during the ignition and development phases of a fire.

This makes tenability analysis one of the key requirements for a safe evacuation. Tenability analysis provides the time available with the occupants for safe egress and it is based on several parameters of tenability criteria. Purser [62] suggests that a room becomes untenable under the following conditions:

- Temperature rise beyond 1200 C,
- Heat flux go over 2.5 kW/m^2, or
- Oxygen falls below 12%.

Hydrogen cyanide and carbon monoxide are also important dangers for humans. The lowest concentration of matter in the air to cause human death is 0.02% for hydrogen cyanide and 0.5% for carbon monoxide for 5 minutes [79]. However, exceeding the above tenability requirements does not mean that people in this environment will always succumb. It depends on the individual's susceptibility. It is therefore very important to consider a margin of safety in the time necessary to evacuate any building.

Another important factor in an evacuation is visibility. It focuses on the distance and time required for occupants to see the exit signs or understand the exit route. Poh [80] states that smoke obscuration reduces visibility, which influences the speed of the occupants, further increasing the time of exposure to toxic gases and heat. In the experiment performed by Jin, [81] it is observed that the speed of people decreased dramatically with the density of smoke from nearly 1.2 m/s to almost 0.3 m/s. The visibility of the smoke is more appropriate to determine the accessibility of exits. When visibility is reduced to less than 10 m, 97% of British and 94% of US populations adopt the "turn-back" behaviour[62][82]. Under these circumstances, people behave as if walking into complete darkness and find their way along the walls. Furthermore, exposure to smoke levels above accepted tenability limits results in sensory irritation and sufficient visual destruction for building occupants to stop attempting to exit. The Purser [62] suggests that the visibility limit should be 5m and 10m for small and large enclosures, respectively.

A building made for the general public, where the occupants are not aware of the internal geometry, a minimum visibility of 13 m is required for a safe evacuation. In a building where the occupants are familiar with the internal design and exits, the minimum visibility should be 4m. Kang [83] states that there is a significant increase in smoke accumulation and that visibility is almost lost between 180 seconds and 240 seconds. Jioh Ryu and Rie [84] states that the smoke approaches the staircase in 240 seconds.

Heat is also important to the safe evacuation of occupants. There are three basic means by which fire victims collapse under the effect of heat: burns to the surface of the body, heat stroke and burns to the respiratory tract. Purser [62] suggested that humans can resist temperatures of up to 60°C for 30 minutes, 100°C for 12 minutes and 120°C for 7 minutes. Mealy [79] suggests that heat intolerable conditions are generally reached in temperatures above 120°C at 1.5 m.

Carbon monoxide is an asphyxia that affects the quantity of hemoglobin in the blood that is required to carry oxygen to the tissues, specifically brain tissue. Mealy [79] explained a way to decide untenable toxic carbon monoxide concentrations. He suggested that the fractionated effective dose (FED), a measure of airborne contaminants absorbed by the occupant [85] is 0.3. This means that for a 30-minute exposure with a tenability of 0.3 FED, a constant concentration of 350 ppm will result in a cumulative dose of 10500 ppm/minute.

Sprinkler systems installed in the building also play a significant role in the safe building evacuation. The National Institute of Standards and Technology (NIST) have performed number of large-scale experiments on building fires to study the effect of sprinklers in the area of fire origin [86]. Leong Poon [87] mentioned that if the activation period of the sprinklers is less than 2 minutes, the fire can be controlled well before it reaches the flashover. Radford [88] mentioned that a fast response sprinkler at a radial distance from one meter will activate at 177 seconds. Considering the operation time of the sprinkler mentioned above, it is always safe to evacuate the building, although the building is equipped with sprinkler system. For the purposes of this study, we confine ourselves to visibility criteria of only 240 seconds as an evacuation process.

3.1.6 Occupants Load

The maximum acceptable occupant load is also important for the safe evacuation of the building. NFPA 101 [41] defines it as the maximum number of people who can occupy a building or part of it at any one time. There is another way of looking at it, as mentioned in the International Building Code (42) which defines it as the number of people for whom the means of evacuation is designed. The requirements vary according to the codes of the respective countries [3][89]. In countries such as the USA, Australia, Spain and India, it is 10 m^2/ person for business occupancy. In the United Kingdom and Hong Kong, it is 6 m^2/person and 9m^2/person respectively.

3.1.7 Available egress components and their challenges

The basic objective of each evacuation component is to safely evacuate all occupants in the event of a fire. In the case of high-rise buildings, this problem is more important because of its typical features that have led to difficulties during fire fighting, rescue and evacuation. In the early stage of the fire, the horizontal smoke dispersion rate is low but it rapidly increases in the fully developed stage. As a result, fire or smoke may spread very rapidly during the fire. As a result, evacuation time is an important factor in determining the time occupants need for a safe evacuation. There are two types of evacuation components, vertical evacuation components and horizontal evacuation components. The vertical egress component is a critical factor for the building evacuation procedure, but there are few components which may affect its efficiency. Few significant components are listed below,

A. Stairs

Stairways are the traditional and safest way to evacuate the building. There are two factors to consider. One is the design factor of the stairs and the other is the behavioural factor of the occupants. Few important design factors of the staircases are their numbers, width, length, location, slope, capacity, ventilation, pressurization system, etc. [88] [90]. Few significant behavioural issues include:

- Ergonomics, motivation levels, group behaviour.
- Influence of gender or role from a behavioural perspective.
- Merging evacuees stream in the floor-stair landing.
- Fatigue to the occupants as they need to travel thousands of steps
- People with disabilities.

- Counter flow of firefighters during evacuation.

All of these factors resulted in a slow discharge time, which led to a long queue on the stairs, including the stairway entrance on each floor. The average human speed on the stairs is ranging from 0.52 m/s to 0.62 m/s and it is 0.45 m/s and 0.43 m/s for kids and elderly people respectively [91]. This low speed could have an adverse effect on the evacuation process in terms of bottleneck, queue and stampede. Individuals who use a wheelchair can also block the stairs. Ventilation (natural or mechanical) is also an essential part of the evacuation. If not properly maintained, it can add to the challenges. Unwanted material kept at the stairs is also a common practice that blocks access to the evacuation, which can lead to delays and also stampede.

B. Evacuation elevators

The traditional concept of not using elevators in case of fire emergencies has been challenged due to the existing disadvantages of the staircase. An accelerated evacuation of the building is also required. An evacuation elevator is the quickest way to evacuate. In various standards, it is permitted and recommended to use elevators, in extreme conditions and with certain precautions [92]. Some of these are NBC, the Singapore Fire Safety Code-2013, the British Standard 9999:2008, the European Standards EN 81, IBC, NFPA 101: Life Safety Code, American Society of Mechanical Engineering and Safety Code for Elevators and Escalators.
But the use of elevators for evacuation presents some design and behavior problems. Some of the problems are,

- Restricted space in the elevator.
- The product of the fire can enter the enclosed lift shaft.
- As the lift moves, smoke can get stuck inside the lift due to negative pressure.

- Operation of an emergency power supply, water inlet and contaminant propagation in the lift car, operation of emergency communication systems.
- An appropriate decision regarding elevator pickup locations and elevator stop counts.
- People's desire to use an elevator in case of fire.
- The limited capacity compared to an enormous occupant load increases the waiting time to use the lifts.

To deal with this problem, the zoning concept has been introduced. The zoning of the building can be done by dividing it into a certain number of floors where elevators can be allocated. Larger and faster shuttle lifts are usually provided to move between the refuge floors and the ground floor without any opening on the other floors. It can eliminate some of the problems mentioned above.

Due to the increasing evacuation time, the use of elevators is a good option for rapid evacuation and this can be achieved with good training. A lift is normally used for people like the disabled or elderly occupants who cannot use the stairs. It is evident that around 3000 lives were saved by using both elevator and stairs for the WTC-2. It is observed that by using elevators and stairs, the evacuation time can be reduced by 36% (110 minutes to 70 minutes). It can be reduced by up to 58% at the initial stage if both a lift and a staircase are used [93]. This strategy is especially helpful in higher occupancy scenarios. There are several other important factors such as perceived risk and pre-evacuation delays. Measures related to gender, age, fitness, education, knowledge, tenure in the building, fire floor location, etc. should also be considered [94].

C. Sky-bridges

A possible method is to introduce the horizontal means of exit at a certain level, i.e.to make use of sky-bridges connect the buildings. The immediate advantage of sky-bridges is that the vertical evacuation distance is minimized. But this is possible only if adjoining buildings are available. The refuge area of the adjacent building can also act as a sky bridge and very helpful in case of emergency.

D. Refuge area

The refuge area is very important in evacuation, especially for people with disabilities and when evacuation is not possible because of a certain situation. The following are some important benefits of the refuge area,

- It is a safe place of rest for the evacuees until further assistance arrives.
- Provide shelter for injured or disabled individuals.
- Use as the command point for emergency teams.
- The use of evacuation elevators from the refuge floor is easier as it serves as a pickup point to accommodate a significant number of evacuees. The area is also safe for the occupants to wait even in emergencies. Few factors can cause the concept to fail, i.e. human behavior problems (crowding or non-use), use for any other purpose, maintenance, etc.

E. Alternative means of escape

1. **Helicopter Operation:** It is very rarely used because it is not a recommended evacuation option. It is extremely hazardous for landing and rescue operations because of air turbulence and rising currents caused by smoke and heat.

There are a few other types of means of escape, i.e. platform rescue devices, escape chutes, and controlled Descent devices [95].

2. **Platform rescue devices:** It is an enclosed platform or set of platforms moving along the guides on the exterior of a building. It may be a mobile type provided by emergency services in case of need or permanent type installed on the building. Many occupants may be evacuated at one time and no special skill is required to operate on-platform life-saving devices. It is very useful for older people and people with disabilities.

3. **Controlled descent devices:** It is the personal equipment installed outside the building that lowers the person at a controlled speed. It is very simple to operate and electricity is not required. But it may not be very efficient for a high occupancy building.

4. **Escape Chute devices:** It is a channel-shaped device made of fire-resistant fabric. This is a vertical or outer slope. The sloping solution normally serves a specific floor and the vertical solution normally allows evacuation of several floors. It is also provided in the separate shaft near the staircase and is very easy to use with basic training.

3.1.8 Means of egress

It is an important parameter for safe evacuation. It has three components namely exit access, exit, and exit discharge [3].

Exit Access: This is the portion from any area of the building to an exit. It starts at the farthest occupied place and ends at the opening of an exit. It is controlled by the traveled distance. It includes access ways, passage, exit access entrance way, corridor, intervening rooms, unenclosed stairways

Exit: It is a protected escape route between exit access and exit discharge. It includes exterior stairways/ramps, passageways, external doors, vertical escape enclosures, horizontal exits, etc.

Exit Discharge: This is an area between the end of the exit and a safety area where the occupants are expected to assemble. It includes a direct way outside the building at ground level, lobbies, egress courts, vestibules, etc.

The exit may be horizontal or vertical. The horizontal exit permits inhabitants to move from one side of a building to the other from a fire-protected area. Here, once the persons pass from a horizontal exit, they must always have a path to another exit that went to an exit or an external safety area [41]. Exit discharge is the path from the end of the exit to the assembly area. This area is a place that is permanent and dedicated to the use of occupants and considered safe[3].

Apart from a staircase, there are few exits such as evacuation elevators, platform rescue devices, escape chutes, controlled descent devices, etc. but all of these components have their limits and disadvantages. Thus, in this study, we have considered only the stairway as an exit being the safest and conventional method of evacuation.

3.1.9 Evacuation

The basic principle of evacuation is to allow the people leave the building in a safe and timely manner. Ideally, the evacuation route should be the same with a pathway in the daily route. It should be always ready for evacuation, continuous with one or more exits and public ways, resistant to fire and smoke, with sufficient capacity, without any obstructions, and suitable for all types of occupants.

During the evacuation, parameters such as the width of the stairs, the building height and the occupant's number are very important. Studies by Galbreath [96] and Pauls [97] have suggested a correlation for the evacuation time calculation where the discharge rate, flow rate, density is considered. Most of them suggested two different relations for two different population slabs, for free or congested flow and flow of occupants on stairs. A single relationship with entire parameters which can be applied for calculating evacuation time is not available which will help to decide the evacuation time and to further decide the width of the staircase and allowed a number of occupants. There are various codes and standards such as NFPA, IBC, NBC, etc. that deal with the means of building evacuation in the event of an emergency. In addition to the width of the stairs, it is also important to have an adequate number of stairs to safely evacuate all occupants in the available time. This means, stairs, as a safe means of exit, we need to take into account the number of stairs and the width of the stairs. According to the NBC, it is based on occupant load, required width per person and travel distance. However, a minimum of two staircases is required for high-rise and special buildings [3].

There are other codes, standards, and a couple of studies that talk about the width and the number of stairs according to certain parameters. These are,

1. **NFPA 5000/NFPA 101** [41] considers the minimum width of the staircase and its numbers based on total occupant load.

2. **British Building Regulations (Document B)**[98] take into account occupant load and travel distance in deciding the quantity of the staircase. And the occupant load and the number of floors to determine the width of the staircase.

3. **Her Majesty's Office** [99] decides the maximum allowed people based on the criteria such as the floor exit, the time required to fill the staircase, rate of flow and width of the staircase.

4. **Galbreath** [96] suggested that evacuation time rely on the number of people above the 1st floor, persons per floor, or the number of people accommodated on the stairs / area of stairs divided by 0.3 m^2/person (whichever is less), discharge rate of the people and number of unit widths.

5. **Jake Pauls** [97] suggested two evacuation times. One for a population of less than 800 and one for over 800 depending on the actual evacuation population per metre of effective stair width.

6. **Melinek and Booth** [97] propose total evacuation duration for two cases, i.e. one during congestions and another for free walk. This is based on the number of floors, occupant load on the every floor, occupant flow on stairs (person /m/s), Effective width of stairs (m), and walking time between adjacent floors.

3.1.10 Concept of Available Safe Evacuation Time (ASET) and Required Safe Evacuation Time (RSET)

Total evacuation time is a complex criterion and is very difficult to predict as it also includes the behaviour of each individual involved. The total duration of the evacuation must be less than the duration at which the tenability is achieved, i.e. RSET should be less than ASET.

RSET consist of two main times,

1. To commence the evacuation movement and.

2. Required to arrive at a safe location.

This concept is demonstrated in detail in fig. 3.2

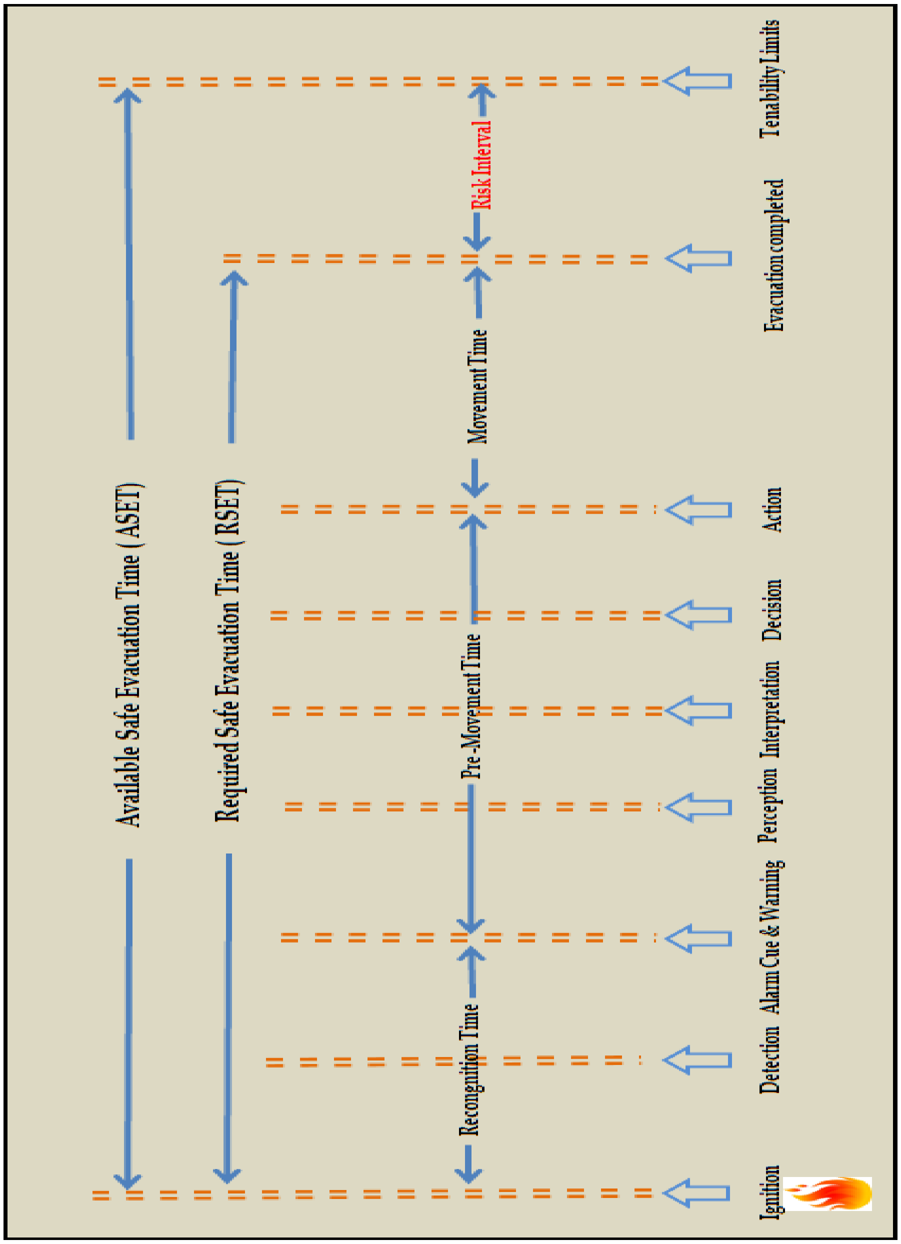


Fig. 3.2: A timeline comparison of the available safe time (ASET) and Required Safe Egress Time (RSET) along with sequence of occupants' response to the fire [62] [100]

The time of initiation is the time the fire started. That's the time the fire begins. Then comes the point where the fire is detected. This happens either by devices or by human beings. Detection time may vary according to the type of fire, location and availability of the detector. There is a delay from detection to alarm activation. In some cases it's almost the same time or it could be late as well. For example, the occupants have manually activated the manual call-in point or the fire alarm may not be activated, not working or not available. As a result, occupants eventually perceive some fire cues or receive a warning from others and this will take some time. Once people understand about the fire, they take a while known as a delay and then they start moving around. The travel time is the total time required from any location in the building to the safe location through the exit route. The required evacuation time is calculated from the time of activation of the alarm until the final person reaches a safe location. The tenability limit is the time during which fire products like narcotic gases, irritating gases, heat, smoke, toxic gases, etc., can affect the occupants. So, the evacuation time should be less than the tenability limit. Preferably, it should be half [62].

Johnson [101] uses the Fire Dynamics Simulator (FDS) model and hand calculations to decide the actuation of the detectors. He predicts that the photoelectric smoke detector activates in 62 seconds using the FDS and 54 seconds using hand calculations.

In accordance with NFPA-72[67], we must add a notification time of 10 seconds for processing the detector signals and activating the notification devices. There are various studies available on pre-evacuation delay times based on actual fire incidents and fire drills. Proulx et al. [102] studied pre-movement time using questionnaire methods from all occupants of the seven-storey Dominion Building located in London. The pre-evacuation time was observed to be less than 5 minutes with an average time of 63 seconds. About 80.2% of evacuees began to evacuate within 90 seconds of the alarm. Johnson [101] mentioned that the occupants waited 60 seconds before exiting the building to take action. Bryan [103] investigated the behaviour of the people who were available during the fire that took place at MGM Grand Hotel in Clark County, Nevada, using questionnaire method. The results showed that the average delay to evacuate for 536 people was 60 seconds. Brennan [104] interviewed 36 participants who evacuated an office building during the fire on the 3rd floor. The pre-evacuation delay varies from 60 seconds to 300 seconds. Gwynne [105] studied two buildings in the UK, one of 11 floors and the other of 4 floors. There were 72 persons in the 11-story building and the pre-evacuation time varied from 40 seconds to 426 seconds with an average of 141.3 seconds. For the 348 occupants of the 4-storey building, it varied between 19 and 269 seconds, with an average time of 101 seconds. Proulx and Pineau [106] reported pre-evacuation delays of more than 1000 people in three buildings. The mean delay was 50 seconds. Sharma et al. [107] collected data on the behaviour of evacuated occupants of a six-storey office building in the UK using surveys and video recordings. Individual pre-evacuation time for the 19 people varied from 10 seconds to 55 seconds with an average of 28 seconds and a standard deviation of 11 seconds. Christoffersen and Soderlind [108] conducted a non-announced fire drill in a 12-storey business building in Copenhagen. He set up video cameras on the stairs on each floor and kept observers on each floor to check the occupants' schedules. The pre-evacuation delay times varied from 12 seconds to 105 seconds.

From all the above studies, it is clear that there is no single pre-evacuation time that can be considered universally. It depends on different factors such as training to the occupants, the frequency of the mock drill, the sound of the alarm system, the position of the occupants in the building, the intensity of the cue, and many more. Thus, if we consider all these time factors required for occupants excluding the movement time, it is the total of the detector activation, its notification and the pre-evacuation time. In this study, with a conservative approach, we are considering 62 seconds for the actuation of the smoke detector, 10 seconds for its notification, and 60 seconds as a pre-evacuation time. We need 132 seconds before starting the evacuation. Therefore, every occupant of a floor must evacuate that floor well below 108 seconds once the evacuation begins (240 seconds–132 seconds). At the same time, however, there are various uncertainties when determining the evacuation time due to various dynamic factors associated with the fire safety. To overcome these uncertainties, a traditional, simple method is to consider the safety factor [109]. However, the choice of safety factors is subjective and depends principally on the experience of the designers. Different scientists have suggested different values. Peng Hua proposed a value of 1.5 [110] for the safety factor. Depeng suggests that it can be considered to be 1.2, 1.5 or 2 [109]. So in this study, we take a safety factor of 1.5, and therefore our target will be 108/1.5=72 seconds.

Occupants take some time to initiate their evacuation once they have perceived some signal of the fire. This time is called delay time and is not easy to estimate. The delay time comprises three subcomponents: Time taken for people's perception of the incident, interpretation, and subsequent action. Perception time is the time taken by the occupants to understand the fire warning signal. It could be a signal from the fire alarm system or communication from other people. It takes time to interpret this information and various steps need to be taken to inspect or obtain further details before they decide to start an evacuation. After the decision of evacuation is made, occupants need to take other steps before start leaving, such as finding valuables, gathering children, other communications, getting dressed, etc.

To calculate the expected total evacuation time, it is now regular practice to add time as a delay in the start of the evacuation. This period can be studied either through drills or from information received from the victims of the fire. Proulx [111] studied this factor when conducting evacuation drills. He observed that the average time delay was 2 minutes and 49 seconds for a good audible alarm. In the winter, the evacuation lasted 5 minutes and 19 seconds because it was necessary to put on a coat, boots, gloves and a hat. In other buildings, where the alarm was not properly audible inside their room, occupants took up to 25 minutes to start with an average of 9 minutes.

Brennan [104] explored this factor from the information from the fire victims. He used a severe fire in an office building that originated in the storage of polyurethane chairs situated on the third floor of a high rise building. From the interview, it was predicted that the average delay time was approximately 2 minutes and 30 seconds.

So the delay time depends on the circumstances and also the weather condition as the collection of valuable and personal goods varies.

3.1.11 Speed of occupants

The speed of the occupants is an important factor to predict the time required to evacuate a building. It depends on the density of persons on the stairs and the width of the stairs. People can move freely in lanes about 22 inches wide measured at shoulder level i.e. unit exit width [112].

Occupants may walk at their normal speed if there is a significant gap between them. However, the closer they come, the more limited the movement is. It is suggested that enough space be provided on the stairs for the occupants of half the floor above the first floor. This is to stand comfortably during an emergency, assuming that persons can stand there at 0.14 square meters per person [96].

The density of the area decides the speed of occupants. The average unrestricted walking speed varies from 1.2 to 1.25 meter/s, if the density is below 0.54 people/m². The speed reduces very drastically with very high densities and reaches a standstill point when the density rises to 4 or 5 people/meter Square, fairly equivalent to the overcrowded lifts [97][112].

The change in speed doesn't only depend on the engineering approach, but also depends on behavioural and physiological factors [113]. NIST [114] has estimated that 6% of the occupants evacuated during the World Trade Centre towers on 11 September 2001 were with mobility problems that hindered the evacuation process.

3.1.12 Staircase width

A. Effective width

The effective width is the part of the staircase that includes a relatively unused area of a staircase where people keep some distance like the walls and central handrail. The reason is that the occupants try to get their bodies away from these places.

The flow of the people directly depends on the effective width of the staircase [115]:

- 150mm from the wall (plus for rough surfaces),
- 90mm from the centre line of a handrail.

According to Pauls [97], the effective width of a stairway is 300 mm (12 inches) smaller than its actual width. For example, a actual width of 1120mm (44 inches) equals an effective width of 812mm (32 inches). This means that we have to reduce by 300mm the width of the staircase designed to obtain the respective effective width of the staircase.

B. Unit exit width:

The exit width is not always measured in meters/feet, but its measurement is linked to its unit that represents the width occupied by a person. The standard unit exit width is equal to 560 mm (22 inches). In some cases, measuring in meters/feet can result in additional expenses without obtaining additional safety. For example, a 44-inch staircase can comfortably accommodate two files of people. If we add 4 inches to make a 4 foot staircase, it will not increase the stair capacity but will add expenses. However, if we add 12 inches to a 44-inch stair, it increases the flow of people by allowing an intermediate staggered file [112]. Thus, for the calculation of the evacuation time, the unit exit width concept is used rather than meters & inches.

3.1.13 Human Behaviour during Fire Situation:

The human behaviour is very complex and unpredictable while responding to a fire emergency. Various efforts are made to decide its relationship with the response to fire emergency especially during an evacuation. Kobes et al. [116] suggested that human behaviour depends on the perception of the occupants about the incident which further depends on the authenticity and seriousness of the indications they have received. The indication mainly includes the fire alarm system and they may believe that it is a false alarm and don't need to respond. There are further more relationships between human behaviour, and their response mentioned by various researchers. As per Yatim [117], it depends on the familiarity of the occupants with similar situations. Cordeiro et al. [118] relates it with the physical characteristics of the building. Proulx [119] relates it with personality, knowledge, experience, gender and professional role of the people. Lack of any factor may lead to panicky and their behaviour may change negatively which will affect the evacuation process. The human behaviour in response to fire varies as per the situation and cannot be general in nature. But it can be simplified in two main stages [120][121], the pre-evacuation stage and the evacuation stage. The pre-evacuation stage is the stage before the actual evacuation starts and the evacuation stage is actual travel to the safe place.

After the fire incident, occupants get the information either by fire alarm or through individual/ group communication or through some indications like smell, smoke, flames, temperature, etc. The behavioural response of the occupants also depends on their ability to hear or see an alarm which mainly depends on the frequency of the alarm signal, the surrounding noise level and the physical condition of the occupant. Once the information is received by the occupants, there are three stages before the start of actual evacuation. These three stages are perception, interpretation and decision making. In perception stage, occupants understand the situation differently and then act accordingly. The perception of the occupants varies as per the information received, their emotions and their earlier memories [120]. After perception, the next stage is the interpretation phase. Here the occupants try to understand the information received as per clues, their awareness, their understanding, past experiences, mental simulations etc. and then decide further action. But in reality, in most of the cases, initially occupants interpret every incident as a normal incident without considering any severe risk and after some time their interpretation may change with the development in the situation. But it is always advisable to assume the worst situation and act accordingly.

Once they interpret about the incident, the third phase is the decision-making in which occupants make decisions for their further mode of actions. This stage comprises of the decision about their action base on their information, training and knowledge and the second part is deciding on the option for this execution. Once decided, people also need to decide on activities needed before the actual action starts like informing other members, gathering kids, collecting valuable, even getting dressed, in some cases, especially residential buildings.

In evacuation stage, the occupants execute the decisions taken in the earlier stage and start actual evacuation as per the guidelines.

There are three human factors which influences the response namely physiological factor, socio- psychological factor and psychological factor. The physiological factor is the ability of an occupant to withstand the ambient conditions created by the fire as per various human aspects like age, size, weight, pre-existing medical issues, the influence of medication, drugs & alcohol.

The socio-psychological factor is the study of behaviour of the individual while interacting with others i.e. behaviour of a person in a social environment. This includes the behaviour like evasion, engagement, affiliation, supportive behavior and role [122].

The psychological factor is the resistance and survival of the occupants due to physical environment resulted from the fire. This is a critical component of life risk assessment. The result from fire may be temperature, visibility due to smoke, oxygen deficiency, exposure to gases and heat flow. The response varies from individual to individual as it depends on the physical condition of the occupants and the quantity & duration of the exposure.

As it is a known fact that smoke causes the major hindrance during building evacuation. Here, smoke opacity plays an important role in visibility and it affects the human mind by reducing the visibility and irritation due to the inhalation of smoke particles. Although smoke does not stop the movement but the reduction in visibility causes decreased evacuation ability. Smoke also have an emotional effect and may increase fear amongst the occupants [123].

The smoke also constitutes carbon monoxide gas. After inhaling, it combines with the haemoglobin and forms oxy-haemoglobin which reduces the ability of the blood to carry oxygen which lead to reduction in thinking ability and also may lead to disability and even fatality.

So overall, any action taken in a particular situation is the result of a complex, behavioral process in addition to random reactions resulting from environmental changes during fire.

The summary of all important factors related to fire and smoke dynamics and building characteristics and their correlation is shown in Fig.3.3

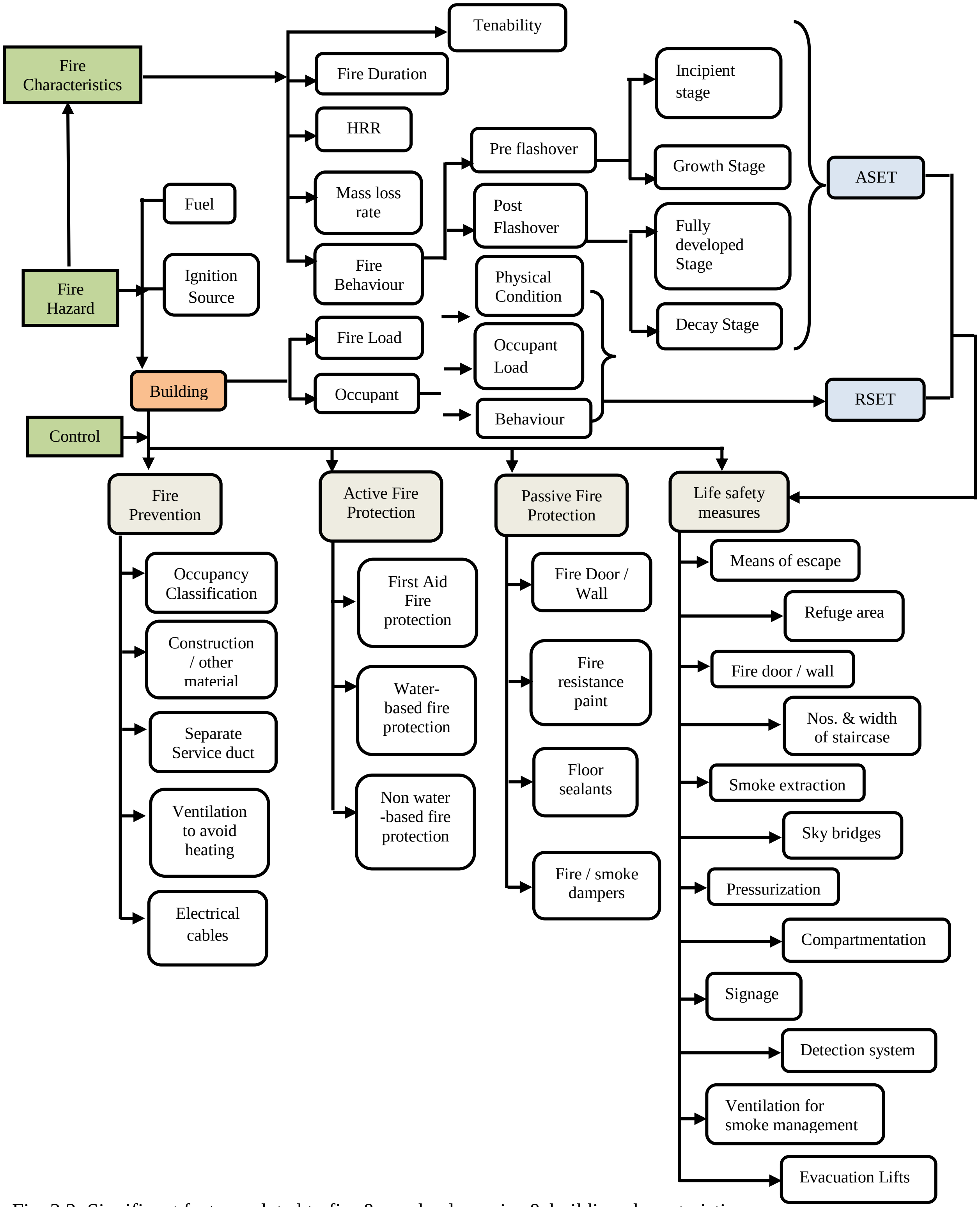


Fig. 3.3: Significant factors related to fire & smoke dynamics & building characteristics

3.2 Current High-Rise Building Evacuation Strategy

Evacuation is one of the most important requirements when it comes to fire management. Broadly speaking, this is the movement of building occupants to a safe area during an emergency. The evacuation during an incident is always a complex phenomenon. There are various factors that determine evacuation that can be grouped according to building geometry, characteristics and human behaviour [124]. The geometry of the building includes the architectural arrangement, size and shape of the building, escape routes, distances travelled, distance between exits, etc. Gwynne et al. [125] stated that responding to an emergency evacuation is directly related to these factors. For instance, there is always a preference for the use of some exits, familiarity with the evacuation route, and the finding way during the evacuation. Fire characteristics govern the development and fire spread in the building. This depends on the compartment's geometry and physical dimensions, fuel load, fuel type and ventilation. Evacuation is expected to happen during the initial stage of ignition of the fire. When skin temperature reaches 72ºC, skin damage occurs. The temperature can attain either by convection and radiation or by direct contact with fire/smoke. That makes evacuation very difficult [126].

The level of active protection and compartmentalization determines the propagation of fire within the building. In the investigation conducted by NFPA [127], office buildings have the highest chance of spreading beyond the place of origin. This propagation of the fire prevents the occupants from moving during their evacuation. Smoke enters stairs as a result of opening and closing doors during evacuation [51]. Smoke causes an obstruction or loss of escape routes that affects the evacuation of a building. A high-rise building itself is very complex and evacuation is highly dependent on the characteristics of vertical evacuation elements such as fire escape chute, lowering devices, evacuation elevators, etc. But all these elements have their limitations and consequently the staircase considers the most reliable evacuation elements. After that, having better evacuation elements is only part of the safe evacuation, but its proper use, the evacuation strategy, is equally important [28]. Sometimes the evacuation of the whole building is very difficult and may not be practical and efficient because of the high density of occupants. We have to understand that an effective evacuation is carried out with moderate density and moderate speed [128]. In such situations, the entire building can be progressively evacuated. We can try to evacuate the occupants only of the affected area, or even decide not to evacuate all occupants. Few studies have addressed issues such as occupant behaviour in the combination of evacuation elevators and stairs but it has few disadvantages [129] [130] [131].

The main evacuation strategies can be summarized into four main alternatives, namely [28],

a) Total evacuation
b) Phased evacuation
c) Defend-in-place and
d) Delayed evacuation.

3.2.1 Total Evacuation

This strategy involves the simultaneous evacuation of all building occupants to the designated safe zone [132]. This is a traditional and conventional method to evacuate buildings. This is the simplest egress strategy in which all building occupants must evacuate once the alarm sounds. In the strategy, the huge population in the evacuation may result in significant densities in the exit. Here, a determining factor is the load of the occupants and the geometry of the means of evacuation of the building. These evacuations are usually scheduled by fire authorities or may be due to an on-site decision by building occupants.

This strategy is always challenging because of the high occupant load and occupants may be exposed to high risk areas during evacuation. Severe congestion at the exit can increase the evacuation time of the building, especially for those most affected. Moreover, with a high occupant load and a higher building height, the total evacuation forms a long queue before entering the stairs. For very large buildings, it sometimes takes hours to walk down the top floors by stairs. The high number of people using the stairs may interfere with access to emergency services. In addition, occupants evacuating stairs may be exposed to other hazards, such as fatigue, skidding on surfaces, etc., that could further impede evacuation.

3.2.2 Phased Evacuation

There are instances where total evacuation in a single stage is not practically feasible and safe, especially for very tall buildings. In such a situation, phased evacuation may be more effective. The objective of the phase-out strategy is to remove occupants from the most critical floors as a priority. Other occupants are "alerted" to an incident and are evacuated only if required. The main goal is to reduce the waiting time and further reduce the number of people in the exit. Fire compartmentalization is an essential part of this strategy [98]. The success of this strategy depends on the fire protection facilities installed in the building, the capability of the staff and the appropriate communication system within the building.

3.2.3 Defend-in-place

Here, the occupants close the door of their compartment, seal the opening and await further instructions. This strategy is widely used primarily for two reasons. First for people with disabilities, since they could not proceed with the evacuation on their own. Second in case all the exits are blocked. While quite a lot of case studies back this strategy, there are few requirements for its implementation. Proulx [133] stated that this strategy is the mostly applicable for residential high-rise building fires such as apartments, dormitories, hotels, etc. In applying this strategy, the main characteristics should be:

- The building should have more than six floors. This is because the lower floors buildings can be quickly evacuated,
- This is mainly applicable to the residential buildings with enclosed compartments.
- The basic tools required restricting smoke/ fire should be available,
- No combustible construction should be there,
- Availability of an alarm system for providing information about the fire to the occupants,
- A voice communication system is mandatory and it should continuously give instructions to the occupants about the updates on the fire and advice accordingly.

Its effectiveness relies heavily on communication between occupants and rescue personnel. The Kuddbygränd fire in Stockholm [134] resulted in 7 deaths, mainly due to a lack of proper communication about the actions expected from the trapped people. In this incident, the occupants did not remain in their compartments, they began to evacuate and died on the stairs. Effective communication is therefore a major reason for the failure of this strategy.

3.2.4 Delayed evacuation

Delayed evacuation occurs when evacuees are temporarily waiting in a dedicated refuge area for outside assistance. Generally, this strategy is applied to rescue the occupants with temporary or permanent disabilities who are not in a position to evacuate on their own and external help is required to reach a place of safety. This strategy is mostly applicable and always helpful for the buildings having people with such disabilities e.g., health care centers.

In all of the strategies discussed above, it is important to note that the RSET must be lower than the ASET so that tenability conditions are not reached for safe occupant egress. The ASET is determined on the basis of tenability criteria. The RSET is decided on various time requirements that include time to activate the detector, time to recognize it, time to respond to occupants, and real travel time.

3.3 Computer modelling for Fire safety

As previously mentioned, occupants of high-rise buildings are at greater risk as other fire situations because of their complexity and high occupancy load. Here, the behaviour of the fire and the evacuation details of the occupants are very important to understand for further course of action. In such situations, rapid evacuation is very important for occupants to reach a safe location long before the tenability is reached. To evaluate this concept, computer simulations are always an appropriate alternative to actual physical simulations, which are always cost-effective, flexible, interactive and safe [135]. Real physical stimulation is always unethical, risky and expensive [136] [137]. Furthermore, in recent decades, fire safety requirements have been shifting from prescriptive-based to performance-based to address complex fire safety issues [138]. All of these computer models have been instrumental in tackling the best fire safety issues. Computer modelling analyses and predicts a structure's response and associated characteristics during a fire for the time required for occupants to safely exit a building. It also helps to decide the optimization of evacuation time. Initially, the models were restricted to the available computer resources. But a significant development has taken place in recent years. Resources are available for complex fire effect calculations and the ability to graphically depict the results. It is mainly classified in fire modelling and evacuation modelling with detector response modelling, endurance fire modelling and some miscellaneous models [139].

3.3.1 Fire Modelling

Fire models are used to illustrate a fire effect. It predicts the fire process and its characteristics [140], such as temperatures, smoke obscuration, gas flow rates, heat fluxes, toxic gas, sprinklers and detectors activation time, reduction in the strength of the building, and structural failure of building elements. Currently, the computer fire models use computational fluid dynamics (CFD) analysis and provide details of the smoke movement, its concentrations and temperature in the affected area. Heat transfer models are also used to study increased in temperature in the surrounding of the fire. This also includes analysis of sprinkler heating to decide suitable position or temperature of a structure to estimate the time that the structure can withstand. Special CFD models also exist such as heat transfer models that are designed exclusively for the study of fire conditions.

Fire modelling is of two types: physical modelling and mathematical modelling [141]. Physical fire modelling burns objects to evaluate their effects which may be full or small scale and it has been from long back. Mathematical models are conclusions of the findings of a physical system that began in the early 1940s and can be divided into probabilistic models and deterministic models. Probabilistic models rely on a series of sequenced events without the use of physical and chemical equations describing the fire process. Deterministic models are based on physical and chemical equations describing the fire process which is then divided into three categories, i.e. hand calculations, zone models, & field models. [28] [142]

Hand calculations are algebraic equations which are developed through experimental correlations. Zone models are the software used to assess fire dynamics. It is divided into two zones, commonly called upper and lower zones. The field models called CFD models, separate a compartment into thousands of small cubes depending on the user's inputs. Lewis Richardson used fluid flow equations for meteorological forecasting for the first time, in early 1920s [143]. Now it is known as CFD which is a general analytical tool for all fluid flow issues, including the fire phenomenon.

According to the Fire Research Division of the National Institute of Standards and Technology [144], few fire models are available and in active use. There are FDS models that are CFD models, CFAST (Consolidated Model of Fire and Smoke Transport) that is a zone model. There are few models, but now they are out of date and no longer used. Some of these models are ASCOS (Analysis of Smoke Control Systems), ASET-B (Available Safe Egress Time - BASIC), ASMET (Atria Smoke Management Engineering Tools), BREAK1 (Berkeley Algorithm for Breaking Window Glass in a Compartment Fire), CCFM (Consolidated Compartment Fire Model version VENTS), ELVAC (Elevator Evacuation), DETACT-QS (DETector ACTuation - Quasi Steady), and DETACT-T2 (DETector ACTuation - Time squared), FIRST (FIRe Simulation Technique), FPETool (Software and Documentation) and LAVENT (Link-Actuated VENT)

3.3.2 Egress Modelling

Evacuation calculations are important to access the level of safety provided in the building and are an important component of performance-based analysis [145]. The egress models are used to obtain more realistic evacuation calculations. There are several evacuation models available and each has unique features with specialties and limitations. Some models are able to examine the movement of huge number of occupants across complex buildings. Some advanced computer evacuation models can import the real floor plans of a building and study the movement of every occupant available on the every part of the building.

These models verify the movement of all types of available occupants having different type of mobility as per requirements. They can also calculate occupant speed and evacuation time during an evacuation. It also studies the interaction among occupants. The detailed information provided by the computer egress models with the output can be available as video animations. An evacuation model provides the time for occupants to evacuate the building and can analyze the occupants' movements through complex structures. Few advanced egress models can import actual building plans, and occupant movement can be seen. The speed of the occupants during the evacuation and the interaction between them can be calculated. An important criterion in assessing the appropriateness of models is their ability to represent various egress components. The decision on the use of elevators should also be made by some models. The results of these models can be calculated by the egress models which can help to make appropriate decisions.

Evacuation models may be categorized based on features and capabilities [146]. This includes the purpose, availability for public use, modelling method, the construction of the model, perception of the model and occupants, behaviour and the movement of the people, usage of fire data, output, usage of CAD drawings, visualization abilities, validation studies, special features, restrictions, etc. Among these features, here are some of the significant features.

To understand the purpose of the model is very important to determine its compatibility with the user. It concerns certain types of buildings. Some models may be used in a particular type of building. It can be categorized to simulate any type of building or only residences or public transport stations or low-rise buildings or buildings with only one route/exit.

Evacuation models can be classified according to a modelling method that may be behavioral, movement or partial behavior. In the behavioral model, occupants perform certain actions together with the movement. There are models that have risk assessment capabilities. Movement models move people from one place to the next place of the building. These models can show overcrowding areas, queues, or blockage in the simulated structure. Some models can be used for optimization too. Partial behavior models are mainly used to calculate occupant movements, but begin to simulate behaviour.

In the grid/structure category, grid/structures are used to evaluate the method of movement of the occupant across the building. It can be a fine network model which split a floor into several small grid cells that the inhabitants move to and fro. It can be a coarse network model that divides the floor into various subsections like corridors, rooms, stairs, etc. and occupants travel from these subsection to subsection. In a continuous network model, space to the structural floor is provided, allowing occupants to move from one point to another all over the building.

Course Network Models: In this type, space is a network of arcs and nodes, representing different sections of the building. For example rooms, stairs, etc. It is the simplest technique to simulate an evacuation situation. The main benefit is that it represents the complex structure. Time can be calculated very quickly, even during the simulation of a complex evacuation scenario. The main limitation is their inability to represent behaviour that may occur during an evacuation.

Fine Network Models: In this model, space is represented as a grid of the uniform cells. This can be occupied by one person at a time. The movement of agents is simulated by a series of stages in the cells of the network. In these models, the location of the occupant can be monitored during the evacuation according to a fine network representation.

Continuous Models: It simulates agents across a system of certain references in the environment. Here, occupant behaviour can be simulated with more flexibility, concerning their location, orientation and distance between agents. This is important for simulating high densities. For this model, more computing time is required to simulate complex scenarios, as agent reference points need to be recalculated each time.

All the available models are shown in Figure 3.4 and a further classification of the evacuation model is shown in Figure 3.5.

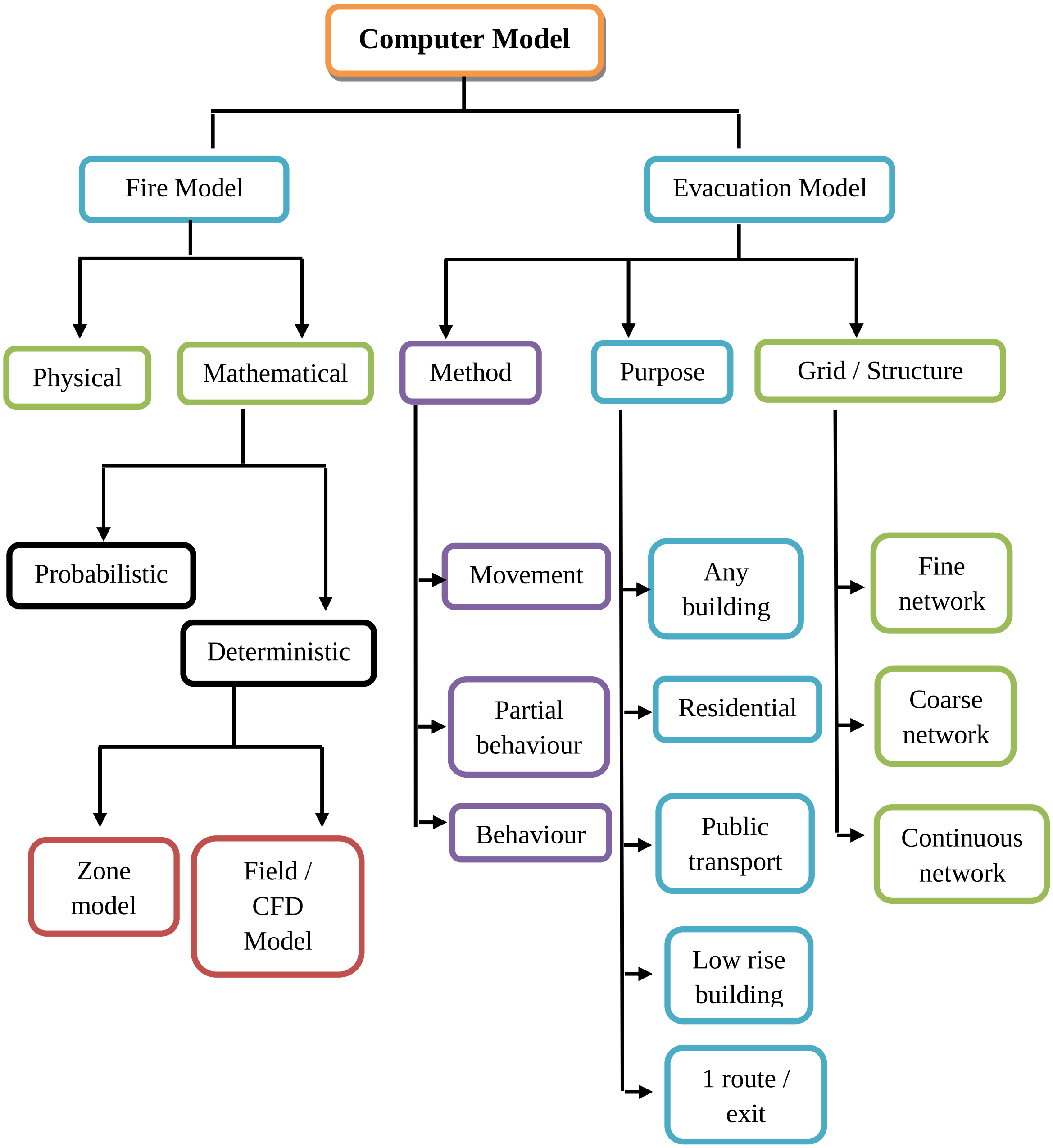


Fig. 3.4: Details of computer modelling for fire safety

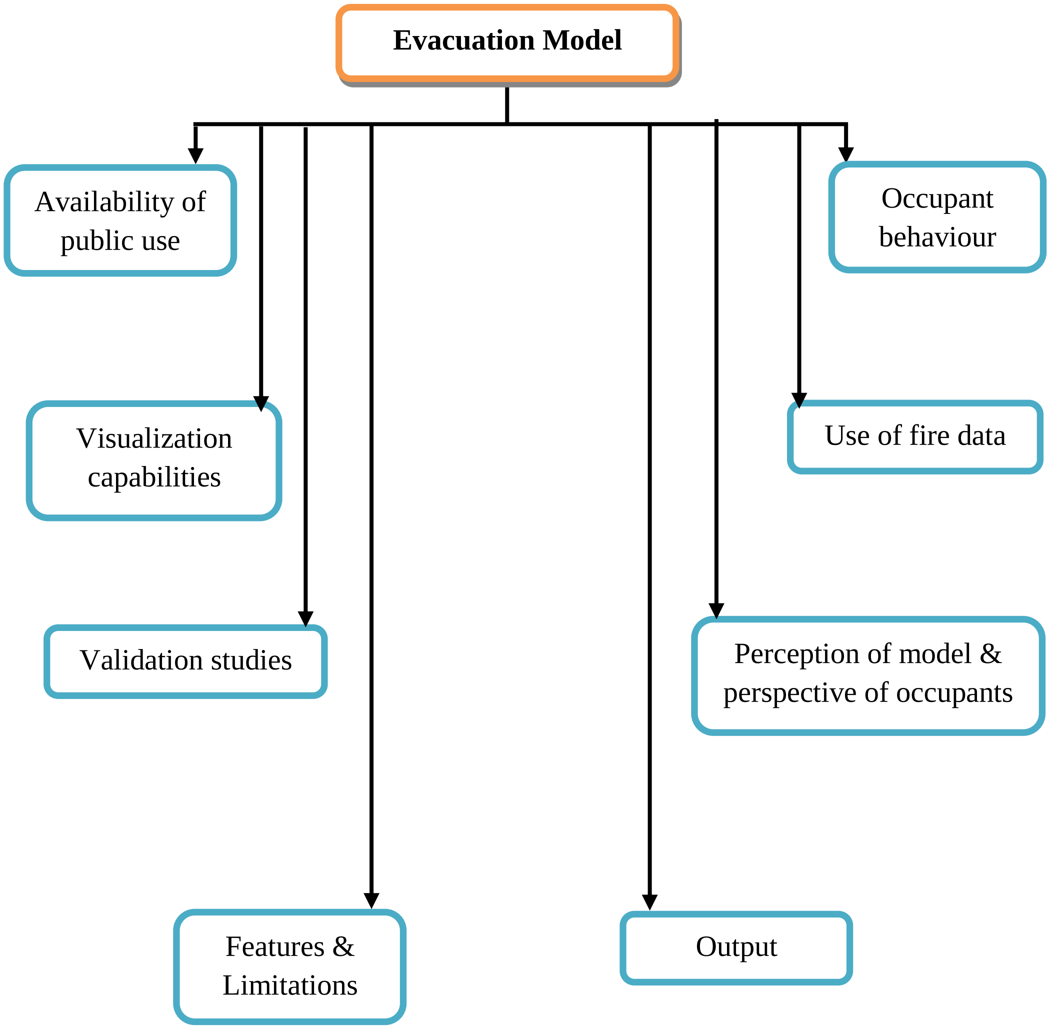


Fig. 3.5: Details of egress models on the basis of various parameters

There are several evacuation models available. A detailed list of evacuation models and their capabilities and limits is given in Table 3.1

Table 3.1: Details of capabilities & limitations of various egress models

Model	**BFIRES-2 [147]**	**Takahashi's Fluid [146] [148]**	**EgressPro [149]**	**EXIT89 [150][151] [152]**	**EGRESS [153]**
Purpose	Low-rise buildings	All buildings	1 route/exit building	Specially HRB	All buildings
Developed in	1982	1989	1991	1991	1991
Available to public	Not in use / Unknown	Not in use	Not in use	Not yet released	Available for consultancy
Modelling method	Behaviour with RA	Movement with optimisation	Movement	Partial behaviour	Behaviour
Grid / Structure	Fine network	Coarse network	Coarse Network	Coarse Network	Fine Network
Perspective of M/O	Individual viewed	Globally viewed	Globally viewed	Individual view	Individual viewed
Behaviour	Rules / Conditional, Probabilistic	No behaviour / Functional analogy	No behaviour	Implicit behaviour / Conditional	Rules / Conditional, Probabilistic
Movement	Users' choice	Functional analogy / Density correlation	Density Correlation	Density correlation	Potential & Density correlation
Fire Data	From another model	No	Certain time	From another model	From another model
CAD	No	No	No	No	No
Visuals	No	2D	No	No	2D
Validation	No	Fire drill	No	Fire Drill	Fire drill

Table 3.1: Continued……….

Model	**CRISP [154] [155]**	**buildingEXODUS [156]**	**Simulex [157] [158] [159]**	**EvacSim [160]**	**ENTROPY [161]**
Purpose	All buildings	All buildings	All buildings	All buildings	1 route/exit building
Developed in	1992	1993	1994	1994	1994
Available to public	Available for consultancy	Available	Available	Not yet released	Unknown
Modelling method	Behaviour with RA	Behaviour	Partial Behaviour	Behaviour	Movement/ Partial behavior
Grid / Structure	Fine Network	Fine Network	Continuous network	Fine network	Coarse network
Perspective of M/O	Individual viewed	Individual viewed	Individual viewed	Individual viewed	Individual / Globally viewed
Behaviour	Rules / Conditional, Probabilistic	Rules / Conditional , Probabilistic	Implicit behaviour	Rules / Conditional, Probabilistic	No behaviour
Movement	Density correlation / emptiness of grid	Density correlation / emptiness of grid	Inter person distance	Density correlation	Acquiring knowledge / functional analogy
Fire Data	From another model	From another model	No	From another model	No
CAD	Yes	Yes	Yes	No	No
Visuals	2/3D	2/3D	3D	No	No
Validation	Fire drill	Fire drill	Fire drill & past experiment	Experiment/ actual fire	Other models

Table 3.1: Continued……….

Model	**ASERI [162]**	**TIMTEX [163]**	**STEPs [164] [152]**	**Legion [165]**	**ALLSAFE [166]**
Purpose	All buildings	Low-rise buildings	All buildings	All buildings	1 route/exit building
Developed in	1995	1996	1997	1997	1998
Available to public	Available	Available	Available	Available	Available for consultancy
Modelling method	Behaviour with RA	Movement	Movement/ Partial behavior	Behaviour	Partial behavior
Grid / Structure	Continuous network	Coarse network	Fine network	Continuous network	Coarse network
Perspective of M/O	Individual viewed	Individual / Globally viewed	Individual viewed	Individual viewed	Globally viewed
Behaviour	Rules / Conditional, Probabilistic	No behaviour	Functional analogy	Artificial intelligence	Implicit behaviour
Movement	Inter person distance	Density correlation	Potential & emptiness of grid	Density correlation & conditional	Unimpeded flow
Fire Data	From another model	No	No	From another model	From another model
CAD	Yes	No	Yes	Yes	No
Visuals	2&3 D	No	3 D	3 D	2 D
Validation	Fire drill	Past experiment	Code requirement	Fire drill & Other models	Other models

Table 3.1: Continued……….

Model	**WAYOUT [167]**	**VEgAS [168]**	**GridFlow4 [169]**	**Pathfinder [139]**
Purpose	1 route/exit building	All buildings	All buildings	All buildings
Developed in	2000	2000	2002	2003 Relaunched in 2011
Available to public	Available	Not in use / Unknown	Available	Available for consultancy & Study purpose
Modelling method	Movement	Behaviour	Partial	Movement
Grid / Structure	Coarse network	Fine network	Continuous network	Fine network
Perspective of M/O	Globally viewed	Individual viewed	Individual viewed	Individual / Globally viewed
Behaviour	No behaviour	Artificial intelligence	Implicit behaviour	No behaviour
Movement	Density correlation	Inter person distance	Density correlation	Density correlation
Fire Data	No	From another model	No	No
CAD	No	Yes	Yes	Yes
Visuals	2 D	3D	2/3 D	2 /3 D
Validations	Fire drills	No	Fire drill / past experiment	Experiment & other models

In the list above, it is observed that each model has its specialty and its limits. Few models aren't validated, few models aren't relevant to high-rise buildings, few models aren’t available for use, visuals are not available for their outputs in a few cases, and a few models are very outdated. So in accordance with the requirements of this study, there are very few models available. Among them, the pathfinder is an agent-based evacuation simulator. It is designed to study complex buildings matches in every way for this study and also available for the purposes of the study. Agent-based simulation remains a preferred and accepted simulation for evacuation of the complex structures because of its capability to model individual decision-making [170].

There is a robust validation process for this simulation that makes it more reliable in capturing the more complex situation and also the interactions between the occupants. This is a good choice since we are analyzing an enormous crowd in this study. It also facilitates the creation of simulation data based on existing information and the visualization of outcome using high-quality visualization method [139]. In this model, occupant parameters can also be controlled by setting speed, initial delay, size, and appearance of groups of occupants. The default setting of any occupant’s speed is 1.19 m/s, his shoulder width is 0.4558 m, and he is selecting the nearest exit [171] and the same has been followed in this study. The default value of 45.58 cm is based on the average of the measurements of men and women from nine countries [168]. Occupants can also be allocated some specific exits to help simulate different stages of familiarity with the exit system. This visualization of the results allows users to navigate through the models and modify the view parameters to analyze complex structures more conveniently [139]. The pathfinder model is based on recent and emerging movement research. To validate that the every component of the simulator are operating correctly, the results are compared to the hand calculations. In this model, to authenticate the behaviour of the simulator, real evacuation situations are recreated and their results are compared. The entire work of verification and validation are available in the Pathfinder's Verification and Validation document [172]. It is also supported by research carried out by Seyfried [173].

CHAPTER 4: OPTIMISATION OF STAIRCASE DESIGN AND ANALYSIS OF EVACUATION STRATEGIES

4.1 Brief about research work

One of the important objectives of fire safety is to ensure the safety of all occupants during a fire. This study proposes the best possible evacuation strategy. Also suggest optimizing evacuation time in terms of evacuation design, especially stairways during the planning phase and evacuation management during an actual emergency. The study focuses on building infrastructure and management. While behavioural aspects are models, simplified and consistent behaviour is assumed for all those mentioned in Section 4.3 below. Variation in the behaviour of persons during fire is not considered in this study.

There are several factors associated with building that may be widely differentiated into individual, organizational, situational and social. Some of these factors are vibrant and may transform during emergency e.g. available fire indications, emotional conditions, smoke density and some factors cannot change e.g. past experience of the people, building design, available escape route. These factors also interact with each other and may further influence the overall process. During the World Trade Center evacuation, the number and intensity of signal and floor level had a direct impact on pre-evacuation delays on 11 September 2001 [110] [174].

The dynamic situation is always affected by the evacuation schedule and it is difficult to analyze and act in crucial times. Therefore, a static evacuation situation is the base and we concentrate solely on the static situation.

The research work is divided into three parts,

- To propose the best staircase configuration for optimizing the building evacuation time.
- To develop a new method for estimation of staircase evacuation time in high-rise buildings
- To propose the best possible evacuation strategy for a high-rise building.

4.2 Research methodology

The research methodology used in this study is divided into the following sections:

1. Identification of significant factors related to fire & smoke dynamics and building performance: - Through literature review
2. Identification of sample building characteristics and decide its zoning: - Through literature review
3. Study and selection of suitable fire and evacuation models: - Through literature review
4. Identification and development of the best possible evacuation strategies for a building to minimize the loss of life.

A. Optimization of travel time during building evacuation:

- Review of existing studies for optimizing evacuation time.
- Identification of the various possibilities of the staircase w.r.t. position of exit doors
- A selection of case study samples with various combinations of multiple floors, occupants and floor area.

  - Application of pathfinder egress model for all these designs for average evacuation travel time
  - Analyze the result of different evacuation travel time
  - Propose the best possible staircase design.

B. **To develop a new method for estimation of staircase evacuation time during building evacuation**
  - Selection of sample case studies with different combinations of the number of floors, occupants, staircase width, and floor area.
  - Application of pathfinder egress model for all these designs for evacuation travel time.
  - Analysis of the results concerning the different input parameters.
  - Develop a mathematical model to determine the evacuation travel time w.r.t. the input parameters.
  - Validate the proposed mathematical model

C. **Proposing best possible evacuation strategy for a model building case study:**
  - Decide the tenability criteria for building evacuation.
  - Selection of a sample case study with different combinations of the number of floors, occupants, and floor area.
  - Identify different possible evacuation possibilities
  - Apply pathfinder model for all these possibilities for evacuation travel time
  - Analysis of the results of evacuation timing w.r.t. acceptable tenability.
  - Propose the best possible evacuation strategy

4.3 Assumptions made for the study

Fire is a very complex scenario with the release of dangerous fuel products like carbon monoxide, carbon dioxide, smoke, thermal radiation, etc. based on combustible material. Its intensity and duration is a function of fuel properties and ventilation. When a high-rise building is involved, a major evacuation factor is added. It is complicated taking into account the additional complications of such a building because of its functional diversification. There are various vertical components like stairs, elevator shafts, pipes, ducts, electrical shafts through which fire can spread very quickly if proper precautions are not taken. This can result in a reduction in available safe evacuation time, the most important for building evacuation. Apart from this, there are also some behavioural factors that affect evacuation time. These factors vary from person to person according to capacity, experience, physical health and culture.

Therefore, the following assumptions are considered in this study,

1. The Pathfinder Evacuation Model is used only for the travel time required for evacuation from the exit access to the final portion of the exit.
2. All occupants begin their evacuation simultaneously after hearing the alarm. The delay time is not taken into consideration during simulation although it is considered as per the literature review.
3. All occupants are physically fit with no mobility impaired occupants in the building.
4. For two exits, individuals use the nearest exit.
5. Emergency staff will not use the same stairs during the evacuation to avoid

reverse flow.

6. The time required for the last evacuated person is considered evacuation time.
7. The width of the staircase landing and mid-landing is the same as the staircase width i.e. 1.5 m.
8. The refuge area is available on the upper floors, where the workload of the occupants will be slightly lower than that of the other floors. However, for the purposes of this study, an equal number of occupants are considered on each floor, taking into account visitor movements.
9. On the ground floor, we take into account the same occupant load which is very difficult to predict.
10. Although the sprinkler system is available, it will be operated after the initial evacuation.
11. All occupants proceed to the evacuation in a disciplined manner.
12. There will be no damage to the stability of the building model during the entire evacuation and no one will be injured during the entire evacuation process.
13. All stairs are free of material obstructions and free for all occupants to evacuate.
14. No occupant returns to his or her place for any reason during evacuation.
15. Basements are available in the building and it is used for parking and other auxiliary services. It is not occupied and hence it is not considered in the study as it will not affect the evacuation process.

CHAPTER 5

OPTIMIZATION OF EVACUATION TIME DURING BUILDING EVACUATION

In this chapter, a systematic review of the existing literature on evacuation optimization is studied and further proposes the best design of the staircase w.r.t. its exit location based on the analysis of the results received.

5.1 Review of existing studies on optimization of evacuation time

Important work is being done in the field of evacuation management, both in experimental and fire modelling [175][176]. A number of suggestions and proposals are made, but there is always some discrepancy between the expected responses of occupants and their actual response to such emergencies [177]. Currently, there is a focus on evacuation management and very little on optimizing evacuations through infrastructure and building design.

Adrian et al. [178] suggested that moving occupants from any affected location to a safe location in the least possible time is the basic concept of evacuation. It may be a threat, a warning, or any other safety reason. Its success depends on the design and infrastructure of the building and the effective management of the evacuation. For evacuation, there are few strategies available, namely phased evacuation, total evacuation, defend in place, and delayed evacuation [179]. But all the evacuation strategies have their advantages, disadvantages, and applicability. Its suitability depends on various features such as the situation, available fire protection facilities, awareness of the occupants of their roles and responsibilities, the physical condition of the occupants and available safety evacuation time. In any evacuation strategy, optimizing the evacuation always plays a key role.

In general, evacuation is studied on the basis of two general approaches. One is a descriptive or observational study and another is a prescriptive or interventional study [180]. The descriptive study learns the behavior of the crowd during emergency situations and the probable response of each individual. This behavior can be modeled in mathematical formulas which are then used to predict the evacuation and their respective characteristics such as time for evacuation, distribution of the density, finding the bottlenecks, etc. [181][177]. The prescriptive study uses this data and the mathematical models got from descriptive studies to further optimize the evacuation processes. Both studies are interconnected as they directly depend on descriptive models and use important inputs [182][183][184]. The prescriptive study helps to achieve the aim of optimization of the evacuation time and helps the occupants to leave the affected area at the minimum possible time. Various studies are available for optimization and are categorized in three broad categories,

- Design and infrastructure of the building
- The setting of paths and departure and
- Behavioural aspects of the occupants

The above three categories are reviewed in details,

5.1.1 Building design and infrastructure

This category is related to the modification of the design and infrastructure of the building to improve the evacuation process. The common challenge during evacuation of high-rise buildings is the bottleneck at the exit due to high occupant load. This has a major impact on the effectiveness of evacuation and probable injuries due to excess crowd pressure [185][186]. There are different ways to make it better.

Normally, an obstacle is considered a major obstacle while evacuating. But surprisingly, it is observed that partial obstruction can enhance the effectiveness of evacuation. Different studies have mentioned different degrees of effectiveness. Some studies suggest that placing a column near the exit can be effective by more than 90% [187], while some studies have reported much less efficiency improvement [188]. In addition, few other studies question this concept. A few studies indicate that it has no significant impact on evacuation times [189]. Thus, the effect of the obstacle is sensitive and may even be harmful depending on the placement of the obstacle and the adjacent geometry [190] [191].

The next important factor in optimizing the evacuation time is the spatial position of the exits. Tavares [192] suggested that the relative distance between exits is an important condition in determining evacuation routes. The greater the distance, the safer is the evacuation. It applies, particularly in densely populated areas. Shao and Yang [193] suggested that the placement of a corner exit is very effective during evacuation. However, few studies do not fully support these suggestions. Haghani and Sarvi [194] suggested that placing corner exits is not always useful and can only be used for extremely narrow exits. Few studies fully dispute this idea of a corner exit for efficient evacuation and suggest that its location should always be in the middle of the wall [193][195]. It is also suggested that two adjacent exits tend to be more overcrowded at one exit, which ultimately increases the evacuation times of the building [196].

Likewise, there are different views, concerning the number of exits and contradict themselves. Few studies have suggested that a single exit with an equivalent width is a good option for efficient egress [193]. Other studies suggest that multiple exits and their proper positioning are more efficient than a single exit of equivalent size [197] [198].

The layout of the exits is also an important parameter in optimizing the evacuation. Few studies have suggested a suitable physical design of exits to improve evacuation efficiency. The study by Lei and Tai [198] suggested that buildings should be designed with exits facing the stairs. Adrian et al. [199] suggested that a physical guidance system in front of an entrance can reduce pushing, and thus density at the entrances. If the width of the exit is adequate, the push behaviour at the bottleneck will not slow the evacuation, i.e. when the exit is wide enough to accommodate two persons passing at the same time, the push will not delay the evacuation. This means the faster-is-slower effect will not take place [200].

The next important factor is the configuration of the building corridor and staircase that addresses occupant merging. There are various studies of occupant merging behaviour in different architectural configurations. The width of the branch has an important influence on the density of flows at the corners [201].

Exit signs also play a major role in optimizing the evacuation. While not part of the building's design and infrastructure, it may be considered an emergency evacuation guide. The proper location of exit signs is an important feature of the building design and makes a significant difference in the evacuation process. The efficient placement of such signs, which depends on the distance of vision, is a fundamental requirement for improving the efficiency of the exit system and ultimately improving evacuation [202].

Visibility also plays a key role in the process of optimizing the evacuation. Evacuation in low visibility is different than evacuation in good visibility. As visibility increases, the evacuation time decreases, but the downward trend gradually slows when more and more people exit the visible area [203]. Visibility is directly associated with the ventilation of the area. Ultimately, evacuation also depends on the efficiency of the building ventilation.

5.1.2 The setting of path & departure

The route or start time of the persons can also optimize the evacuation time of the building. This is largely related to path planning and occupant departure schedules. Path planning optimization studies focus on actions and strategies at the individual level rather than on the entire population. For a small population, the shortest path to exit is the most effective option, but its effectiveness decreases rapidly with an increase in population [204].

Departure times are also a good choice to optimize evacuation. In general, it is assumed that the rapid movement of the occupants is required for efficient evacuation. But it is observed that a waiting time is a good strategy for improving the efficiency of evacuation time [205]. Likewise, various studies advocate minimizing evacuation time due to proper planning of departure time and avoiding the faster-is-slower effect. The aim is to alleviate congestion at bottlenecks through the strategically synchronized move-wait-restart method [180].

The appropriate allocation of exits also plays a significant role in optimizing evacuation time. It is suggested that the exit nearest the affected area may not always support good optimization. It should be assessed according to the optimization of the last evacuated person leaving the building [206]. Regarding the choice of the path to the exit, the evacuation may be of two main types. One is static that signifies the shortest path and the other is dynamic that signifies the fastest path to an exit even if it is not the shortest. In the dynamic type, the focus is on assigning occupants to those exits by which the time for complete evacuation is optimized. This is achieved by distributing occupants among exits in a uniform manner, so that the evacuation load is effectively distributed in exits. [207].

The evacuation strategy with the joint use of evacuation lifts and stairs is also an efficient method for optimizing the evacuation. The best-acceptable practice is to assemble in the refuse area from where occupants can be evacuated further by using an evacuation elevator [208][209].

There is also a need to revisit an old assumption that waiting strategies are more effective than the strategy that all occupants respond to the evacuation cues. It is observed that the instantaneous response strategy creates more dense bottlenecks compared with the wait strategy. But this does not have an effect on the overall evacuation time and, from a time reduction perspective, it is the best strategy [210].

5.1.3 Behavioural modification

In the behavioural aspects of optimizing evacuation, occupants are allowed to select their path or leaving time that cannot be centrally controlled. In this case, the important precondition is to provide effective instruction or training to all people so that they can collectively lead to a more efficient evacuation process [211]. In this method, planning for the whole crowd is taken into account, not individual actions and strategies. There are different ways of optimizing evacuation time through behavioral changes.

Crowded exits are always a major reason for delayed evacuation. In such situations, evacuation becomes more effective by introducing a virtual leader to control evacuation [212]. The effectiveness of leadership depends mainly on the visibility of the area and the number of leaders and their positions. Where visibility is good, the leadership effect cannot be effective and can be worthless. The quantity and position of the leaders depend on the familiarity of the building layout for the occupants. Where occupants are not familiar with the design of the building, the number and positions of leaders play an important role [213]. But at the same time, more leaders can hinder the evacuation process also [214].

Behavioral aspects also play a significant role in the bottleneck for improved flow efficiency. Although a traditional concept of faster-is-slower is a universally accepted phenomenon [215], few studies challenge this concept [216] [217]. Friction between occupants is the key to the quick movement of people. As the pushing power enhances, compression between the occupants at the bottleneck is not enough to slow people in motion, so a faster-is-slower effect is converted to a faster-is-faster [218]. The faster-is-slower is observed only if the door is extremely narrow [219].

Body orientation also plays a considerable role in the effectiveness of evacuation. When people walk in the direction of their long axis i.e. longitudinal orientation, the flow is considerably reduced relative to their short axis i.e. transversal orientation [220].

The level of impatience, selfishness and cooperative behavior of people also influences the effectiveness of evacuation. A crowd of competitors escaping through an exit may result in a standstill, which badly affect the evacuation time [200]. In the case of cooperative behaviour, there are few studies to verify the relationship between egress dynamics and egress behaviour. It is noted that the urgency of evacuation decreases cooperation between evacuees. Individual hyper rationality and imitation in evacuees enhance cooperation between evacuees and reduce evacuation efficiency [221]. But selfish behavior negatively affects the total time to evacuate [222]. On similar ground, neither a totally cooperative nor completely selfish attitude is optimal. An intermediate behavior leads to the lowest evacuation time [223] [224].

In reduced visibility, evacuation strategies using a variety of navigational methods, such as moving alongside the wall, following the general direction of the people or the general position also gives good results in the evacuation optimization process [203]. Walking near the wall is more useful at low densities and following the general movement of the people is more useful at high densities [225]. Behavioural changes to pre-evacuation and related delays also play an important role in optimization. Occupant training and awareness are also helpful to increase evacuation efficiency and reduce evacuation time by more than 20% [226].

The optimization of the evacuation can also be achieved from aspects of occupant locomotion from a behavioral point of view through the rhythm of the occupants. The slow walking which is in rhythm gets a better results in the high-density area. [227].

The set of parameters necessary to optimize the evacuation is mentioned in Figure 5.1.

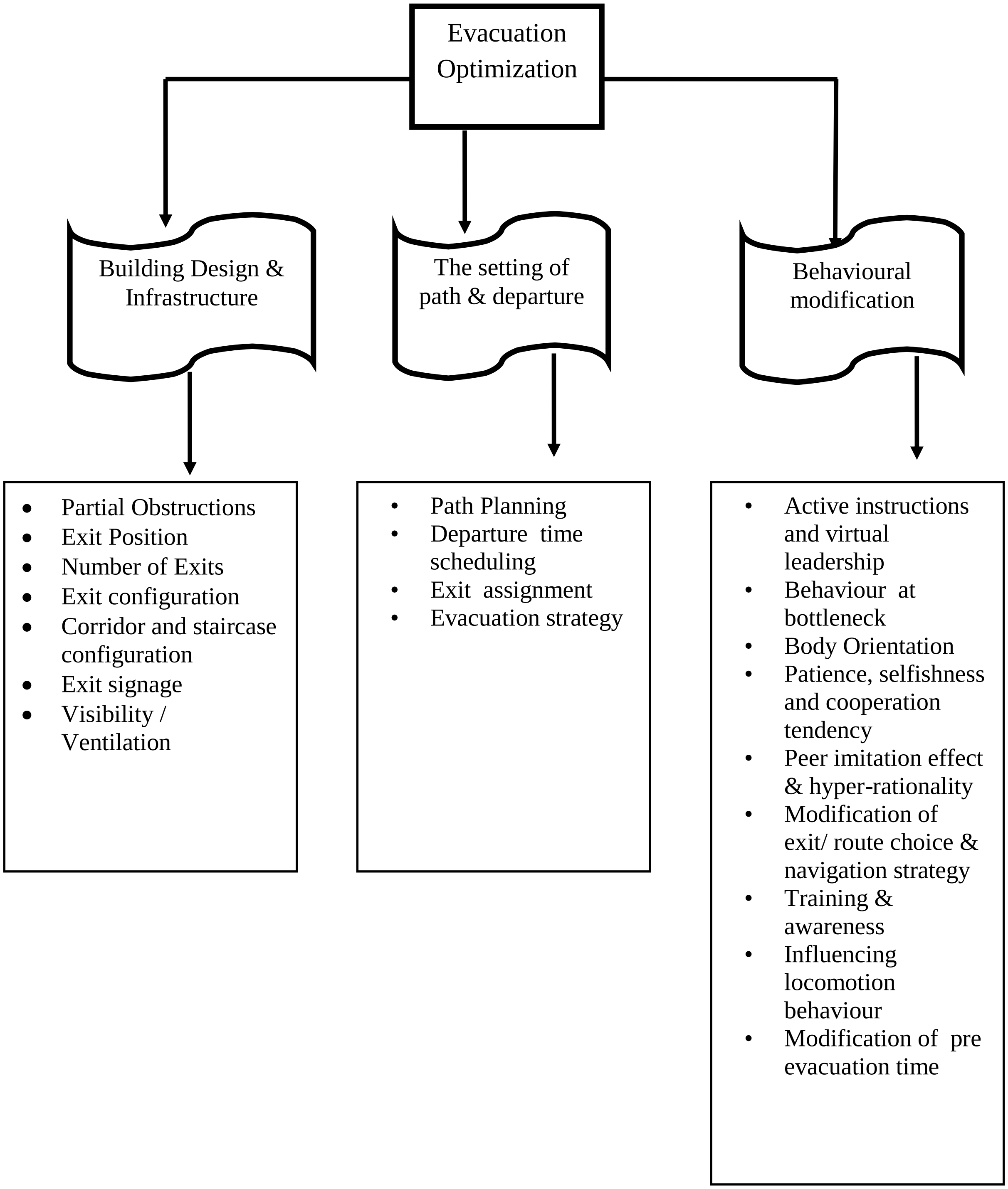


Fig. 5.1: Various categories of evacuation optimization methods

5.2 An evacuation optimization study by using various staircase configuration w.r.t. the position of the door

Quick evacuation prior to tenability is an important requirement for any emergency planning. Several factors contribute to this optimisation and are discussed in detail in the first part of this study. When a big group of occupants requires evacuation from a building, one of the most critical design factors is the position of the exit doors in the stairs. In an emergency, when people are panicked and afraid for their lives, they try to go forward with force in congested exits that create another bottleneck. To overcome this, one of the important factors from the point of view of the design of a building is the possibilities of the configuration of the stairs and doors. The best setup for optimizing the evacuation time is proposed in this study.

5.2.1 Building case study model considered for the study

The building used in the case study represents a practical layout of the tall commercial buildings. Being commonly used, with a high occupant load and a very high fire load, the case study is fairly complex for the worst-case scenario for this study. In accordance with national and international codes [3] [41] [42], the case study model is classified in the business occupancy category. In this study, an occupant load of 10 m^2/person was taken into account. Floor areas of 900m^2, 750m^2 and 600m^2 up to 50 floors are considered for study purposes. As the height of the ceiling depends on the type of occupancy and varies accordingly, we considered 3.6m in this study as the occupancy is in a business category. There are various codes and standards which suggest this requirement of the number of exits, but all are unanimous on an agreement of a minimum of two staircases for a high-rise building of business occupancy. A travel distance is also an important factor when determining the number of exits and their location. NBC referred to it as 30 meters that we considered in this study. The next significant factor is the width of the stairway. NBC and IBC suggest that the minimum width of the stairs is 1.5m and 1.21m respectively for a business building. In this study, we consider the two stairs of 1.5 m wide. Also for the purposes of this study, we look at the width of 2 m. The general floor plan is illustrated in Figure 5.2.

With regard to the width of the exit door, the NBC refers to it as 100 cm, the NFPA 101 refers to it as 81 cm and a few local codes [228] refer to it as 100 cm. We have considered the 100 cm width of the staircase door. Different sample building models are taken with the floors of the difference of 5 floors. The lowest height of the building is 5 floors as we focus only on high-rise buildings i.e. building height above 15m according to NBC. The highest building considered is the ground floor and 50 floors above it for study.

The ground floor serves for reception, meeting rooms and other various activities. All the upper floors are for office use. There are three basements for parking and others auxiliaries of the building. The whole building is covered by a fire protection and detection system. Here, the ground floor is covered by a total number of floors for evacuation with the same occupant load as the upper floors. But the basements are not taken into account because they are not intended to be occupied and will not affect the process of evacuation of the building.

Therefore, we examined sixty building model simulations as indicated in Table 5.1.

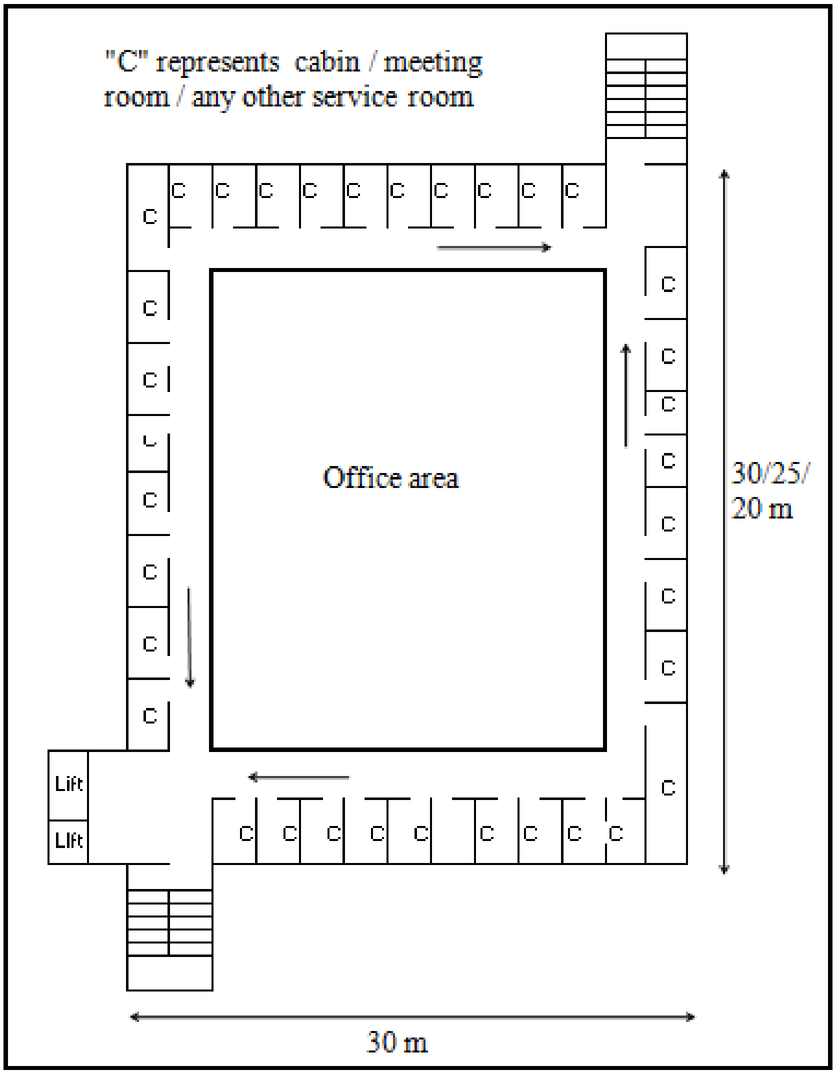
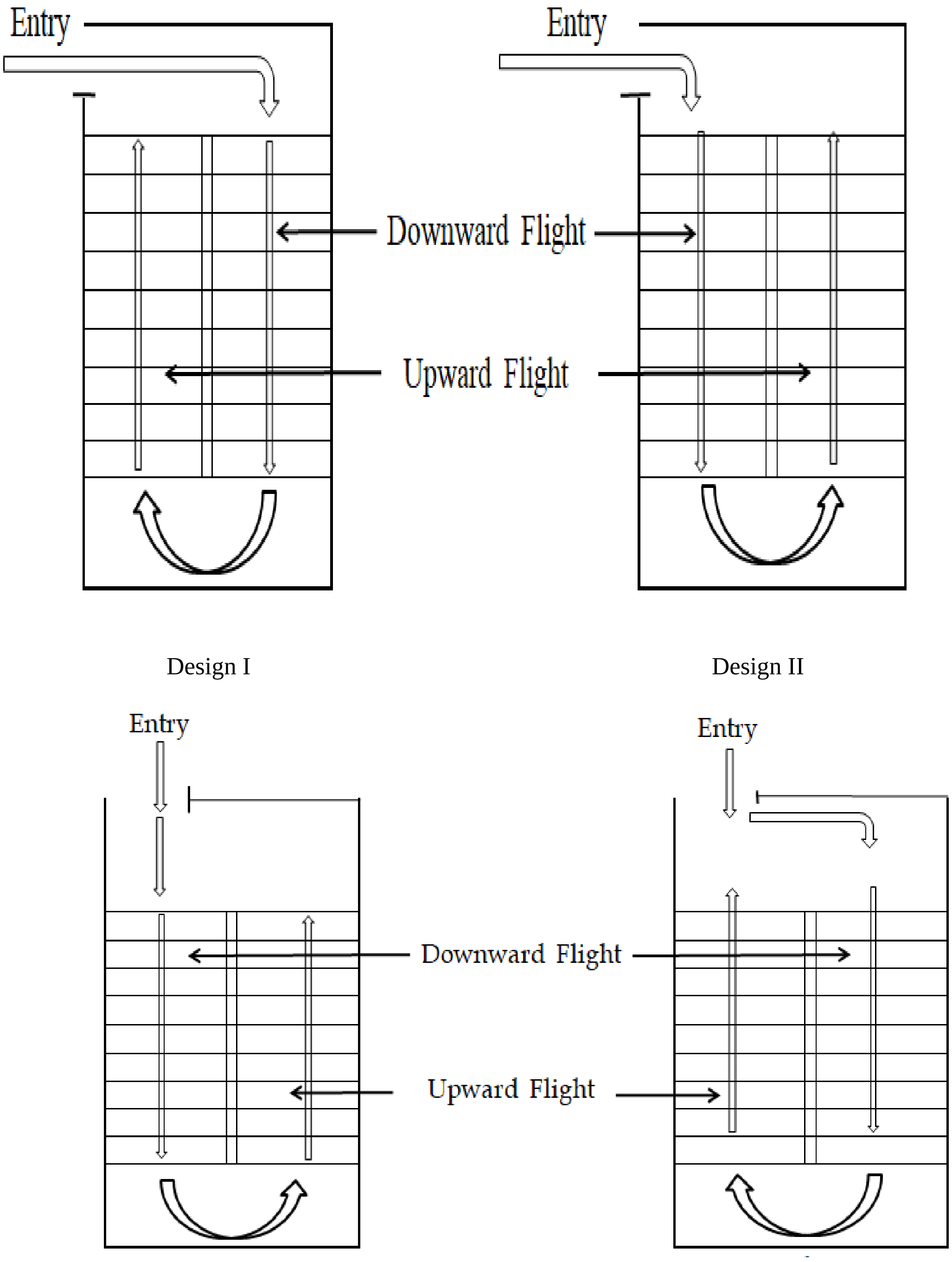


Fig. 5.2: General floor plan of the building model

5.2.2 Staircase designs with respect to the placement of the exit door

There are six main possibilities of setting up the exit door on the stairs as shown in Figure 5.3.



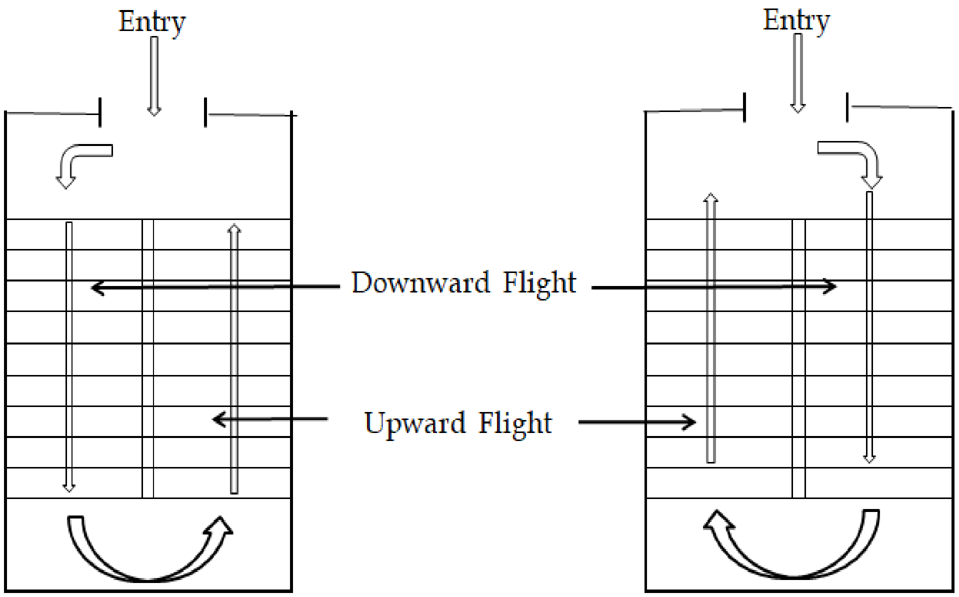
Design I

Design II

Design III

Design IV

Fig. 5.3: Various staircase designs for optimization of the evacuation time



Design V

Design VI

Fig. 5.3: Various staircase designs for optimization of the evacuation time
(Continued……….)

Table 5.1: Details of sample building models to study optimization of evacuation time

Sr. No.	**Floor Area (m^2)**	**No. of floors**	**Occupant Load per floor**	**Sr. No.**	**Floor Area (m^2)**	**No. of floors**	**Occupant Load per floor**
Staircase width = 1.5 m				**Staircase width = 2 m**			
1	900	51	90	31	900	51	90
2	900	46	90	32	900	46	90
3	900	41	90	33	900	41	90
4	900	36	90	34	900	36	90
5	900	31	90	35	900	31	90
6	900	26	90	36	900	26	90
7	900	21	90	37	900	21	90
8	900	16	90	38	900	16	90
9	900	11	90	39	900	11	90
10	900	6	90	40	900	6	90
11	750	51	75	41	750	51	75
12	750	46	75	42	750	46	75
13	750	41	75	43	750	41	75
14	750	36	75	44	750	36	75
15	750	31	75	45	750	31	75
16	750	26	75	46	750	26	75
17	750	21	75	47	750	21	75
18	750	16	75	48	750	16	75
19	750	11	75	49	750	11	75
20	750	6	75	50	750	6	75
21	600	51	60	51	600	51	60
22	600	46	60	52	600	46	60
23	600	41	60	53	600	41	60
24	600	36	60	54	600	36	60
25	600	31	60	55	600	31	60
26	600	26	60	56	600	26	60
27	600	21	60	57	600	21	60
28	600	16	60	58	600	16	60
29	600	11	60	59	600	11	60
30	600	6	60	60	600	6	60

5.2.3 Application of the egress models to the sample buildings

A pathfinder evacuation model is applied to each of the model buildings for the six staircase design to obtain the average evacuation time. The results are presented in Figure 5.2. It is observed that the evacuation time depends on two important parameters. One is the distance traveled by the occupants and the other is the total jam time of the occupants in the evacuation process i.e. the time the occupants were unable to travel due to congestion. The details are mentioned in Table 5.3 & 5.4.

Table 5.2: Results of evacuation time for sample building models to study optimization

Sr. No.	Floor area (Sq. m.)	No .Of floors	No. of occupants per exit	Maximum Evacuation Time (Seconds)					
				Design I	Design II	Design III	Design IV	Design V	Design VI
Staircase width = 1.5 m									
1	900	51	90	1799.42	1847.20	1820.50	1813.20	1778.	1795.4
2	900	46	90	1623.67	1697.17	1649.32	1634.40	1604.	1619.2
3	900	41	90	1434.30	1482.30	1461.40	1453.90	1452.	1441.1
4	900	36	90	1259.00	1299.30	1299.97	1273.37	1261.	1264.4
5	900	31	90	1082.30	1123.15	1114.07	1090.60	1086.	1092.6
6	900	26	90	918.82	938.15	939.17	932.30	910.3	911.50
7	900	21	90	731.87	753.77	751.90	737.80	737.3	735.45
8	900	16	90	570.10	567.10	566.92	572.15	562.1	560.70
9	900	11	90	381.50	383.37	389.22	380.60	387.5	381.40
10	900	5	90	204.75	203.60	208.30	210.50	210.5	201.32
11	750	51	75	1547.80	1606.40	1552.72	1598.80	1563.	1596.8
12	750	46	75	1398.27	1449.52	1401.55	1446.76	1414.	1441.9
13	750	41	75	1247.50	1285.20	1246.02	1294.57	1248.	1280.5
14	750	36	75	1101.02	1129.55	1092.87	1131.17	1100.	1132.7
15	750	31	75	936.77	967.05	939.87	971.10	953.8	972.52
16	750	26	75	785.92	810.52	783.15	819.02	797.3	815.15
17	750	21	75	631.10	653.27	637.10	654.24	642.5	652.85
18	750	16	75	483.00	492.47	478.42	501.62	482.4	497.55
19	750	11	75	331.60	332.22	326.65	341.50	339.6	338.72
20	750	5	75	177.50	179.47	175.32	181.50	178.5	184.70
21	600	51	60	1233.20	1276.77	1224.50	1241.25	1285.	1287.9
22	600	46	60	1109.60	1154.05	1118.60	1120.80	1155.	1157.6
23	600	41	60	986.30	1022.90	992.40	999.72	1038.	1027.7
24	600	36	60	864.10	900.57	868.10	876.67	907.7	900.00
25	600	31	60	749.50	779.32	750.85	753.60	779.3	776.00
26	600	26	60	627.70	651.85	634.67	634.40	650.5	649.85
27	600	21	60	505.07	525.77	509.10	512.10	530.3	524.32
28	600	16	60	386.47	397.80	387.20	390.65	403.4	396.20
29	600	11	60	266.37	272.92	268.97	269.80	275.5	274.07
30	600	5	60	144.52	148.10	143.95	146.20	150.8	150.87
Staircase width = 2.0 m									
31	900	51	90	1381.37	1444.42	1402.05	1375.55	1436.	1444.5
32	900	46	90	1240.40	1302.72	1263.10	1243.75	1292.	1299.5
33	900	41	90	1104.85	1161.15	1123.00	1107.70	1153.	1161.0
34	900	36	90	972.30	1020.42	991.65	971.20	1013.	1017.8
35	900	31	90	841.05	878.20	848.65	838.15	871.8	881.35
36	900	26	90	706.32	734.45	713.52	704.27	729.2	732.80
37	900	21	90	571.50	590.42	577.77	566.52	592.0	596.77
38	900	16	90	434.80	452.72	437.65	438.32	449.6	454.67
39	900	11	90	301.22	311.05	303.00	327.20	312.2	309.82
40	900	5	90	165.17	170.25	165.87	163.10	170.6	168.67
41	750	51	75	1166.57	1197.45	1226.32	1195.65	1199.	1198.3
42	750	46	75	1081.17	1080.92	1107.82	1075.82	1081.	1084.9
43	750	41	75	938.75	967.45	984.10	965.57	963.5	961.50
44	750	36	75	825.62	844.85	866.15	848.10	846.5	846.15
45	750	31	75	711.37	734.20	747.70	727.05	729.6	728.55
46	750	26	75	601.30	614.87	626.90	610.50	614.2	610.22
47	750	21	75	487.65	498.75	509.55	497.80	497.4	492.42

Table5.2: Continued……….

Sr. No.	Floor area (Sq. m.)	No .Of floors	No. of occupants per exit	Maximum Evacuation Time (Seconds)					
				Design I	Design II	Design III	Design IV	Design V	Design VI
48	750	16	75	370.87	373.10	388.97	378.50	379.4	378.27
49	750	11	75	254.80	261.55	267.12	262.87	262.8	263.02
50	750	5	75	146.85	144.57	147.15	148.32	148.3	146.20
51	600	51	60	996.32	992.47	995.57	992.25	1019.	988.50
52	600	46	60	898.65	895.85	897.22	899.32	917.9	892.15
53	600	41	60	801.27	800.02	801.47	800.65	819.5	792.55
54	600	36	60	706.22	703.75	704.67	703.97	717.6	694.47
55	600	31	60	609.17	605.55	611.97	607.40	623.3	600.12
56	600	26	60	511.17	508.87	510.52	510.67	524.9	502.72
57	600	21	60	413.72	414.45	414.55	411.12	424.6	406.97
58	600	16	60	319.10	319.07	318.27	317.75	326.5	310.27
59	600	11	60	224.07	219.77	218.55	222.45	227.7	212.70
60	600	5	60	125.50	123.57	123.87	125.50	128.8	118.45
			Average	**757.14**	**778.30**	**767.12**	**767.02**	**772.7**	**772.62**

Table 5.3: Results of jam time for sample building models to study optimization

Sr. No.	Floor area (sq. m.)	No. of floors	No. of occupants per exit	Maximum Jam Time (Seconds)					
				Design I	Design II	Design III	Design IV	Design V	Design VI
				Staircase width = 1.5 m					
1	900	51	90	948.08	929.67	929.90	918.22	910.52	917.52
2	900	46	90	828.27	848.72	839.52	823.52	822.20	814.05
3	900	41	90	723.75	728.52	753.05	746.95	764.80	727.62
4	900	36	90	639.12	641.27	665.12	643.92	648.77	642.35
5	900	31	90	560.70	546.67	564.67	557.32	543.75	534.60
6	900	26	90	477.27	465.85	432.52	461.62	464.75	465.75
7	900	21	90	372.92	371.17	392.62	374.20	371.52	379.47
8	900	16	90	294.37	273.77	296.65	285.07	291.52	277.55
9	900	11	90	183.42	187.87	188.60	187.60	193.22	187.57
10	900	5	90	93.17	88.15	79.05	94.30	98.85	94.35
11	750	51	75	638.95	626.17	664.25	685.47	619.05	678.50
12	750	46	75	583.02	579.05	564.45	619.12	575.35	604.80
13	750	41	75	500.22	522.07	500.07	548.57	506.12	575.15
14	750	36	75	456.00	453.77	433.65	476.32	447.25	475.22
15	750	31	75	394.22	374.27	375.32	405.42	377.55	415.52
16	750	26	75	339.10	343.02	328.00	348.07	312.90	346.97
17	750	21	75	264.22	262.50	253.95	280.92	248.72	281.80
18	750	16	75	192.52	184.95	194.05	223.20	185.75	206.20
19	750	11	75	133.77	125.00	144.20	142.80	132.82	140.05
20	750	5	75	61.60	67.85	68.85	66.02	64.85	70.20
21	600	51	60	204.82	220.42	210.60	420.47	257.40	263.25
22	600	46	60	196.77	195.75	207.77	391.95	247.00	236.67
23	600	41	60	172.72	197.50	176.05	344.30	233.85	236.30
24	600	36	60	161.72	164.02	144.55	327.10	199.02	189.87

Table 5.3: Continued..........

Sr. No.	Floor area (sq. m.)	No. of floors	No. of occupants per exit	Maximum Jam Time (Seconds)					
				Design I	Design II	Design III	Design IV	Design V	Design VI
25	600	31	60	130.90	145.92	155.45	254.25	165.40	168.65
26	600	26	60	118.10	111.15	104.27	216.35	143.05	139.65
27	600	21	60	89.00	107.25	99.45	185.40	114.40	113.75
28	600	16	60	64.92	74.12	69.42	137.12	82.00	85.35
29	600	11	60	59.22	54.42	54.07	94.00	60.97	63.17
30	600	5	60	28.37	32.47	30.22	50.90	37.02	38.70
Staircase width = 2.0 m									
1	900	51	90	232.77	311.85	285.85	259.75	296.07	280.72
2	900	46	90	223.55	276.67	228.15	215.40	287.07	281.77
3	900	41	90	210.52	257.02	229.65	220.10	241.42	234.90
4	900	36	90	170.20	234.47	197.72	189.75	224.45	235.30
5	900	31	90	151.90	202.35	165.42	152.50	186.22	223.52
6	900	26	90	146.25	180.05	126.00	145.57	159.35	157.52
7	900	21	90	119.02	143.40	113.42	107.37	136.65	151.82
8	900	16	90	83.10	115.12	90.20	101.17	105.02	119.37
9	900	11	90	61.65	72.50	68.55	77.80	78.57	82.70
10	900	5	90	40.92	45.45	28.10	31.82	49.65	43.17
11	750	51	75	70.52	90.05	103.65	96.42	95.80	92.00
12	750	46	75	85.70	94.55	95.62	81.00	102.87	86.35
13	750	41	75	61.57	80.47	105.85	81.15	87.17	84.52
14	750	36	75	62.87	70.65	81.85	72.40	76.22	86.17
15	750	31	75	49.80	64.07	80.52	58.90	75.37	64.40
16	750	26	75	44.62	45.87	63.52	49.62	53.62	66.55
17	750	21	75	47.20	52.27	52.35	53.25	51.67	46.87
18	750	16	75	32.32	36.42	50.77	36.72	59.95	49.20
19	750	11	75	24.00	28.87	35.80	38.70	33.65	32.90
20	750	5	75	20.05	19.47	22.30	25.42	26.90	23.95
21	600	51	60	25.02	26.00	30.05	25.95	38.95	29.40
22	600	46	60	28.57	29.92	24.85	26.57	32.63	31.05
23	600	41	60	24.55	22.20	27.07	23.27	27.72	26.12
24	600	36	60	25.47	25.95	22.92	22.32	27.37	23.22
25	600	31	60	21.45	19.90	21.47	20.12	27.27	22.47
26	600	26	60	21.20	22.57	22.42	19.82	25.45	21.95
27	600	21	60	19.22	18.22	21.55	18.95	26.07	22.07
28	600	16	60	17.40	17.27	18.17	15.68	25.62	19.37
29	600	11	60	21.75	14.07	17.45	16.02	23.20	19.15
30	600	5	60	14.60	16.84	13.32	13.62	14.75	16.17
			Average	201.15	209.30	206.08	226.79	213.62	217.42

Table 5.4: Results of travel distance for sample building models to study optimization

Sr. No.	Floor area (sq. m.)	No. of floors	No. of occupants per exit	Maximum Distance (m)					
				Design I	Design II	Design III	Design IV	Design V	Design VI
Staircase width = 1.5 m									
1	900	51	90	816.48	700.28	698.75	782.69	725.13	723.12
2	900	46	90	698.86	637.57	630.10	723.61	646.52	666.29
3	900	41	90	643.79	591.33	575.90	659.42	588.01	588.36
4	900	36	90	576.31	520.24	498.84	570.28	519.00	505.51
5	900	31	90	493.09	449.46	429.88	501.46	426.02	457.53
6	900	26	90	419.46	379.54	362.73	430.54	398.23	386.33
7	900	21	90	331.61	307.73	278.07	335.63	324.19	331.40
8	900	16	90	265.47	243.60	257.63	275.45	268.86	270.24
9	900	11	90	204.03	177.24	166.61	204.82	176.81	191.88
10	900	5	90	142.20	99.79	100.66	101.61	104.71	100.78
11	750	51	75	684.29	683.17	680.35	679.93	692.59	672.70
12	750	46	75	622.41	617.59	626.74	618.37	616.95	612.06
13	750	41	75	554.05	557.82	552.68	557.40	554.78	566.28
14	750	36	75	492.29	403.68	489.45	494.26	491.21	492.00
15	750	31	75	428.64	425.71	425.01	421.41	434.22	434.29
16	750	26	75	361.34	355.92	356.54	361.99	362.80	354.35
17	750	21	75	294.69	290.58	294.01	291.85	291.28	291.22
18	750	16	75	224.85	232.06	226.01	226.41	229.48	232.35
19	750	11	75	164.03	162.72	160.45	164.79	160.57	156.59
20	750	5	75	98.82	94.96	94.92	95.07	93.97	94.10
21	600	51	60	670.99	676.21	675.71	680.05	671.01	658.30
22	600	46	60	608.66	623.40	605.76	612.92	606.30	600.35
23	600	41	60	537.65	547.63	554.09	545.75	547.49	538.28
24	600	36	60	476.49	480.09	485.33	486.92	479.86	471.18
25	600	31	60	415.33	413.04	417.07	415.01	415.95	410.17
26	600	26	60	354.85	354.98	345.79	346.43	352.19	350.39
27	600	21	60	286.46	287.23	285.64	287.73	283.21	281.95
28	600	16	60	233.09	226.76	225.24	222.48	227.44	219.27
29	600	11	60	158.33	154.82	156.18	155.27	156.91	150.69
30	600	5	60	91.12	90.39	91.23	90.63	90.11	88.12
Staircase width = 2.0 m									
1	900	51	90	776.55	780.95	776.44	776.41	783.55	782.72
2	900	46	90	692.87	709.46	705.78	695.21	706.42	709.63
3	900	41	90	648.51	631.27	639.59	642.63	634.91	629.55
4	900	36	90	568.03	569.89	566.08	567.02	562.87	546.18
5	900	31	90	478.92	491.73	488.11	483.92	488.21	477.33
6	900	26	90	416.69	401.77	414.45	423.78	402.59	408.50
7	900	21	90	337.69	336.79	328.68	335.09	331.69	328.68
8	900	16	90	265.12	257.83	268.43	255.59	258.64	256.62
9	900	11	90	190.29	189.17	185.57	197.12	180.90	183.86
10	900	5	90	110.17	109.72	114.79	110.74	109.30	108.69
11	750	51	75	746.42	746.46	776.37	752.39	747.78	753.39
12	750	46	75	710.84	684.03	687.28	678.58	680.38	678.77
13	750	41	75	604.08	603.56	603.69	610.13	600.42	603.56
14	750	36	75	536.58	539.78	552.44	532.34	544.06	530.43
15	750	31	75	465.42	460.50	472.60	461.87	465.28	459.41
16	750	26	75	391.77	389.00	389.77	389.72	391.36	392.75

Table 5.4: Continued……….

Sr. No.	Floor area (sq. m.)	No. of floors	No. of occupants per exit	Maximum Distance (m)					
				Design I	Design II	Design III	Design IV	Design V	Design VI
17	750	21	75	328.26	314.75	322.24	316.75	318.70	311.64
18	750	16	75	250.92	237.56	243.86	252.78	254.95	244.92
19	750	11	75	174.92	172.77	174.51	173.66	181.03	172.36
20	750	5	75	107.62	101.51	106.19	101.10	100.52	102.39
21	600	51	60	718.07	707.40	724.35	719.87	733.67	705.08
22	600	46	60	650.16	658.91	656.17	654.16	656.12	636.53
23	600	41	60	582.32	586.98	577.12	585.37	583.82	572.99
24	600	36	60	522.40	516.84	535.30	514.98	526.66	503.96
25	600	31	60	449.67	453.65	445.14	446.69	451.70	438.25
26	600	26	60	377.40	368.57	378.71	376.46	378.78	377.76
27	600	21	60	303.75	305.78	310.17	309.84	312.49	302.63
28	600	16	60	237.73	232.44	235.42	234.06	247.92	234.85
29	600	11	60	171.30	163.96	168.55	164.24	166.53	166.33
30	600	5	60	102.13	98.85	99.15	94.65	96.77	93.07
			Average	421.10	410.12	411.57	419.96	413.90	410.15

5.2.4 Results and discussion

The fundamental objective of this study is to review the various possibilities of optimization in case of emergency so that the occupants reach a safe place in the shortest possible time. This study provides a theoretical foundation and technical support to the Architectural Design and Emergency Management team. It also helps priorities the evacuation of occupants who are in immediate danger. In the first part of this study, various methods of optimisation of total evacuation time are examined. It is mainly classified in three categories, namely building design & infrastructure, setting of path & departure, and the behavioural aspects of the occupants. In all these studies, it is observed that there are mixed views and outcomes and even, some studies have challenged each other for their effectiveness. Thus, in general, one cannot reach the conclusion of anyone for the best optimization design. The main reason is that the effectiveness of the evacuation depends on a variety of other building and occupant behaviour parameters such as location, width of exit, state of mind of occupants, etc. It is therefore always advisable to decide on the efficiency of the building parameters on a case by case basis.

In the subsequent study, different case study models of six possible models of stairs w.r.t. its place of door is considered. It is observed that the total duration of the evacuation varies according to the design of the stairs. Here, the average total evacuation value of the 60 building models is considered for each design. The values are 757.14 seconds, 778.30 seconds, 767.12 seconds, 767.02 seconds, 772.74 seconds, and 772.62 seconds respectively for the designs I to VI.

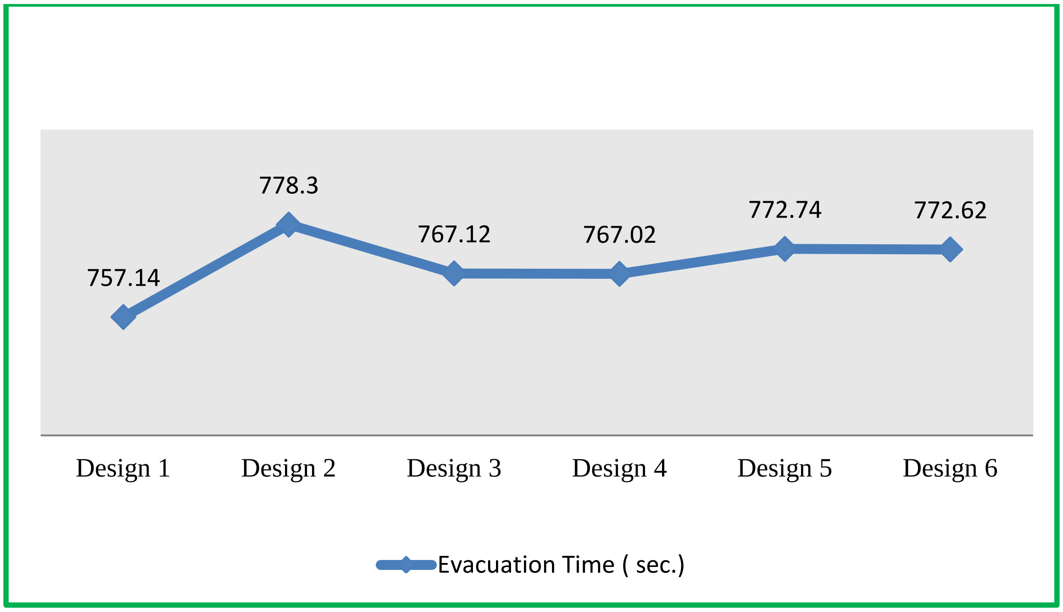


Fig. 5.4: Evacuation time calculated for different designs

Accordingly, the best result is by design I among all designs that are studied. Factors which may depend on the evacuation time results are distance traveled and jam time, i.e. the time when each person is stuck due to overcrowding as indicated in Tables 5.3 and 5.4. It is observed that the mean jam period for Design 1 is 201.15 seconds, which is the lowest compared to the other designs, though its travel distance is on a higher side. In some cases, the occupants returned from one staircase to another due to the congestion at the stairway entrance, which increased the travel distance. The worst design is observed for design no. 2 i.e. 778.30 seconds and the reason for this is the higher jam time and travel distance of the occupants. From this study, it is very clear that jamming time is a major cause of long evacuation time.

It is further observed that the evacuation time of building designs with a stair width of 1.5 m is much more than the stair width of 2 m. In this study, the mean value for a stair width of 1.5 m is 863.97 seconds versus 674.32 seconds for a stair width of 2 m. The main reason is the jam time of 342.15 seconds for 1.5 m versus the jam time of 82.1 seconds for 2 m. It is also observed that the travel distance is greater for 2 m of the stairway width (428.63 m) than for 1.5 m (400.14 m). This is due to larger landings and mid landings, but does not affect the total evacuation time.

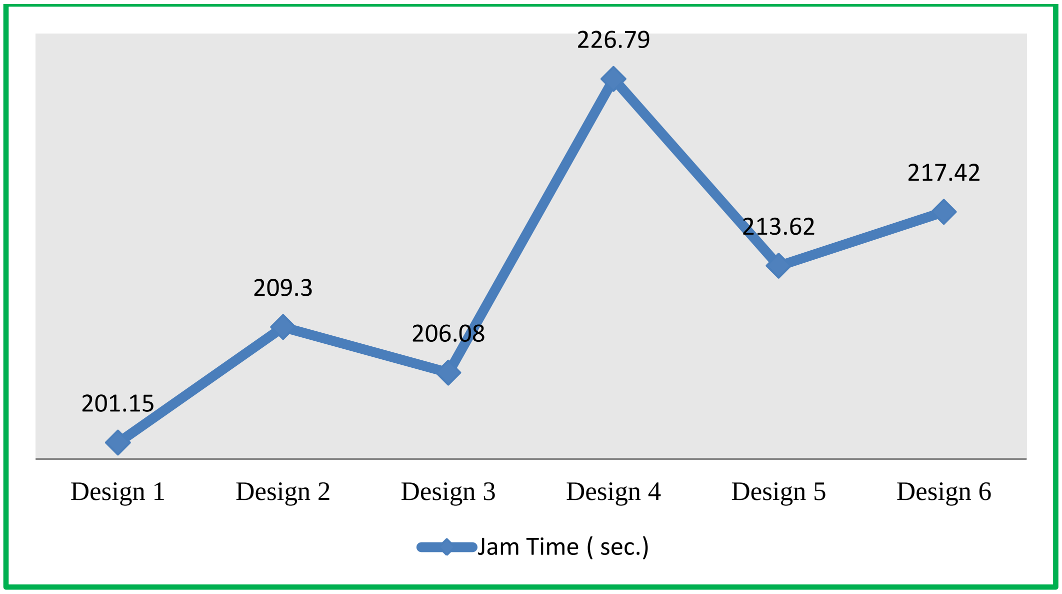


Fig. 5.5: Jam time for different designs

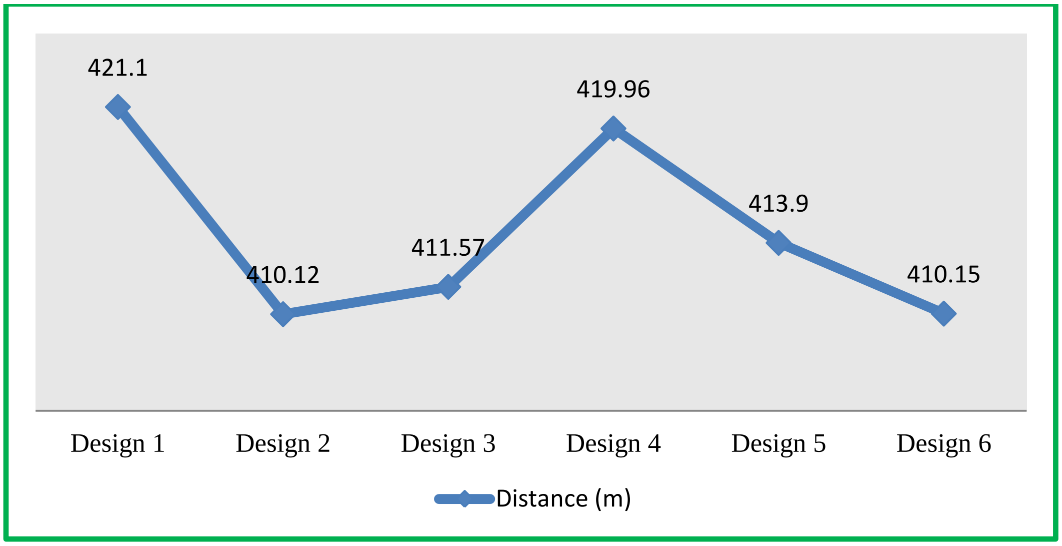


Fig. 5.6: Maximum distance travelled for different designs

CHAPTER 6: DEVELOPMENT OF A NEW METHOD FOR ESTIMATION OF STAIRCASE EVACUATION TIME IN THE EVENT OF A FIRE

In this chapter, a new and simple mathematical method is developed to determine the evacuation time during the evacuation of high-rise buildings by considering basic parameters such as stair width, occupant load and number of storey. In addition, various correlations of these parameters are discussed as well. In this study, one hundred and twenty model building simulations are considered with different combinations of building parameters like floor area, stair width and occupant load. The width of the stairs and occupant load complies with national and international codes [3] [41] [42].

6.1 Building case study model considered for this study

Given the need to meet current challenges in a high-rise building, the Model Case Study is considered in the category of business occupancy with the maximum allowable occupant load. A floor area is 600 m^2, 500 m^2 and 400 m^2 with a different number of floors. The height of the ceiling depends on the type of occupancy and it is 3.6 m for the business occupancy that we considered in this study. The next important factor is the width of the staircase. NBC and IBC suggest the minimum stairway width of 1.5 m and 1.21 m respectively for a business building. In this study, we consider the two 1.5 m wide building staircases. Again for research purposes, we consider the width of 2 m.

The width of the stairwell door according to the NBC is 100 cm, the NFPA 101 mentions it as 81 cm, and few local codes [228] mention it as 100 cm. We therefore considered the width of the staircase door to be 100 cm.

There is a maximum of 50 floors excluding the ground floor with a difference of 5 floors as mentioned in Table 6.1. The lowest height of the building is 5 floors as we focus only on high-rise buildings i.e. height of the building above 15 m according to NBC. The highest building considered is the ground floor and fifty floors. The ground floor serves for reception, meeting rooms and other various activities. All the upper floors are designed for office use. There are three basements for parking and others auxiliaries of the building. The whole building is covered by a fire protection and detection system. The ground floor is taken into account in the total number of floors to be evacuated with the same number of people as the upper floors. But the basements are not taken into account because they are not intended to be occupied and will not affect the process of evacuation of the building.

Table 6.1: Different building parameters to develop a new method for evacuation time

Sr. No.	Floor Area (sq. m.)	No .Of floors	Occupant Load per exit	Sr. No.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit
Staircase width = 1.5 m; Effective Width= 1.2 m				**Staircase width = 1.5 m; Effective Width= 1.2 m**			
1	600	51	60	31	500	51	50
2	600	46	60	32	500	46	50
3	600	41	60	33	500	41	50
4	600	36	60	34	500	36	50
5	600	31	60	35	500	31	50
6	600	26	60	36	500	26	50
7	600	21	60	37	500	21	50
8	600	16	60	38	500	16	50
9	600	11	60	39	500	11	50
10	600	6	60	40	500	6	50
11	600	51	50	41	500	51	40
12	600	46	50	42	500	46	40
13	600	41	50	43	500	41	40
14	600	36	50	44	500	36	40
15	600	31	50	45	500	31	40
16	600	26	50	46	500	26	40
17	600	21	50	47	500	21	40
18	600	16	50	48	500	16	40
19	600	11	50	49	500	11	40

Table 6.1: Continued……….

Sr. No.	Floor Area (sq. m.)	No .Of floors	Occupant Load per exit	Sr. No.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit
Staircase width = 1.5 m; Effective Width= 1.2 m				**Staircase width = 1.5 m; Effective Width= 1.2 m**			
20	600	6	50	50	500	6	40
21	600	51	40	51	400	51	40
22	600	46	40	52	400	46	40
23	600	41	40	53	400	41	40
24	600	36	40	54	400	36	40
25	600	31	40	55	400	31	40
26	600	26	40	56	400	26	40
27	600	21	40	57	400	21	40
28	600	16	40	58	400	16	40
29	600	11	40	59	400	11	40
30	600	6	40	60	400	6	40
Staircase width = 2.0 m; Effective Width= 1.7 m				Staircase width = 2.0 m; Effective Width= 1.7 m			
61	600	51	60	91	500	51	50
62	600	46	60	92	500	46	50
63	600	41	60	93	500	41	50
64	600	36	60	94	500	36	50
65	600	31	60	95	500	31	50
66	600	26	60	96	500	26	50
67	600	21	60	97	500	21	50
68	600	16	60	98	500	16	50
69	600	11	60	99	500	11	50
70	600	6	60	100	500	6	50
71	600	51	50	101	500	51	40
72	600	46	50	102	500	46	40
73	600	41	50	103	500	41	40
74	600	36	50	104	500	36	40
75	600	31	50	105	500	31	40
76	600	26	50	106	500	26	40
77	600	21	50	107	500	21	40
78	600	16	50	108	500	16	40
79	600	11	50	109	500	11	40
80	600	6	50	110	500	6	40
81	600	51	40	111	400	51	40
82	600	46	40	112	400	46	40
83	600	41	40	113	400	41	40
84	600	36	40	114	400	36	40
85	600	31	40	115	400	31	40
86	600	26	40	116	400	26	40
87	600	21	40	117	400	21	40
88	600	16	40	118	400	16	40
89	600	11	40	119	400	11	40
90	600	6	40	120	400	6	40

6.2 Application of the egress model to the sample buildings

The pathfinder evacuation model is applied to each building and the evacuation time for each building is obtained as shown in Table 6.2.

Table 6.2: Results of evacuation time of different building models

S. N.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit	Unit Width (Number)	Evacuation Time (Seconds)
Staircase width = 1.5 m; Effective width 1.2 m					
1	600	51	60	2.00	2361.98
2	600	46	60	2.00	2137.55
3	600	41	60	2.00	1892.30
4	600	36	60	2.00	1668.35
5	600	31	60	2.00	1433.48
6	600	26	60	2.00	1199.50
7	600	21	60	2.00	967.60
8	600	16	60	2.00	728.18
9	600	11	60	2.00	495.78
10	600	6	60	2.00	263.40
11	600	51	50	2.00	1982.70
12	600	46	50	2.00	1781.18
13	600	41	50	2.00	1589.13
14	600	36	50	2.00	1392.20
15	600	31	50	2.00	1191.85
16	600	26	50	2.00	1000.53
17	600	21	50	2.00	802.53
18	600	16	50	2.00	616.93
19	600	11	50	2.00	417.90
20	600	6	50	2.00	225.00
21	600	51	40	2.00	1583.38
22	600	46	40	2.00	1428.50
23	600	41	40	2.00	1283.20
24	600	36	40	2.00	1118.60
25	600	31	40	2.00	967.13
26	600	26	40	2.00	812.50
27	600	21	40	2.00	654.03
28	600	16	40	2.00	493.70
29	600	11	40	2.00	342.30
30	600	6	40	2.00	184.25
31	500	51	50	2.00	1991.08
32	500	46	50	2.00	1780.00
33	500	41	50	2.00	1587.28
34	500	36	50	2.00	1392.78
35	500	31	50	2.00	1198.85
36	500	26	50	2.00	1000.50
37	500	21	50	2.00	811.13
38	500	16	50	2.00	610.13
39	500	11	50	2.00	417.40
40	500	6	50	2.00	219.63

Table 6.2: Continued……….

S. N.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit	Unit Width (Number)	Evacuation Time (Seconds)
41	500	51	40	2.00	1579.73
42	500	46	40	2.00	1432.98
43	500	41	40	2.00	1273.00
44	500	36	40	2.00	1120.55
45	500	31	40	2.00	956.00
46	500	26	40	2.00	802.90
47	500	21	40	2.00	647.30
48	500	16	40	2.00	493.40
49	500	11	40	2.00	337.05
50	500	6	40	2.00	184.73
51	400	51	40	2.00	1577.55
52	400	46	40	2.00	1423.20
53	400	41	40	2.00	1270.90
54	400	36	40	2.00	1118.20
55	400	31	40	2.00	960.13
56	400	26	40	2.00	805.13
57	400	21	40	2.00	651.20
58	400	16	40	2.00	503.13
59	400	11	40	2.00	340.90
60	400	6	40	2.00	182.15
Staircase width = 2.0 m; Effective width 1.7 m					
61	600	51	60	3.00	1822.55
62	600	46	60	3.00	1649.40
63	600	41	60	3.00	1468.98
64	600	36	60	3.00	1284.63
65	600	31	60	3.00	1103.00
66	600	26	60	3.00	925.23
67	600	21	60	3.00	750.13
68	600	16	60	3.00	565.45
69	600	11	60	3.00	388.53
70	600	6	60	3.00	210.43
71	600	51	50	3.00	1526.93
72	600	46	50	3.00	1374.80
73	600	41	50	3.00	1226.40
74	600	36	50	3.00	1076.50
75	600	31	50	3.00	929.08
76	600	26	50	3.00	775.90
77	600	21	50	3.00	626.20
78	600	16	50	3.00	477.70
79	600	11	50	3.00	329.80
80	600	6	50	3.00	179.90
81	600	51	40	3.00	1226.93
82	600	46	40	3.00	1111.13
83	600	41	40	3.00	989.70
84	600	36	40	3.00	868.08
85	600	31	40	3.00	747.40
86	600	26	40	3.00	629.80
87	600	21	40	3.00	509.93
88	600	16	40	3.00	386.05
89	600	11	40	3.00	271.43

Table 6.2: Continued……….

S. N.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit	Unit Width (Number)	Evacuation Time (Seconds)
90	600	6	40	3.00	149.40
91	500	51	50	3.00	1518.98
92	500	46	50	3.00	1365.95
93	500	41	50	3.00	1228.65
94	500	36	50	3.00	1077.18
95	500	31	50	3.00	928.50
96	500	26	50	3.00	773.25
97	500	21	50	3.00	629.80
98	500	16	50	3.00	479.80
99	500	11	50	3.00	329.28
100	500	6	50	3.00	177.03
101	500	51	40	3.00	1229.25
102	500	46	40	3.00	1109.53
103	500	41	40	3.00	985.68
104	500	36	40	3.00	872.80
105	500	31	40	3.00	750.33
106	500	26	40	3.00	629.65
107	500	21	40	3.00	510.83
108	500	16	40	3.00	388.40
109	500	11	40	3.00	272.28
110	500	6	40	3.00	150.08
111	400	51	40	3.00	1223.78
112	400	46	40	3.00	1106.63
113	400	41	40	3.00	983.65
114	400	36	40	3.00	862.88
115	400	31	40	3.00	747.25
116	400	26	40	3.00	628.00
117	400	21	40	3.00	507.78
118	400	16	40	3.00	388.53
119	400	11	40	3.00	270.33
120	400	6	40	3.00	149.65

6.3 Results and discussion:

The following are key conclusions based on the above findings.

1. Building evacuation time increases with an increase in floors and occupant load.

2. The evacuation time is longer for the staircase with a width of 1.5 m compared to the staircase with a width of 2 m.

3. The evacuation time for 51 storey buildings with 40 occupants per 400 square meter floor from a 1.5m wide staircase is 1577.55 seconds (Sr. No. 51), similar evacuation for 500 sq. m from 1.5 m wide staircase is 1579.73 seconds (Sr. No. 41) and for 600 sq. m wide staircase is 1583.38 seconds (Sr. No. 21). Similarly, reading for 2 m of staircase width is 1223.78 seconds, 1229.25 seconds & 1226.93 seconds respectively (sr. no. 111,101 & 81). With the above observation, it can be concluded that with the increase of the floor surface, there is very little variation in the evacuation time. Even in a few cases, it is slightly less when the floor area is higher. The reason may be less congestion at the exit because of more traveling time for larger area.

6.4 Estimation of the evacuation time:

In addition to the above conclusions, all results are well studied for their inter-relationship between evacuation time, building parameters and number of occupants. It is primarily for the stairs which is the most important element in the evacuation process during the design of the building. The staircase is therefore studied in detail as illustrated in Figure 6.1. In total, eight steps are considered between landing and mid-landing with 17.78 cm riser and 27.94 cm tread, which is well consistent with all national and international standards. The run (the horizontal distance between the landing & mid landing) is 2.5 m and the total length of the step from landing to mid landing i.e. ‘B’ is 3.08 m.

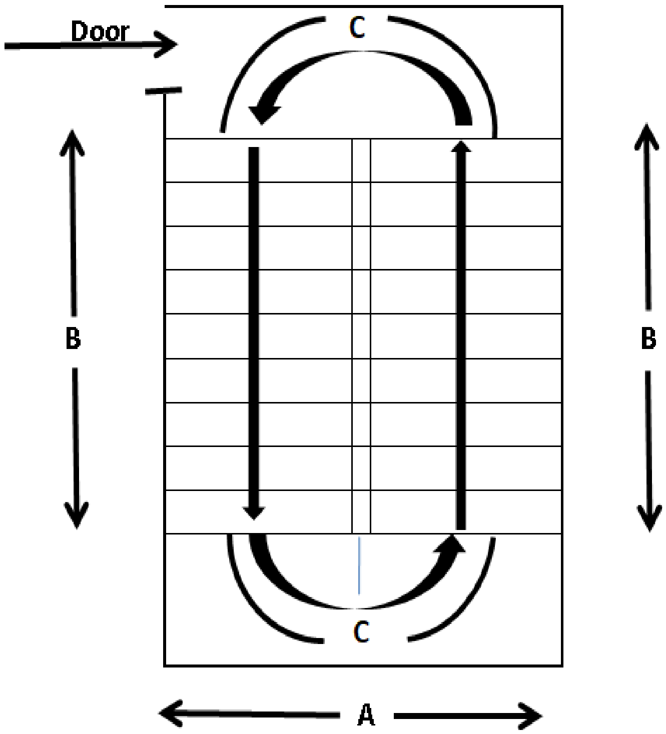


Fig. 6.1: Details for occupants' path in the staircase

'C' is the travel distance on the landing and mid landing of the staircase. This is distance will be half of the circumference i.e. ½ π × diameter. Here, the diameter is 1.5 meters and 2.0 meters.

So, for 1.5 m width, 'C' will be 3.14 × 1.5 / 2 i.e. 2.35 m & total travel distance will be 2.35 × 2 + 3.08 × 2 i.e. **10.86 m.**

Similarly, for 2.0 m width of 'C' will be 3.14 × 2.0 / 2 i.e. 3.14 m & total travel distance will be 3.14 × 2 + 3.08 × 2 i.e. **12.44 m.**

All these parameters are analysed in detail by means of different combinations for their correlation. A relationship is obtained with a constant which we refer to as an evacuation factor (α). The relationship is

(Maximum time of evacuation in second × completed number of units of effective width of the staircase) / (Number of floor × Travel distance × Number of occupants per floor per exit)

i.e.

$$\alpha = t \times u/(o \times n \times d) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. 6.1}$$

Where,

t : Maximum time in seconds

u : Number of unit width

o : Number of occupants per floor per exit

n : Number of floors in a building

d : Travel distance in the staircase between two floors

Applying above mentioned mathematical model, we get an evacuation factor as mentioned in table 6.3.

Table 6.3: Results after applying proposed correlation

Sr. No.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit	Effective Width (m)	Evacuation Time (Seconds)	Evacuation Factor
			Staircase width = 1.5 m			
1	600	51	60	1.2	2361.98	0.0853
2	600	46	60	1.2	2137.55	0.0856
3	600	41	60	1.2	1892.30	0.0850
4	600	36	60	1.2	1668.35	0.0853
5	600	31	60	1.2	1433.48	0.0852
6	600	26	60	1.2	1199.50	0.0850
7	600	21	60	1.2	967.60	0.0849
8	600	16	60	1.2	728.18	0.0838
9	600	11	60	1.2	495.78	0.0830
10	600	6	60	1.2	263.40	0.0808
11	600	51	50	1.2	1982.70	0.0859
12	600	46	50	1.2	1781.18	0.0856
13	600	41	50	1.2	1589.13	0.0857
14	600	36	50	1.2	1392.20	0.0855
15	600	31	50	1.2	1191.85	0.0850
16	600	26	50	1.2	1000.53	0.0850
17	600	21	50	1.2	802.53	0.0845

Table 6.3: Continued……….

Sr. No.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit	Effective Width (m)	Evacuation Time (Seconds)	Evacuation Factor
18	600	16	50	1.2	616.93	0.0852
19	600	11	50	1.2	417.90	0.0840
20	600	6	50	1.2	225.00	0.0829
21	600	51	40	1.2	1583.38	0.0858
22	600	46	40	1.2	1428.50	0.0858
23	600	41	40	1.2	1283.20	0.0865
24	600	36	40	1.2	1118.60	0.0858
25	600	31	40	1.2	967.13	0.0862
26	600	26	40	1.2	812.50	0.0863
27	600	21	40	1.2	654.03	0.0860
28	600	16	40	1.2	493.70	0.0852
29	600	11	40	1.2	342.30	0.0860
30	600	6	40	1.2	184.25	0.0848
31	500	51	50	1.2	1991.08	0.0863
32	500	46	50	1.2	1780.00	0.0855
33	500	41	50	1.2	1587.28	0.0856
34	500	36	50	1.2	1392.78	0.0855
35	500	31	50	1.2	1198.85	0.0855
36	500	26	50	1.2	1000.50	0.0850
37	500	21	50	1.2	811.13	0.0854
38	500	16	50	1.2	610.13	0.0843
39	500	11	50	1.2	417.40	0.0839
40	500	6	50	1.2	219.63	0.0809
41	500	51	40	1.2	1579.73	0.0856
42	500	46	40	1.2	1432.98	0.0861
43	500	41	40	1.2	1273.00	0.0858
44	500	36	40	1.2	1120.55	0.0860
45	500	31	40	1.2	956.00	0.0852
46	500	26	40	1.2	802.90	0.0853
47	500	21	40	1.2	647.30	0.0851
48	500	16	40	1.2	493.40	0.0852
49	500	11	40	1.2	337.05	0.0846
50	500	6	40	1.2	184.73	0.0850
51	400	51	40	1.2	1577.55	0.0854
52	400	46	40	1.2	1423.20	0.0855
53	400	41	40	1.2	1270.90	0.0856
54	400	36	40	1.2	1118.20	0.0858
55	400	31	40	1.2	960.13	0.0856
56	400	26	40	1.2	805.13	0.0855
57	400	21	40	1.2	651.20	0.0857
58	400	16	40	1.2	503.13	0.0869
59	400	11	40	1.2	340.90	0.0856
60	400	6	40	1.2	182.15	0.0839
Staircase width = 2.0 m						
61	600	51	60	1.7	1822.55	0.0814
62	600	46	60	1.7	1649.40	0.0817
63	600	41	60	1.7	1468.98	0.0816
64	600	36	60	1.7	1284.63	0.0813
65	600	31	60	1.7	1103.00	0.0810
66	600	26	60	1.7	925.23	0.0810
67	600	21	60	1.7	750.13	0.0814

Table 6.3: Continued……….

Sr. No.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit	Effective Width (m)	Evacuation Time (Seconds)	Evacuation Factor
68	600	16	60	1.7	565.45	0.0805
69	600	11	60	1.7	388.53	0.0804
70	600	6	60	1.7	210.43	0.0799
71	600	51	50	1.7	1526.93	0.0818
72	600	46	50	1.7	1374.80	0.0817
73	600	41	50	1.7	1226.40	0.0818
74	600	36	50	1.7	1076.50	0.0817
75	600	31	50	1.7	929.08	0.0819
76	600	26	50	1.7	775.90	0.0816
77	600	21	50	1.7	626.20	0.0815
78	600	16	50	1.7	477.70	0.0816
79	600	11	50	1.7	329.80	0.0819
80	600	6	50	1.7	179.90	0.0819
81	600	51	40	1.7	1226.93	0.0822
82	600	46	40	1.7	1111.13	0.0825
83	600	41	40	1.7	989.70	0.0825
84	600	36	40	1.7	868.08	0.0824
85	600	31	40	1.7	747.40	0.0824
86	600	26	40	1.7	629.80	0.0828
87	600	21	40	1.7	509.93	0.0830
88	600	16	40	1.7	386.05	0.0824
89	600	11	40	1.7	271.43	0.0843
90	600	6	40	1.7	149.40	0.0851
91	500	51	50	1.7	1518.98	0.0814
92	500	46	50	1.7	1365.95	0.0812
93	500	41	50	1.7	1228.65	0.0819
94	500	36	50	1.7	1077.18	0.0818
95	500	31	50	1.7	928.50	0.0819
96	500	26	50	1.7	773.25	0.0813
97	500	21	50	1.7	629.80	0.0820
98	500	16	50	1.7	479.80	0.0820
99	500	11	50	1.7	329.28	0.0818
100	500	6	50	1.7	177.03	0.0806
101	500	51	40	1.7	1229.25	0.0823
102	500	46	40	1.7	1109.53	0.0824
103	500	41	40	1.7	985.68	0.0821
104	500	36	40	1.7	872.80	0.0828
105	500	31	40	1.7	750.33	0.0827
106	500	26	40	1.7	629.65	0.0827
107	500	21	40	1.7	510.83	0.0831
108	500	16	40	1.7	388.40	0.0829
109	500	11	40	1.7	272.28	0.0846
110	500	6	40	1.7	150.08	0.0855
111	400	51	40	1.7	1223.78	0.0820
112	400	46	40	1.7	1106.63	0.0822
113	400	41	40	1.7	983.65	0.0820
114	400	36	40	1.7	862.88	0.0819
115	400	31	40	1.7	747.25	0.0824
116	400	26	40	1.7	628.00	0.0825
117	400	21	40	1.7	507.78	0.0826
118	400	16	40	1.7	388.53	0.0830

Table 6.3: Continued……….

Sr. No.	Floor Area (sq. m.)	No. of floors	Occupant Load per exit	Effective Width (m)	Evacuation Time (Seconds)	Evacuation Factor
119	400	11	40	1.7	270.33	0.0840
120	400	6	40	1.7	149.65	0.0852

The mean (**α**) is 0.0836 for the sample of 120 models with a standard deviation of 0.001834

We can rearrange eqn. 6.1 to get a mathematical model for evacuation time,

$$t = \propto \times o \times n \times d/w$$

i.e.

$$t = 0.0836 \times o \times n \times d/w \qquad \text{……………… Eqn. 6.2}$$

Eqn. 6.2 can be used as a mathematical model to determine the evacuation time of a high-rise building. This excludes the pre-evacuation delay of 132 seconds as mentioned earlier in this study.

6.5 Working examples

Example 1:

How long will the evacuation be without taking into consideration the evacuation delay for the following details?

Occupants per floor and exit = 45.

Number of storey in the building = 30.

Staircase width = 1.5m.

Solution:

We have eqn. 6.2 i.e.

$\mathrm{t} = 0.0836 \times o \times n \times d/w$

In this example,

o= 45,
n= 30,
d= 10.52 m for 1.5 m width
w = 1.2 m

Therefore,

$\mathrm{t} = 0.0836 \times 45 \times 30 \times 10.86/1.2$

t = 1021.38 seconds

Therefore, the time to evacuate the building without considering the evacuation time will be 1021.38 seconds.

Example 2:

How long will the evacuation be without taking into consideration the evacuation delay for the following details?
Occupants per floor and exit = 60.
Number of storey in the building = 45.
Staircase width = 2 m.

Solution:

We have eqn. 6.2 i.e.

$\mathrm{t} = 0.0836 \times o \times n \times d/w$

In this example,

o= 60,
n= 45,
d= 12.44 m for 2.0 m width
w = 1.7 m

Therefore

$t = 0.0836 \times 60 \times 45 \times 12.44/1.7$

t = 1651.73 seconds

Therefore, the evacuation time for the building without considering the evacuation time will be 1651.73 seconds.

6.6 Validation and verification of the proposed model

To confirm the accuracy of this mathematical model, we need to validate it with evacuation time from actual fire cases or fire drills. There are very few studies available in the literature which matches the parameters mentioned in this study. Few studies are available but not in the high-rise buildings. The following three studies are available to validate the proposed study.

Validation I:

Fabio et al.[229] in his study "Computer Simulation and Fire Drill in an Educational Building" considered building evacuation drills with two exits. The drill began at 0925 minutes with the activation of a visual and audible fire alarm system. It involved 329 participants with 78 people on the ground floor, 151 people on the second floor, 87 people on the third floor and 13 people on the fourth floor. It took 173 seconds to complete this drill. The time count began with the fire alarm and ended with the last occupant exiting the building via the fire exit. 257 individuals were evacuated from Exit 1 and 72 individuals were evacuated from Exit 2. The width of the stairway was 1.4 meters. Here, the pre-evacuation time was close to zero being a planned exercise. For validation purposes, we are considering the egress of Exit 1 in 173 seconds out of a total of 257 occupants.

As proposed in this study, we will use eqn. 6.2, with the above mentioned parameter and reviewed the result

$$t = 0.0836 \times 64.25 \times 4 \times 10.86/1.2$$

t = 194.44 seconds

The result comes very close to the real results. The slight difference can be due to the uneven distribution of occupants on the various floors, the width of the 1.4 m stairs, and the height of the ceiling is not mentioned.

Validation II:

Galbreath [230] in its study 'A Survey of exit facilities in high office buildings', a study was carried out on 10 office buildings to study the relationship between the time of evacuation in practical exercises, the number of occupants and the stairway area. He also mentioned it in his paper "The time of evacuation by stairs into high buildings" [96]. On 10 buildings, we only consider building numbers 6, 7 and 8 as the width of its stairs is very close to 150 cm. The width of the stairs of other buildings is very low and cannot be compared. Details of his survey and the results of the proposed new method are given in Table 6.4.

Table 6.4: Result validation with drill conducted by Galbreath

Sr.No.	Building Number	Number of floors	Staircase width	Person per floor	Number of stairs	Person per floor per stairs	Time of evacuation during drill (seconds)	Evacuation time by using the proposed model (seconds)
1	6	11	132 cm	110	2	55	390	445
2	7	9	132 cm	111	2	56	330	370
3	8	9	132 cm	133	4	34	270	225

The results are very close to the results of the survey. There is a slight difference that can be due to the shorter width of the stairs. Furthermore, the ceiling height is not stated.

Validation III:

Eric Rivers et al. [231] conducted the evacuation drill at a 30-storey office building located in Broad Street New York, in 2002. The evacuation was carried out in 1385 persons and was completed in about 18 minutes.

After application of eqn. 6.2 with the above mentioned parameter, the results are.

$$t = 0.0836 \times 1385 \times 10.864/1.2$$

t = 1047.86 seconds, i.e. 17.46 minutes

The results are very close to the drill times.

So the proposed method for estimating evacuation time is well verified and validated. It may be considered to design and manage the evacuation of any high-rise building.

CHAPTER 7: IMPROVISED EVACUATION STRATEGY FOR A HIGH RISE BUILDING

This study suggests a suitable evacuation strategy for a high-rise building using a model case study. This is carried out based on important parameters such as occupancy load, tenability factors, evacuation time and various determining factors. The basic concept of ASET and RASET is taken into account in this study. Normally, the ASET is linked to the tenability criteria and the RSET is linked to the time required for a safe evacuation according to various building parameters. There are a number of determinants. One of them is the tenability factor. As mentioned earlier, we take visibility as well as other factors mentioned below to determine a safe evacuation time of 72 seconds.

7.1 Determining factors for deciding the evacuation strategy

Various determinants of safe evacuation determine the success of the evacuation. Obviously, of the many determining factors, the time required for evacuation of the building is the most important determining factor. But it is also important to understand that evacuation of the building as a whole is not always important. All that matters is to leave the affected area of the building well in time. This is also important as the exit doors cannot be closed unless all occupants move out of the affected area, otherwise smoke can continue to enter from the exit.

Kuligowski [91] and David [232] studied various buildings under different emergency and other conditions and suggested three different types of factors that influence the success of the evacuation. The most commonly used factors are the speed of the occupants in distance per unit time (m/s), population density of persons per unit area (persons/m^2) and occupant flow rate i.e. amount of people passing through a certain point in the building elements, such as a staircase or doors (person/m/sec)

If the density of the population exceeds a certain limit, the conditions will become very uncomfortable and the movement of the occupants will be very difficult. Nelson and McLennan's research (quoted in Shi Pu [233]) suggests that:

- If the population density is below 0.54 persons/m^2, it is possible to maintain a normal speed.
- If the population density is more than 3.8 persons/m^2, there is no or very little movement.

Between these limits, the speed depends on the density that is given by:

$\mathrm{S} = K - 0.0266 \times K \times D$ ……………… Eqn. 7.1

Where,

S : Practical movement speed (m/s)
D : Population density (person /m^2)
K : Standard movement speed and depends on the type of area as for corridors, doors and ramps are 1.4.

Simo et al. [234] suggested that the flow rate (person/ m/s) can be calculated as

$\text{Flow rate} = \mathrm{N}/\{\mathrm{w} \times (\mathrm{t}_1 - \mathrm{t}_2)\}$ ……………… Eqn.7.2

Where,
N : Number of people entering the staircase
w : Width of the door (m)

t_1 : Time the last person entered in the staircase
t_2 : Time the first person entered in the staircase

Apart from these factors, the time required for movement through the stairs, particularly by the occupants of the affected floor, is also an important factor in determining the evacuation strategy. It is always assumed that all emergency exit doors remain fully closed throughout the fire, as open stairway doors can have a serious impact on smoke management throughout the building. This can lead to contamination of the stairs throughout the building and create a dangerous situation for all occupants. It depends on the difference in pressure due to the temperature, the speed and direction of the wind, the extent of the openings, the humidity, the location of the fire source, and many other factors of that nature. In addition, the staircase also becomes a smoke duct and distributes the smoke on the remaining floors [235]. This can be achieved by closing the door as soon as possible once everyone leaves the respective floor.

Based on the above studies, the following determinants are taken into account to determine the best evacuation strategy.

1. Time taken to evacuate impacted floors.
2. Time required to clear most affected zones of the floors.
3. Time required to evacuate the remaining floors in the building.
4. Time required to evacuate the entire building.
5. Occupant speed during the evacuation of the zone of the most affected floor.
6. Population density during the evacuation of the zone of the most affected floor.
7. Flow rate during evacuation of most affected floor.

7.2 Building model considered for the study

A 50-storey case study model (186.3 m high) used for the study represents today's high-rise commercial buildings (Figure 7.1). An occupant load of 10 m^2/person is taken into consideration in this study. A floor area is considered as 800 m^2 with a length of 32 m & width of 25 m. So there will be 80 people on the floor. The ceiling for business occupancy is 3.6 m, which we have taken into consideration in this study. There are two stairways for the model building. In this study, the required travel distance is maintained to 30m. Here we consider both the stairs of 1.5 m width and the exit door of 100 cm as suggested by NBC [3]. An overall plan is shown in Figure 7.2.

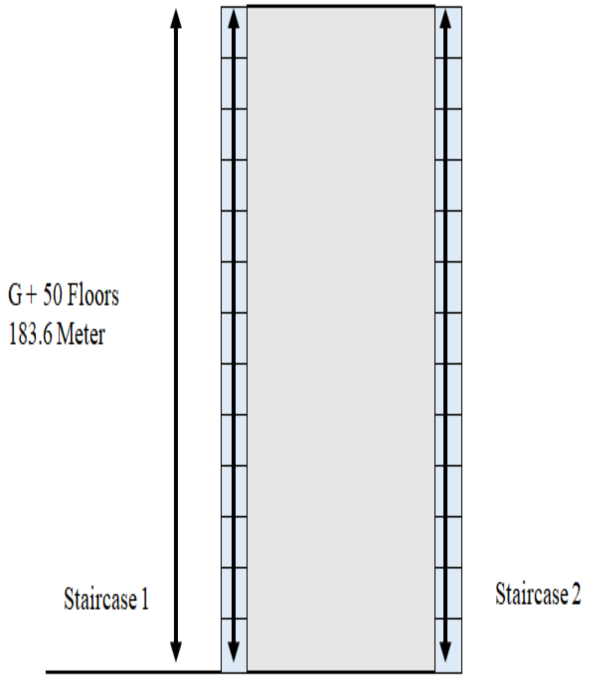


Fig. 7.1: Schematic representation of the model building

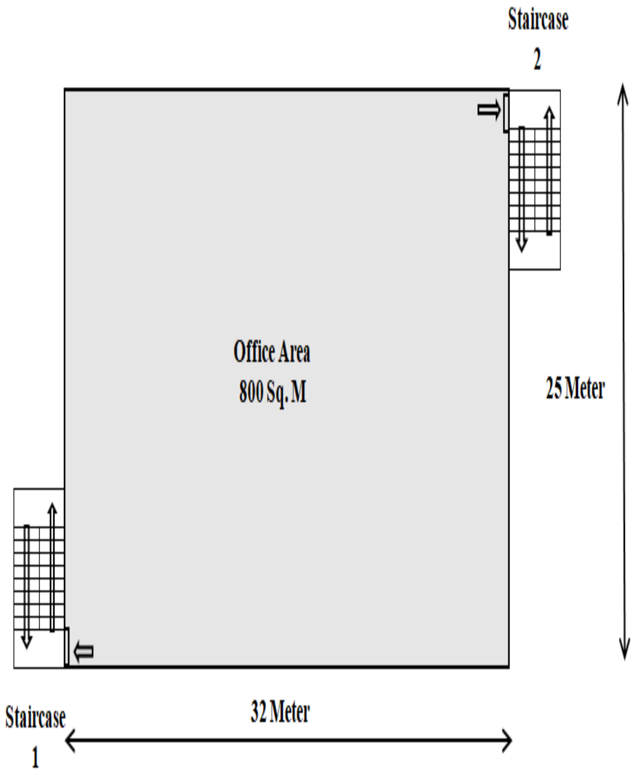


Fig. 7.2: Floor plan representation of model used for the study

The refuge area is provided every 24 meters and every 15 meters, as required by the NBC. The ground floor serves for reception, meeting rooms and other various activities. All the upper floors are designed for office use. There are 3 basements for parking and other building auxiliaries. The whole building is covered by a fire protection and detection system. Here, the ground floor is taken into consideration in a total number of floors for evacuation. But the basements are not taken into account because they are not intended to be occupied and will not affect the process of evacuation of the building.

7.3 Different evacuation strategies

As the refuge area is necessary at the 24th meter high of the building, then after every 15 meters (after every 4th floor). It is located on the 7th floor, 11th floor, 15th floor. 19th floor, 23rd floor, 27th floor, 31st floor, 35th floor, 39th floor, 43rd floor and the 47th floor as shown in Figure 7.3

As I mentioned before, there are basically four evacuation strategies. Out of these, defend in place strategy is normally applied for disabled occupants and is very situation-specific. In a delayed evacuation strategy, normally occupants could not perform self-rescue and wait in the refuge area for external help. So, in this study, these two strategies are not taken into account, and only the total evacuation strategy and the phased evacuation strategy are taken into account.

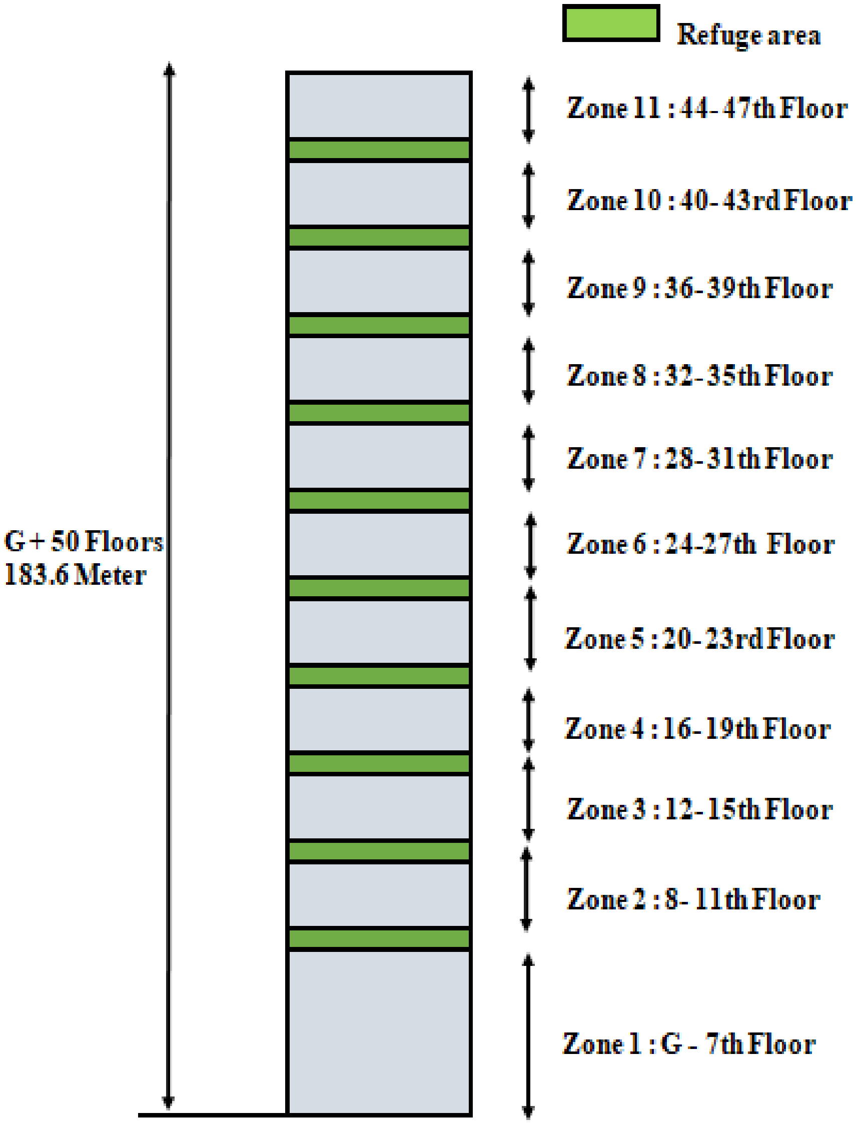


Fig. 7.3: Schematic representation of the side view of the building for strategy II

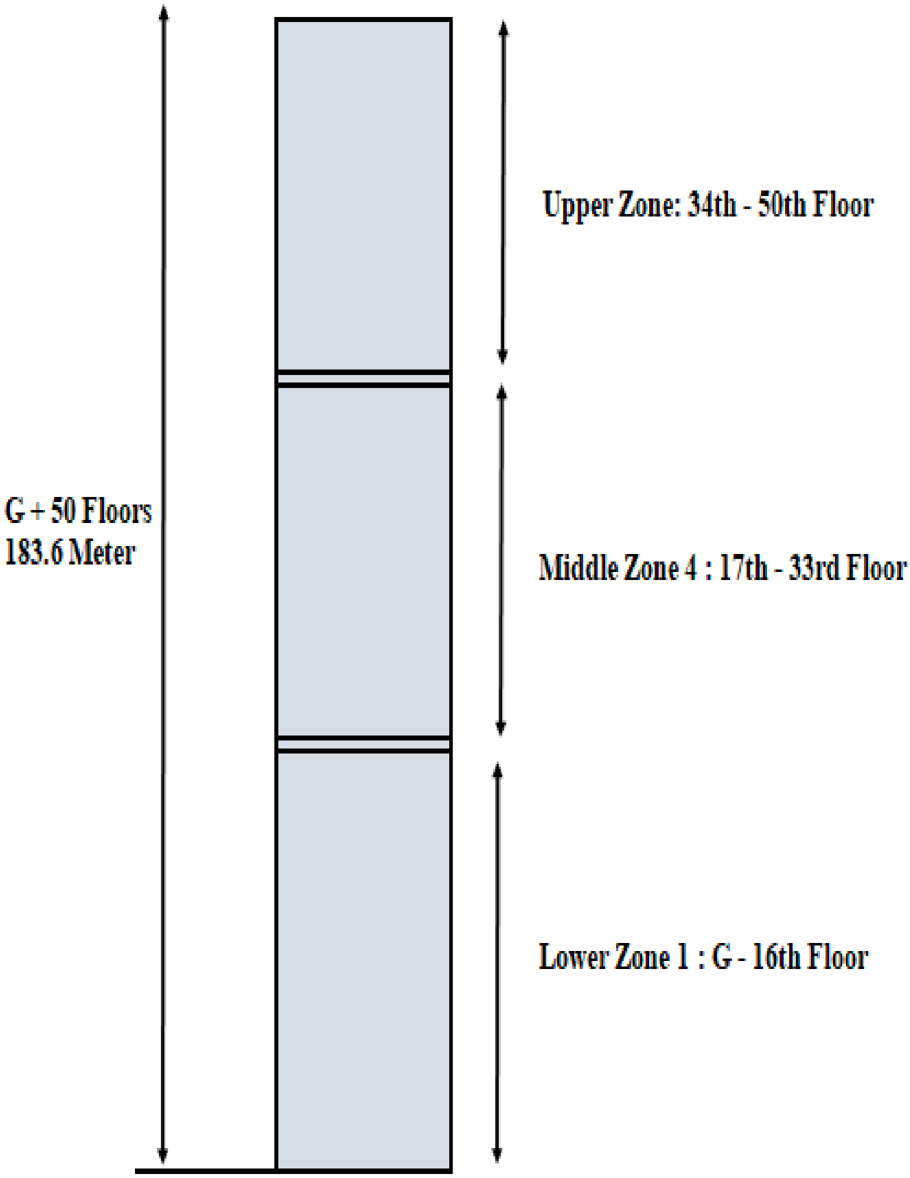


Fig. 7.4: Schematic representation of the side view of the building for strategy III

In the phase evacuation strategy, three possible options as mentioned below are considered.

Therefore, the four evacuation strategies, including the total evacuation strategy, are:

Strategy I : Total evacuation strategy

Strategy II : The building is divided into zones between the refuge areas i.e. zone 1 will be G – 7thfloor, zone 2 will be 8-11thfloor, zone 3 will be 12-15thfloor, zone 4 will be 16-19thfloor, zone 5 will be 20-23th floor, zone 6 will be 24-27thfloor, zone 7 will be 28th -31 floor, zone 8 will be 32-35thfloor, zone 9 will be 36-39thfloor, zone 10 will be 40-43rdfloor, zone 11 will be 44-47thfloor and 48th -50th will be 12th zone. [Figure 7.3].

Strategy III : The entire building is divided into a lower zone, middle zone, and upper zone i.e. from the ground floor to the 16th floor, from the 17th to the 33rd floor and from the 34th to the 50th floor. [Figure 7.4].

Strategy IV : A zone of three floors that includes the fire floor, an upper level of the fire floor and a lower level of the fire floor. So, there will be a total of 49 fire zones.

7.4 Application of egress model to the different evacuation strategies

The four strategies are considered and assessed based on different determinants of a safe evacuation. These considerations are described in detail in Section 7.1 of this chapter. Evacuation of the balance building is also contemplated. Detailed findings are presented in Table 7.1.

Table 7.1: Details of findings and corresponding determinants for the evacuation strategy-I

S. N.	Evacuation Strategy	Evacuation Time (Seconds)							
		Floor	Building	Balance building	Total	Staircase # 1	Staircase # 2	Average Staircase	Average Building
	Strategy I								
	Complete building	63	1644.28	0.00	1644.28	1525.00	1636.00	1580.50	793.36
	Strategy II								
	Zone								
1	Zone 1	60	251.78	1555.28	1807.06	245.00	232.00	238.50	121.34
2	Zone 2	58	270.23	1525.18	1795.40	121.00	134.00	127.50	191.97
3	Zone 3	60	328.18	1530.60	1858.78	122.00	132.00	127.00	245.31
4	Zone 4	62	394.38	1519.70	1914.08	121.00	135.00	128.00	298.65
5	Zone 5	61	454.35	1526.15	1980.50	120.00	136.00	128.00	348.45
6	Zone 6	60	516.65	1520.28	2036.93	119.00	132.00	125.50	397.97
7	Zone 7	58	570.53	1523.70	2094.23	121.00	136.00	128.50	444.53
8	Zone 8	60	630.20	1519.95	2150.15	120.00	134.00	127.00	489.04
9	Zone 9	58	685.05	1535.10	2220.15	122.00	135.00	128.50	532.47
10	Zone 10	58	740.10	1530.25	2270.35	119.00	133.00	126.00	574.72
11	Zone 11	58	788.68	1508.55	2297.23	121.00	131.00	126.00	616.20
12	Zone 12	58	750.03	1556.35	2306.38	89.00	99.00	94.00	617.13
	Average	59.25	531.68	1529.26	2060.93	128.33	139.08	133.71	406.48
	Strategy III								
	Zone								
1	Lower	60	540.40	1357.30	1897.70	507.00	533.00	520.00	262.11
2	Middle	64	851.53	1118.30	1969.83	510.00	563.00	536.50	543.51
3	Upper	64	1129.80	1104.28	2234.08	512.00	559.00	535.50	792.98
	Average	62.67	840.58	1193.29	2033.87	509.67	551.67	530.67	532.87

Table 7.1: Continued……….

S. N.	Evacuation Strategy	Evacuation Time (Seconds)							
		Floor	Building	Balance building	Total	Staircase # 1	Staircase # 2	Average Staircase	Average Building
	Strategy IV								
	Fire Floor								
1	1st	55	90.73	1610.05	1700.78	81.00	84.00	82.50	46.66
2	2nd	60	121.80	1589.50	1711.30	92.00	97.00	94.50	70.73
3	3rd	57	140.23	1589.45	1729.68	91.00	100.00	95.50	87.02
4	4th	56	158.65	1577.50	1736.15	90.00	100.00	95.00	101.41
5	5th	63	171.50	1552.50	1724.00	89.00	97.00	93.00	115.36
6	6th	58	184.18	1561.58	1745.75	90.00	100.00	95.00	129.30
7	7th	56	200.40	1550.93	1751.33	92.00	99.00	95.50	144.33
8	8th	62	217.78	1561.03	1778.80	91.00	101.00	96.00	157.35
9	9th	58	228.40	1560.20	1788.60	90.00	98.00	94.00	170.02
10	10th	56	245.60	1561.08	1806.68	91.00	99.00	95.00	183.30
11	11th	57	267.58	1547.53	1815.10	92.00	100.00	96.00	199.04
12	12th	56	282.40	1543.28	1825.68	93.00	97.00	95.00	212.46
13	13th	56	297.68	1557.23	1854.90	91.00	102.00	96.50	225.27
14	14th	56	310.03	1558.70	1868.73	90.00	99.00	94.50	237.77
15	15th	56	326.08	1553.30	1879.38	91.00	100.00	95.50	250.31
16	16th	56	336.73	1558.93	1895.65	91.00	98.00	94.50	261.53
17	17th	58	353.38	1560.13	1913.50	93.00	98.00	95.50	274.68
18	18th	56	370.58	1550.98	1921.55	88.00	101.00	94.50	286.67
19	19th	60	384.70	1564.98	1949.68	91.00	101.00	96.00	298.94
20	20th	59	400.35	1563.53	1963.88	93.00	102.00	97.50	310.74
21	21st	59	417.28	1550.60	1967.88	90.00	100.00	95.00	322.51
22	22nd	57	426.63	1644.08	2070.70	89.00	99.00	94.00	333.07
23	23rd	60	442.28	1557.50	1999.78	90.00	101.00	95.50	344.98
24	24th	57	458.93	1549.95	2008.88	92.00	99.00	95.50	356.43
25	25th	63	474.83	1493.20	1968.03	91.00	101.00	96.00	367.69
26	26th	59	485.53	1554.10	2039.63	92.00	102.00	97.00	378.45

Table 7.1: Continued……….

S. N.	Evacuation Strategy	Evacuation Time (Seconds)							
		Floor	Building	Balance building	Total	Staircase # 1	Staircase # 2	Average Staircase	Average Building
27	27th	58	500.53	1553.35	2053.88	90.00	99.00	94.50	389.56
28	28th	57	513.35	1557.08	2070.43	90.00	99.00	94.50	400.40
29	29th	58	529.63	1554.90	2084.53	90.00	102.00	96.00	411.04
30	30th	54	541.25	1547.90	2089.15	90.00	101.00	95.50	421.36
31	31st	58	552.83	1552.10	2104.93	91.00	97.00	94.00	431.86
32	32nd	56	568.05	1561.10	2129.15	91.00	99.00	95.00	442.26
33	33rd	56	581.38	1551.30	2132.68	89.00	100.00	94.50	452.96
34	34th	55	591.23	1546.43	2137.65	90.00	99.00	94.50	463.01
35	35th	56	601.88	1557.50	2159.38	93.00	98.00	95.50	476.33
36	36th	61	613.40	1542.88	2156.28	89.00	99.00	94.00	483.61
37	37th	59	624.20	1542.90	2167.10	89.00	101.00	95.00	494.03
38	38th	57	634.75	1555.75	2190.50	90.00	101.00	95.50	504.28
39	39th	56	645.33	1550.48	2195.80	91.00	101.00	96.00	514.55
40	40th	61	655.10	1551.28	2206.38	90.00	101.00	95.50	524.78
41	41st	58	665.68	1557.28	2222.95	92.00	100.00	96.00	534.93
42	42nd	60	676.48	1555.60	2232.08	91.00	99.00	95.00	545.11
43	43rd	58	686.63	1565.20	2251.83	89.00	97.00	93.00	555.57
44	44th	57	696.85	1553.65	2250.50	90.00	100.00	95.00	565.63
45	45th	56	707.90	1559.10	2267.00	89.00	101.00	95.00	576.16
46	46th	56	718.03	1561.10	2279.13	92.00	100.00	96.00	586.11
47	47th	59	728.63	1550.00	2278.63	92.00	101.00	96.50	596.50
48	48th	56	738.88	1555.48	2294.35	91.00	99.00	95.00	606.52
49	49th	58	750.03	1556.35	2306.38	89.00	99.00	94.00	617.13
	Average	57.67	455.43	1558.38	2013.81	90.45	99.35	94.90	356.32

Table 7.2: Details of the results and corresponding determining factors for evacuation strategy -II

S.N.	Evacuation Strategy	Average distance (m)	Occupant's Speed (m / s)	Population density (Persons / m^2)	Population Flow rate(person sec^{-1} m^{-1})
	Strategy I				
1	**Total building**	**318.30**	**0.40**	**5.26**	**0.63**
	Strategy II				
	Zone				
1	Zone 1	60.43	0.50	4.75	**0.67**
2	Zone 2	125.86	0.66	3.92	**0.69**
3	Zone 3	168.45	0.69	3.75	**0.67**
4	Zone 4	211.02	0.71	3.65	**0.65**
5	Zone 5	252.39	0.72	3.56	**0.66**
6	Zone 6	294.14	0.74	3.48	**0.67**
7	Zone 7	333.49	0.75	3.42	**0.69**
8	Zone 8	374.09	0.76	3.34	**0.67**
9	Zone 9	412.91	0.78	3.29	**0.69**
10	Zone 10	451.96	0.79	3.23	**0.69**
11	Zone 11	489.89	0.80	3.18	**0.69**
12	Zone 12	512.39	0.83	3.00	**0.69**
	Average	**307.25**	**0.73**	3.55	**0.68**
	Strategy III				
	Zone				
1	Lower	114.14	0.44	5.08	**0.67**
2	Middle	305.49	0.56	4.41	**0.63**
3	Upper	492.27	0.62	4.10	**0.63**
		303.97	**0.54**	**4.53**	**0.64**
	Strategy IV				
	Fire floor				
1	1st floor	30.43	0.65	3.94	**0.73**
2	2nd floor	42.32	0.60	4.22	**0.67**
3	3rd floor	53.44	0.61	4.14	**0.70**
4	4th floor	64.53	0.64	4.02	**0.71**
5	5th floor	75.63	0.66	3.92	**0.63**
6	6th floor	86.37	0.67	3.85	**0.69**
7	7th floor	97.38	0.67	3.82	**0.71**
8	8th Floor	107.84	0.69	3.76	**0.65**
9	9th floor	118.57	0.70	3.70	**0.69**
10	10th floor	129.40	0.71	3.65	**0.71**
11	11th floor	140.18	0.70	3.66	**0.70**
12	12th floor	150.91	0.71	3.63	**0.71**
13	13th floor	161.47	0.72	3.60	**0.71**
14	14th floor	171.92	0.72	3.56	**0.71**
15	15th floor	182.21	0.73	3.54	**0.71**
16	16th floor	192.33	0.74	3.50	**0.71**
17	17th floor	202.88	0.74	3.48	**0.69**
18	18th floor	212.78	0.74	3.46	**0.71**
19	19th floor	223.51	0.75	3.43	**0.67**
20	20th floor	233.58	0.75	3.41	**0.68**
21	21st floor	243.63	0.76	3.39	**0.68**
22	22nd floor	253.65	0.76	3.36	**0.70**
23	23rd floor	263.97	0.77	3.34	**0.67**
24	24th floor	273.75	0.77	3.33	**0.70**
25	25th floor	283.41	0.77	3.31	**0.63**

Table 7.2: Continued……….

S.N.	Evacuation Strategy	Average distance (m)	Occupant's Speed (m / s)	Population density (Persons / m^2)	Population Flow rate(person sec^{-1} m^{-1})
26	26th floor	293.46	0.78	3.29	**0.68**
27	27th floor	303.46	0.78	3.27	**0.69**
28	28th floor	312.82	0.78	3.26	**0.70**
29	29th floor	322.88	0.79	3.23	**0.69**
30	30th floor	332.75	0.79	3.21	**0.74**
31	31st floor	341.96	0.79	3.20	**0.69**
32	32nd floor	351.47	0.79	3.19	**0.71**
33	33rd floor	361.41	0.80	3.17	**0.71**
34	34th floor	370.57	0.80	3.16	**0.73**
35	35th floor	379.73	0.80	3.17	**0.71**
36	36th floor	389.73	0.81	3.13	**0.66**
37	37th floor	399.33	0.81	3.11	**0.68**
38	38th floor	408.53	0.81	3.10	**0.70**
39	39th floor	418.10	0.81	3.09	**0.71**
40	40th floor	427.52	0.81	3.08	**0.66**
41	41st floor	437.35	0.82	3.07	**0.69**
42	42nd floor	446.05	0.82	3.06	**0.67**
43	43rd floor	456.20	0.82	3.05	**0.69**
44	44th floor	464.91	0.82	3.04	**0.70**
45	45th floor	474.93	0.82	3.03	**0.71**
46	46th floor	484.38	0.83	3.02	**0.71**
47	47th floor	493.71	0.83	3.01	**0.68**
48	48th floor	502.81	0.83	3.01	**0.71**
49	49th floor	512.39	0.83	3.00	**0.69**
	Average	**279.24**	**0.76**	**3.39**	**0.69**

7.5 Result & Discussions:

In this section, the major findings and results of the study are analysed and summarized. The focus is on the evacuation of the most affected people such as the fire floor, nearby floors, the time required to clear the stairway and further evacuate the remaining floors as required. Evacuation of the whole building will be very difficult and unsafe, especially for high-rise buildings. The time required to evacuate the entire building is not always important, the important thing is to leave the place affected on time. The results and analysis for each strategy studied are presented below.

Strategy I

During the total evacuation, the minimum time required to evacuate any floor is 63 seconds and a flow rate from the stairway door of 0.63 person sec-1 m-1. But it is observed that few occupants come back to the floor due to the congestion on the stairs. They entered the stairs again after some time that is as long as 585 seconds, which is much more than the 72-second tenability limit. The total evacuation time for the building is 1644.28 seconds, or close to 28 minutes.

The average speed of the occupants during the evacuation is 0.40 m/s and the population density is 5.26 persons/m^2, which is very high.

Strategy II

In this strategy, a pathfinder model independently applies to all 12 zones of the building model. It is observed that the time required to evacuate a floor ranges from 58 seconds to 62 seconds with an average time of 59.25 seconds. In this strategy, because of the reduced congestion in the stairs, it is observed that the occupants did not return to the respective floors.

The average flow rate is 0.68 person sec-1 m-1 varying from 0.65 person sec-1 m-1 to 0.69 person sec-1 m-1. The average time taken to clear the affected zone is 531.68 seconds, ranging from 251.78 seconds to 788.68 seconds. The higher values are caused by the evacuation of the upper zones. Once the affected zone is evacuated, occupants of the remaining zones may start their evacuation. The evacuation of other zones can be decided according to its needs and can await further instructions according to the behavior of the fire. The average evacuation time for occupants of the remaining 11 zones of the building is 1529.26 seconds, ranging from 1519.70 seconds to 1556.35 seconds. Therefore, the average total evacuation time for all occupants will be 2060.93 seconds, going from 1795.40 to 2306.38 seconds.

The average speed of the occupants of the respective affected zones is 0.73 m/s varying from 0.50 m/s for lower floors to 0.83 m/s for upper floors. The mean population density is 3.55 persons/m^2, ranging from 4.75 persons /m^2 to 3.00 persons /m^2, which is also higher.

Strategy III

In this strategy, a pathfinder model is applied to the three zones of the building i.e. lower zone, middle zone, and upper zone independently. The average evacuation time was found to be 62.67 seconds, with 64 seconds for the lower and middle zones and 60 seconds for the upper zone. Similar to Strategy I, it is observed that during the evacuation of the upper zone, few occupants returned to the respective floors and then returned to the stairs after 172 seconds.

The average flow rate is 0.64 person sec-1 m-1 varying from 0.63 person sec-1 m-1 to 0.67 person sec-1 m-1. The evacuation time is 540.40 seconds, 851.53 seconds and 1129.80 seconds respectively for the lower, middle and upper zones with an average time of 840.58 seconds. The evacuation time of the remaining floors is 1104.28 seconds, 1111.30 seconds and 1357.30 seconds respectively for the lower, middle and upper zones with an average time of 1193.29 seconds. Thus, the average total evacuation time for all occupants will be 2033.87 seconds, ranging from 1897.70 seconds to 2234.08 seconds.

The average speed of the occupants is 0.54 m/s with 0.62 m/s for the upper zone, 0.56 m/s for the middle zone and 0.44 m/s for the upper zone. The average population density is 4.53 people/m^2 with 4.10 people/m^2 for the upper zone, 4.41 people/m^2 for the middle zone and 5.08 people/m^2 for the lower zone. This is also on the higher side.

Strategy IV

A pathfinder model is applied independently to all 49 fire zones. The average time required to clear floors in the area is 57.67 seconds, ranging from 55 seconds to 63 seconds. The mean flow rate of 0.69 person sec-1 m-1 is between 0.63 person sec-1 m-1 and 0.74 person sec-1 m-1. The average time required to evacuate the affected zone is 457.43 seconds ranging from 90.73 seconds for the lower floors and 750.03 seconds for the upper floors.

The average evacuation time for the occupants of the remaining floors of the building is 1558.38 seconds ranging from 1493.20 seconds to 1644.08 seconds. This means that the average total evacuation time for all occupants will be 2013.81 seconds, ranging from 1700.78 seconds to 2306.38 seconds.

The average speed of the occupants during the evacuation of the respective zones is 0.76 m/s between 0.65 m/s and 0.83 m/s. The average population density is 3.39 people/m^2 ranging from 3 people/m^2 to 4.22 people/m^2. Table 7.2 summarizes the full analysis.

Table 7.3: Summary of various determining factors of evacuation strategy- I

SN	Evacuation Strategy	Evacuation Time (Seconds)					
		Floor	Building	Balance	Total	Average Staircase duration	Average time
1	Strategy I	63.00	1644.28	0.00	1644.28	1580.50	793.36
2	Strategy II	59.25	531.68	1529.26	2060.93	133.71	406.48
3	Strategy III	62.67	840.58	1193.29	2033.87	530.67	532.87
4	Strategy IV	57.67	455.43	1558.38	2013.81	94.90	356.32

Table 7.4: Summary of various determining factors of evacuation strategy -II

SN	Evacuation Strategy	Average distance (m)	Occupant's Speed (m / s)	Population density (Persons / m^2)	Population Flow rate (person sec^{-1} m^{-1})
1	Strategy I	318.30	0.40	5.26	0.63
2	Strategy II	307.25	0.73	3.55	0.68
3	Strategy III	303.97	0.54	4.53	0.64
4	Strategy IV	279.24	0.76	3.39	0.69

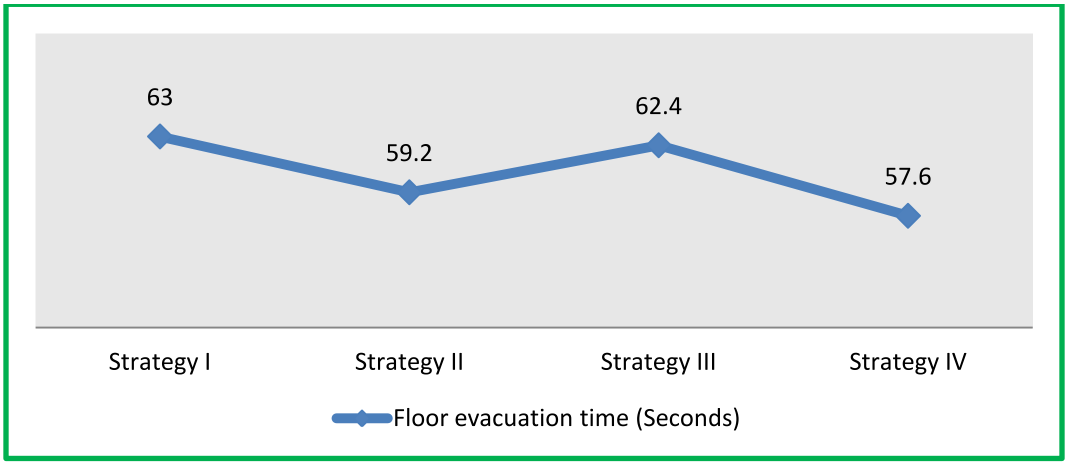


Fig. 7.5: Comparison of floor evacuation time

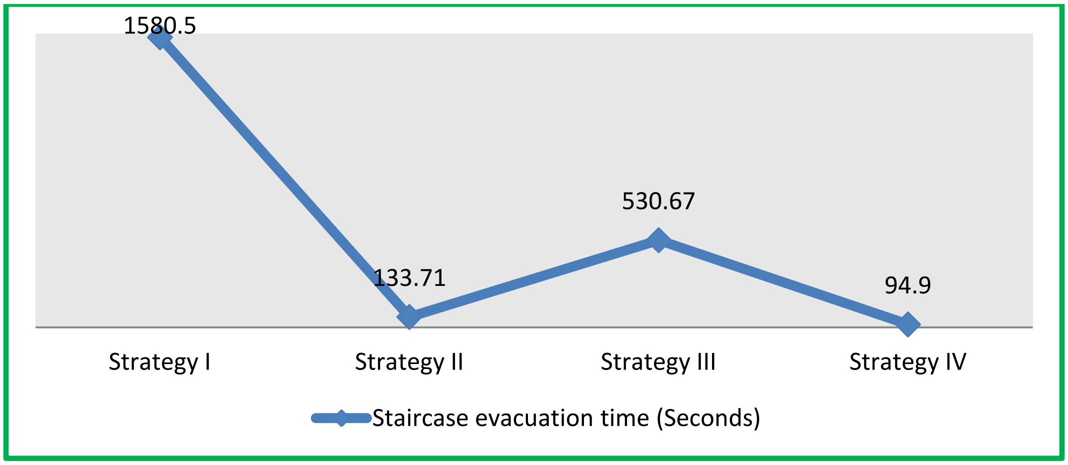


Fig. 7.6: Comparison of staircase evacuation time

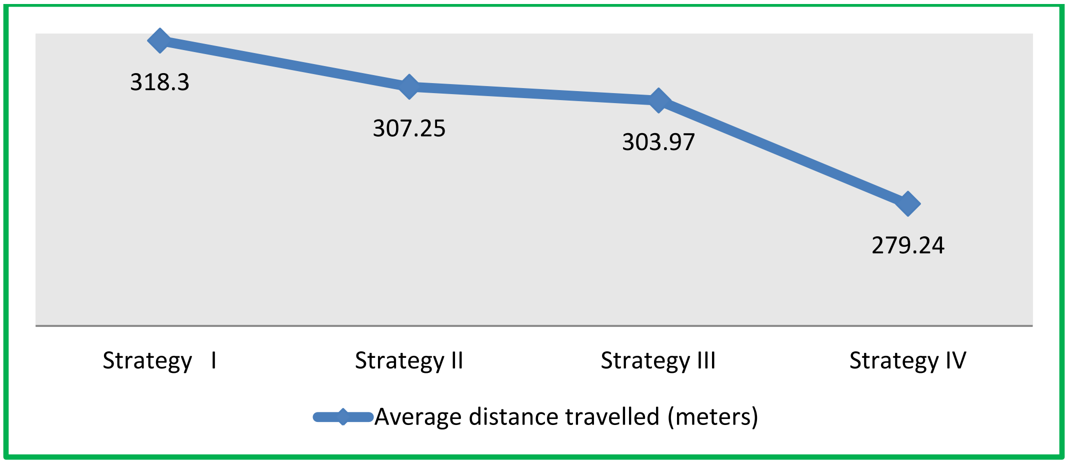


Fig. 7.7: Comparison of average distance travelled

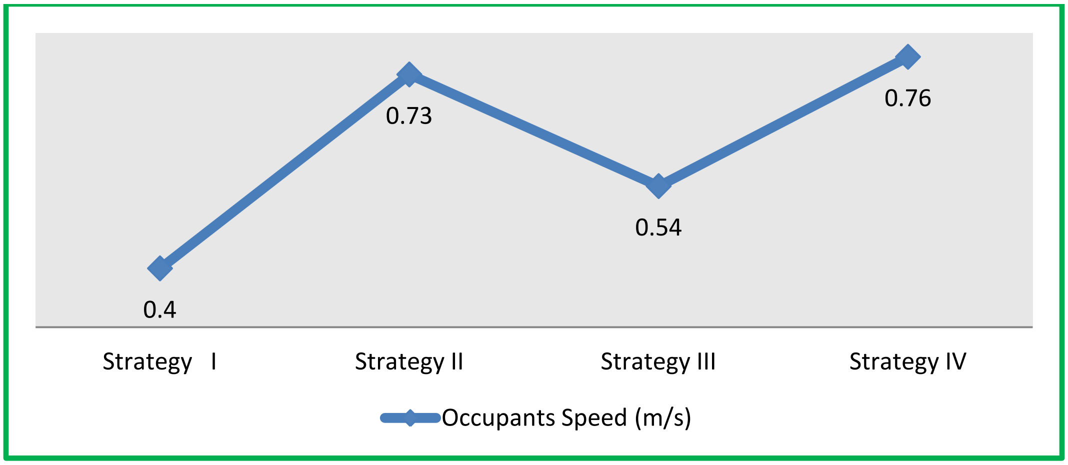


Fig. 7.8: Comparison of speed of the occupants

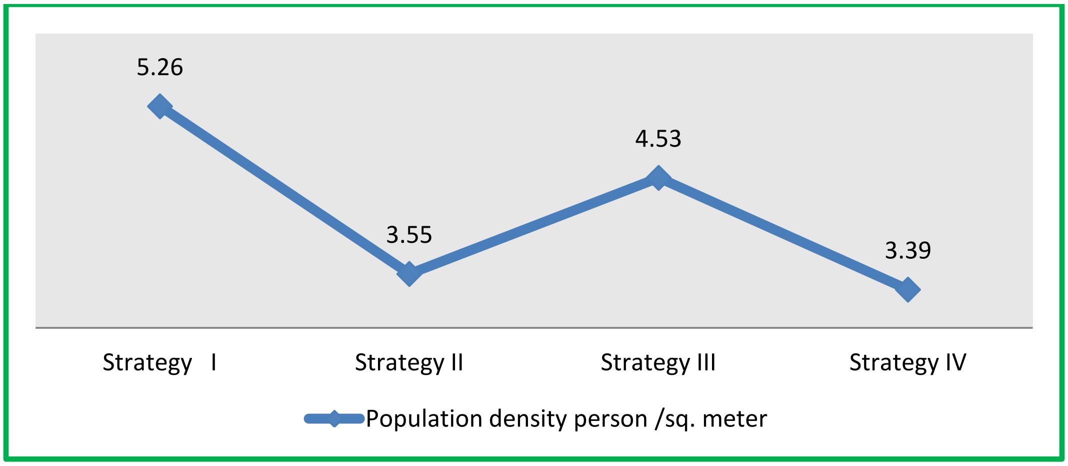


Fig. 7.9: Comparison of population density

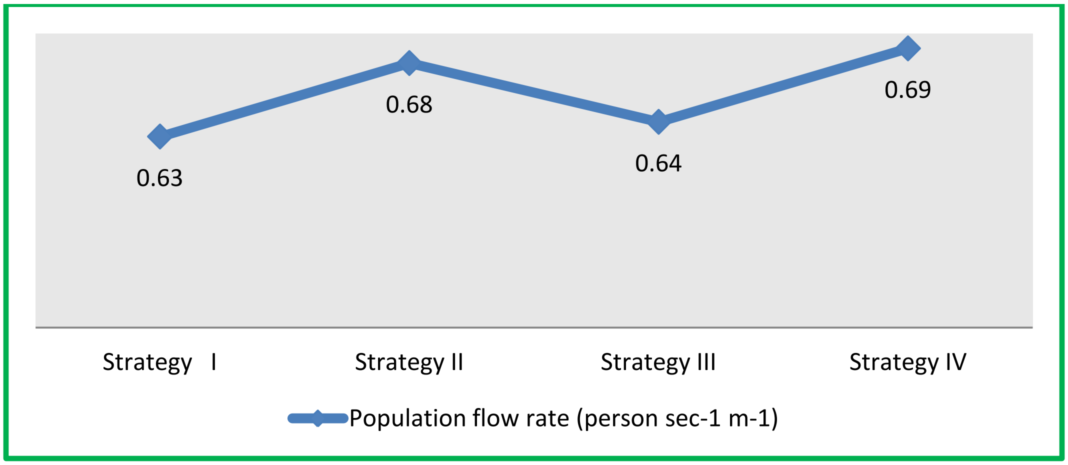


Fig. 7.10: Comparison of population flow rate

In all four strategies, the floor occupants successfully exited the floor well below the 72-second tenability limit. However, due to high exit congestion, few occupants return to the floor, the floor evacuation may not be completed for Strategy I & III.

The next factor is the time it takes for the occupants of the respective fire zone to safely exit the building. This factor is important as the occupants of the remaining part of the building cannot be admitted unless all the occupants of the fire zone are outside the stairs. Secondly, the counter-flow of emergency services may be readily possible once this is done. Strategy IV works best with a minimum of time. The time required to evacuate all occupants, including the remaining floors of the building, is minimal in Strategy IV compared to other progressive strategies. Similarly, other determining factors such as occupant speed, population density and flow rate are the best case of strategy IV.

As mentioned by Nelson and Maclennan [233], with a population density exceeding 3.8 persons/m^2, there is little or no movement possible. Based on this concept, Strategy IV will be the safest choice of any strategy.

We assume that evacuation will begin immediately after the 132-second pre-evacuation period. But there are few aspects like the functioning of a fire detection system, the behavior of the occupants, occupant load, building geometry, the temptation to use elevators, the combined use of different evacuation components, and much more, which can alter the overall evacuation decision. Therefore, evacuation models should offer sufficient flexibility in terms of the number of floors depending on the severity. For example, we can take five floors where one is fire floor, two upper floors and two below floors and so on.

In addition, tenability is a very dynamic factor that depends on fire load, ventilation, smoke management, directional intervention and much more. As such, building managers/designers should be aware of the expected fire load and possible occupancy of the building.

In this strategy, one must keep in mind that only the most affected people leave the building and that the majority of people remain in their place to save these people. Thus, the reliability of this study strongly depends on the awareness, behaviour and trust of the people and the decisions of the building management.

CHAPTER 8: SUMMARY, CONCLUSION AND FUTURE STUDIES

Due to the rapid urbanization of large cities, it is necessary to build high-rise buildings and, eventually, the challenges associated with a fire emergency are increasing. This study focuses on best practices for fire evacuation in terms of design and administration. A detailed literature review is conducted for important factors related to fire and smoke dynamics, building performance, existing evacuation strategies, computer building evacuation models and analysis of evacuation time optimization methods. The studies to optimize total evacuation time are mainly classified into three categories: building design and infrastructure, occupant path/departure, and occupant behavioural aspects. It is because all these studies have mixed results and one cannot go for any conclusion for the best optimization design. It is always advisable to decide on its effectiveness case by case.

The research consists of three parts. The first is the stairway design proposal for the best evacuation time. The second is a suggestion for a new methodology for calculating evacuation time. And the third is the proposal for the best evacuation strategy for a high-rise building based on different determinants.

In the first study, different case study models of construction of six possible stairways are examined. The best result is a design I among the six designs. It is noted that the average jam period for Design I is the lowest compared to other designs, although its travel distance is higher. It is also observed that, in some cases, occupants return from one staircase to the other due to the high occupant load at the exit. That increases the travel distance. But the jam time is a major cause of long evacuation time.

In addition, it is observed that the evacuation time with a stair width of 1.5 m is much more than the stair width of 2 m. The travel distance is more than 2m from 1.5m, mainly due to larger landings and mid- landings. But it does not affect the entire evacuation time of the building.

In the second part, the evacuation time is analysed for different building case studies. All results are studied for their inter-relationship between evacuation time, building parameters and occupancy.

It is observed that there is a relation between all of the above parameters with a constant factor and we called it an evacuation factor (α). The relationship obtained is

$$\alpha = \frac{\text{Maximum time of evacuation in seconds} \times \text{completed number of unit of effective width of staircase}}{\text{Number of floor} \times \text{Travel distance} \times \text{Number of occupants per floor per exit}}$$

This relation is just for travel time. For a better result, 132 seconds delay time can be added to the result.

Apart from the mathematical development model, there are a few other observations such as the relationship between the evacuation time, the number of floors, the number of occupants and the width of the stairs. Furthermore, it is observed that with the increase in the floor area, there is very little variation in the evacuation time and even in a few cases, it is slightly lower. The reason is the congestion clearance when it takes longer to reach the stairs if there is a large floor area.

The main objective of this study is to avoid the exposure of occupants who are not exposed to an immediate fire hazard and to give priority to occupants who are exposed to an immediate hazard. With this objective, in the third part of the study, visibility is considered tenability as one of the determining factors in the decision to evacuate. The loss of visibility occurs within 240 seconds, which is the maximum time available for occupants who are directly at risk. However, taking into account the other delay factors and a safety factor, the net time available is only 72 seconds.

In addition to the evacuation time, other factors such as the time required for the remaining evacuation of the building, the time required for the complete evacuation, occupant speed, population density and flow rate is also studied and analyzed. It is suggested that strategy IV, in which three floors i.e. fire floor, one upper and one lower floor, makes it more effective. However, it is also suggested that, depending on the severity of the fire and the fire protection response available, the area may be decided as the fire floor, two upper floors and two lower floors and so on.

The following are some additional factors that should be considered for an improved and safe evacuation strategy.

1. The concept of horizontal evacuation should also be taken into account in addition to vertical evacuation. This is important considering the challenges of vertical evacuation and the trend of vertical fire propagation. But to achieve this, the concept of passive fire protection, especially compartmentalization is very important. This is very useful for buildings having temporary/permanent immobile people.

2. In this study, assumptions are made to simplify some parameters which are very dynamic and can change from situation to situation and person to

person. This can be addressed with regular awareness, training at all levels, and regular mock drills.

As mentioned earlier, fire is a very complex phenomenon and its intensity and duration depend primarily on the fuel and ventilation properties available in the area. When it comes to a high-rise building, a very significant evacuation factor accompanies it. When we talk about evacuation, it mainly depends on the design of the infrastructure, path setting, and behaviour of the people & all these factors affect the evacuation process. This study examines the first two factors in detail. The behavioural factor is excluded as it varies from person to person depending on the individual's ability, experience, physical health, and culture. In addition, there may be various other real-time problems faced by the occupant which affect their behaviour and ultimately affect the evacuation process. Some of the issues are the presence of physically unfit persons as in the case of hospitals, panic behavior during fire emergencies and much more. In addition, with the increase in the height of buildings and the reduction in the physical capacity of persons, fatigue is also a major concern. All these parameters are hard to judge being very subjective and therefore in this study some assumptions are made for these parameters. So, in future studies, these dynamic parameters can be further evaluated for their impact on the evacuation process.

Only a staircase is used for the evacuation process and refuge area is also used to consider the evacuation strategy. There are few other evacuation components available like evacuation lift, escape chutes, lowering devices, sky bridges, etc. As a result, future research could focus on the study and use these components.

Various tenability criteria are examined in detail and visibility is used as a criterion to determine the best possible evacuation strategy. Additional tenability criteria may also be considered for future studies.

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APPENDIX

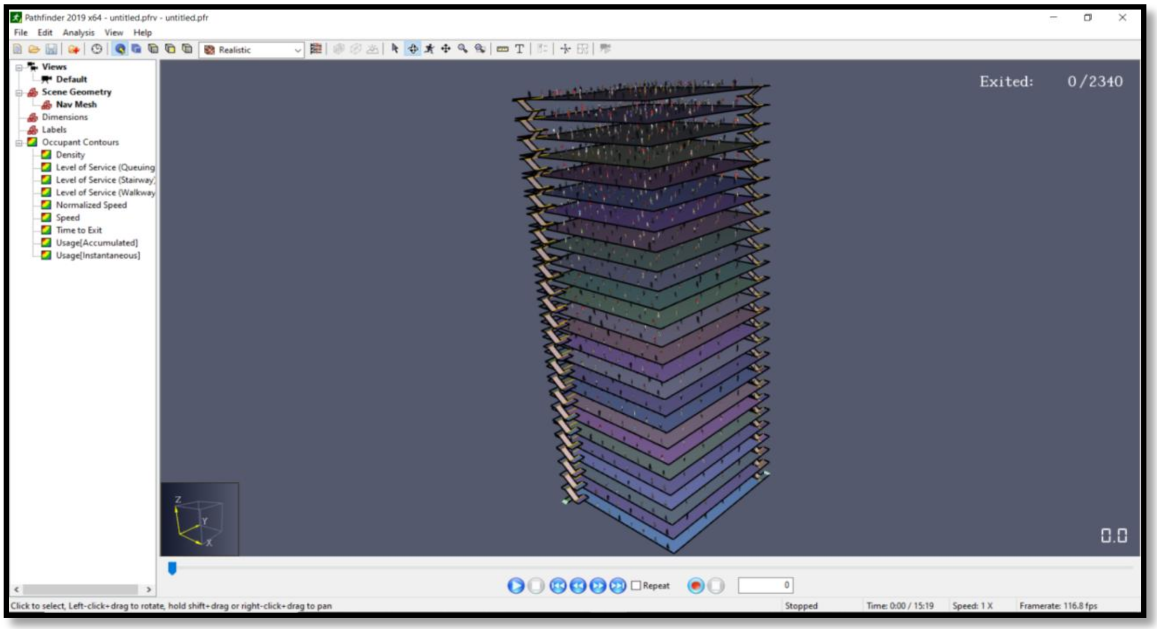


Fig. 1: Evacuation of 25 storied building using pathfinder evacuation model

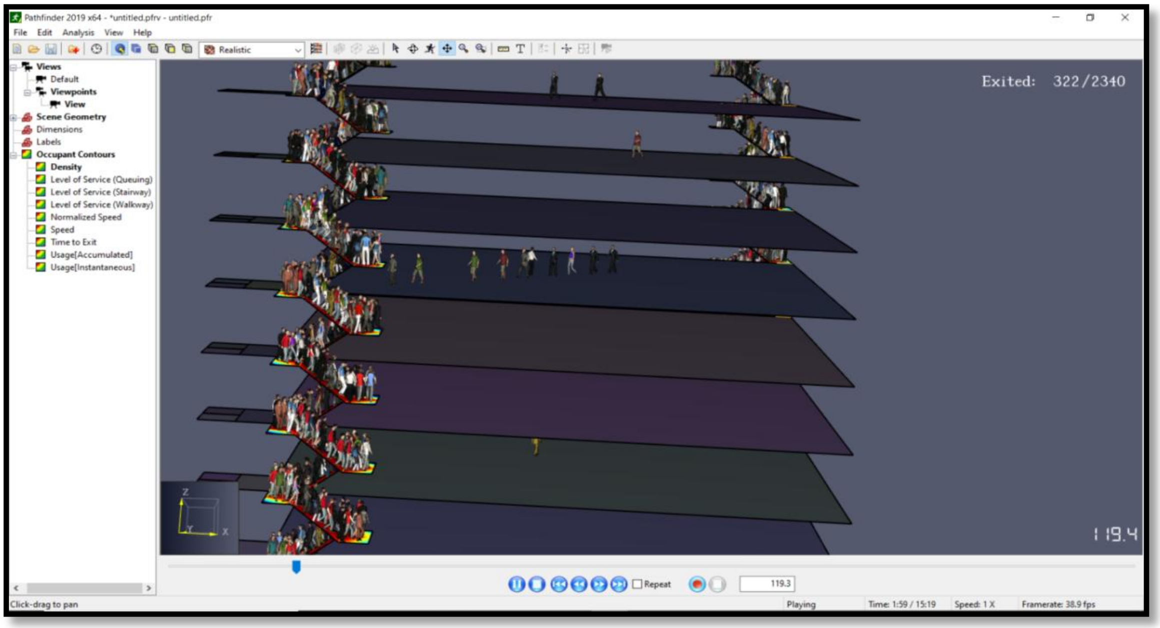
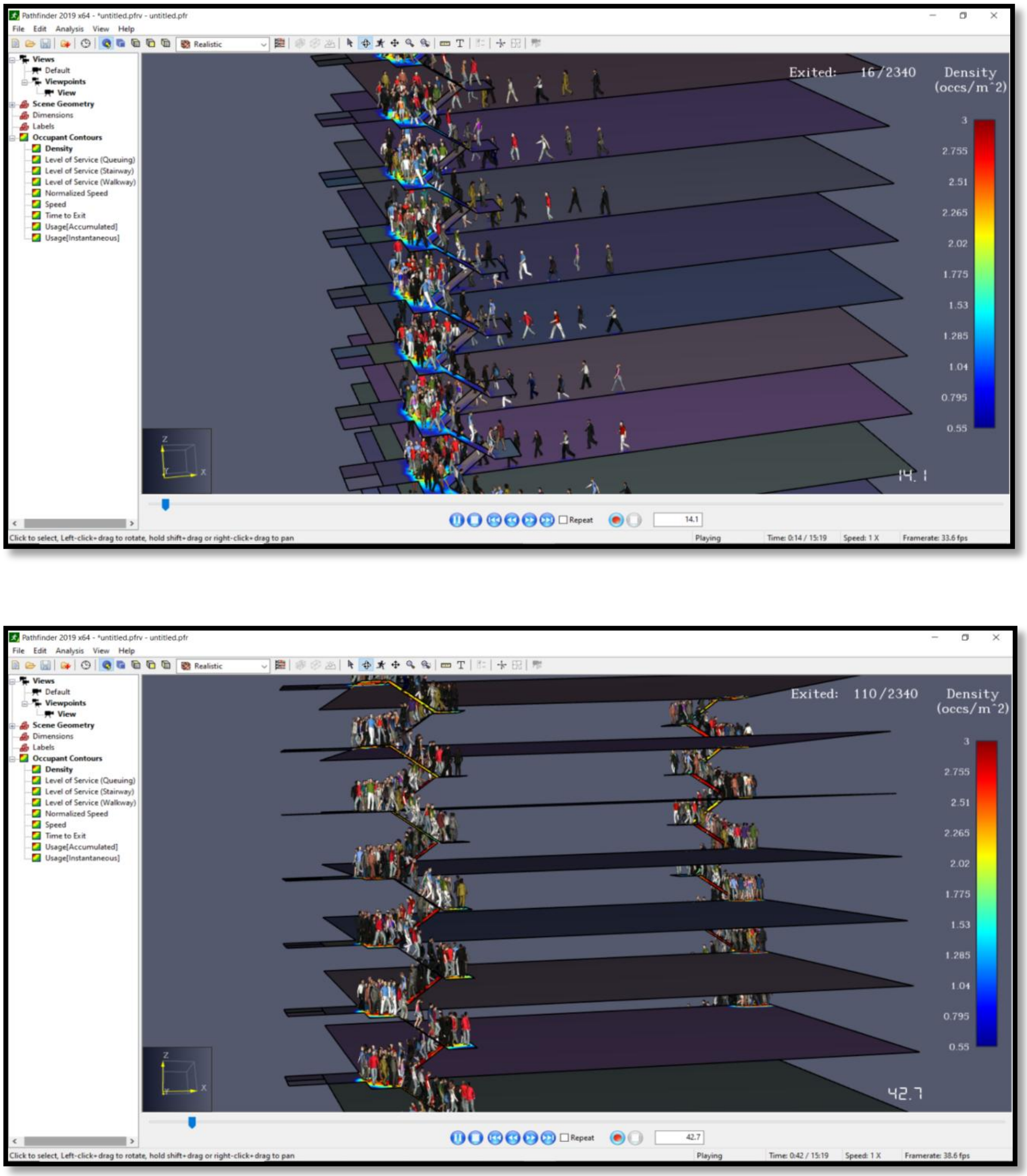
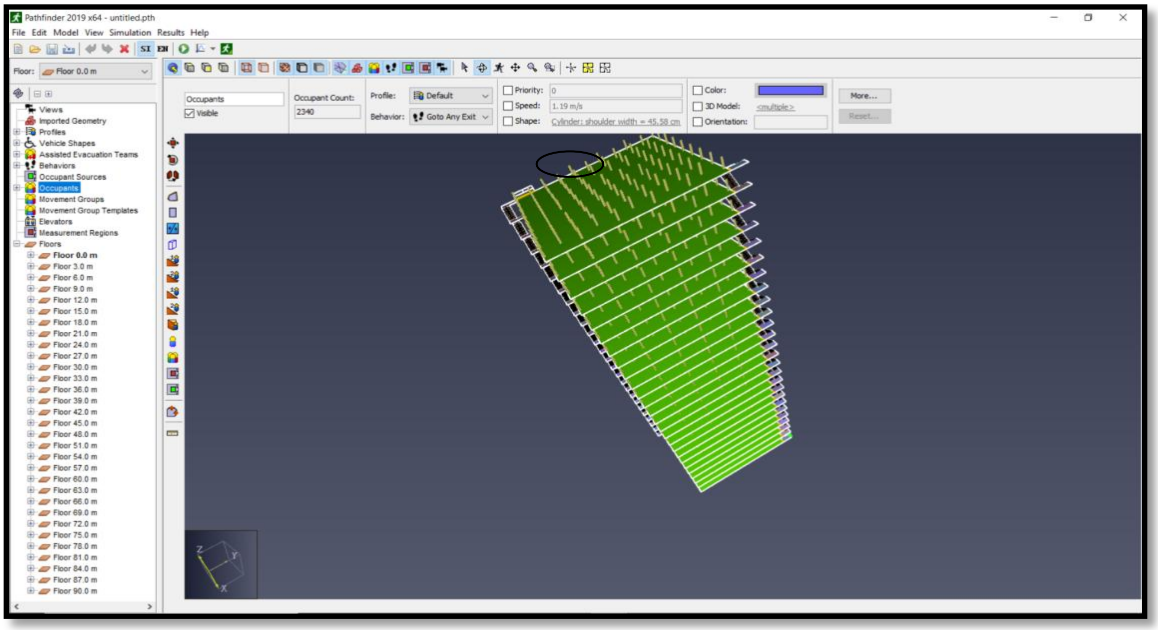


Fig. 2: The snapshot showing people are using other staircase due to congestion as mentioned in section 7.5



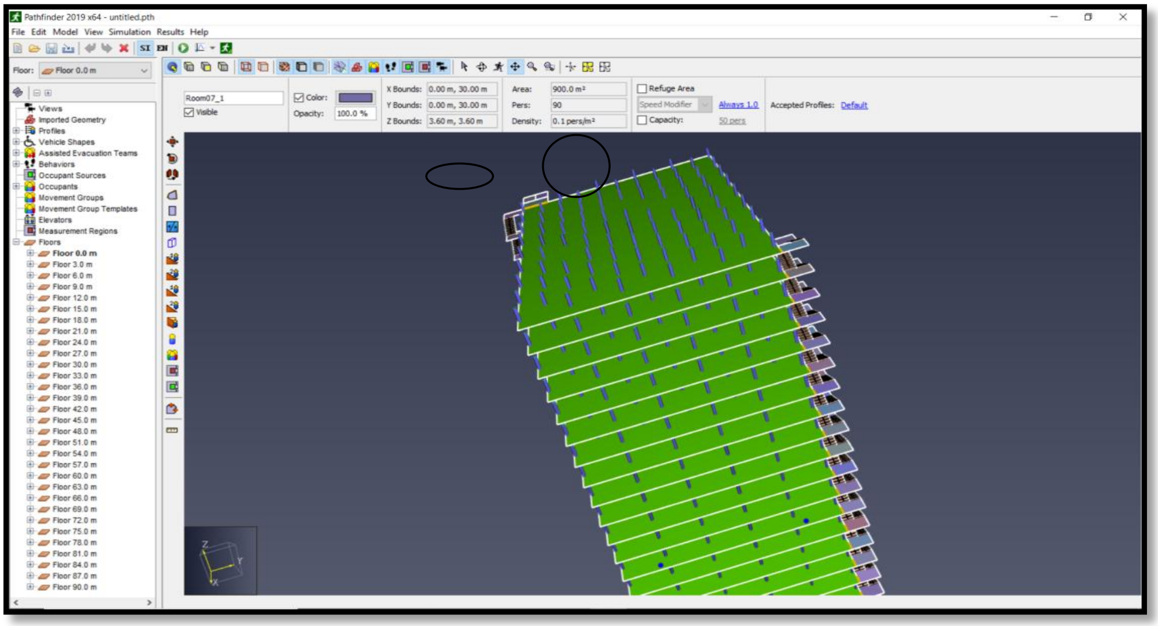
Click to select, Left-click+drag to rotate, hold shift+drag or right-click+drag to pan

Fig. 3: The snapshot showing congestions in the staircase.



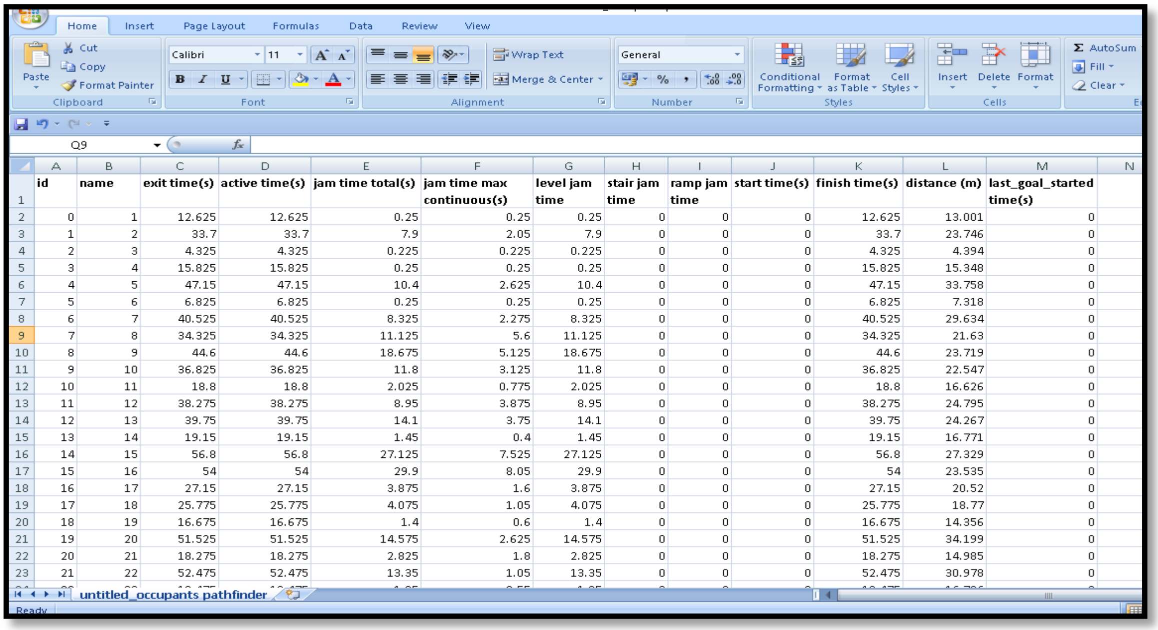
Occupants
☑ Visible
Occupant Count: 2340
Profile: Default
Behavior: Goto Any Exit
☐ Priority: 0
☐ Speed: 1.19 m/s
☐ Shape: Cylinder: shoulder width = 45.58 cm
☐ Color:
☐ 3D Model: <multiple>
☐ Orientation:

Fig. 4: The snapshot showing the speed of the occupants



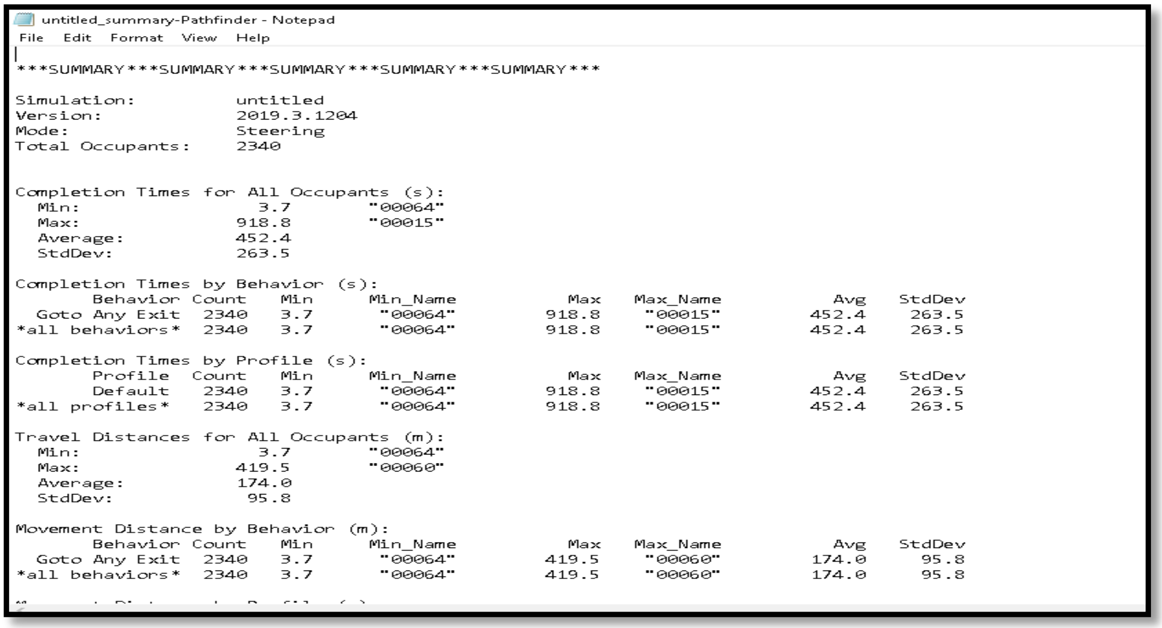
Room07_1
☑ Visible
☑ Color:
Opacity: 100.0 %
X Bounds: 0.00 m, 30.00 m
Y Bounds: 0.00 m, 30.00 m
Z Bounds: 3.60 m, 3.60 m
Area: 900.0 m²
Pers: 90
Density: 0.1 pers/m²
☐ Refuge Area
Speed Modifier Always 1.0
☐ Capacity: 50 pers
Accepted Profiles: Default

Fig.5: The snapshot showing occupant density & floor height



id	name	exit time(s)	active time(s)	jam time total(s)	jam time max continuous(s)	level jam time	stair jam time	ramp jam time	start time(s)	finish time(s)	distance (m)	last_goal_started time(s)
0	1	12.625	12.625	0.25	0.25	0.25	0	0	0	12.625	13.001	0
1	2	33.7	33.7	7.9	2.05	7.9	0	0	0	33.7	23.746	0
2	3	4.325	4.325	0.225	0.225	0.225	0	0	0	4.325	4.394	0
3	4	15.825	15.825	0.25	0.25	0.25	0	0	0	15.825	15.348	0
4	5	47.15	47.15	10.4	2.625	10.4	0	0	0	47.15	33.758	0
5	6	6.825	6.825	0.25	0.25	0.25	0	0	0	6.825	7.318	0
6	7	40.525	40.525	8.325	2.275	8.325	0	0	0	40.525	29.634	0
7	8	34.325	34.325	11.125	5.6	11.125	0	0	0	34.325	21.63	0
8	9	44.6	44.6	18.675	5.125	18.675	0	0	0	44.6	23.719	0
9	10	36.825	36.825	11.8	3.125	11.8	0	0	0	36.825	22.547	0
10	11	18.8	18.8	2.025	0.775	2.025	0	0	0	18.8	16.626	0
11	12	38.275	38.275	8.95	3.875	8.95	0	0	0	38.275	24.795	0
12	13	39.75	39.75	14.1	3.75	14.1	0	0	0	39.75	24.267	0
13	14	19.15	19.15	1.45	0.4	1.45	0	0	0	19.15	16.771	0
14	15	56.8	56.8	27.125	7.525	27.125	0	0	0	56.8	27.329	0
15	16	54	54	29.9	8.05	29.9	0	0	0	54	23.535	0
16	17	27.15	27.15	3.875	1.6	3.875	0	0	0	27.15	20.52	0
17	18	25.775	25.775	4.075	1.05	4.075	0	0	0	25.775	18.77	0
18	19	16.675	16.675	1.4	0.6	1.4	0	0	0	16.675	14.356	0
19	20	51.525	51.525	14.575	2.625	14.575	0	0	0	51.525	34.199	0
20	21	18.275	18.275	2.825	1.8	2.825	0	0	0	18.275	14.985	0
21	22	52.475	52.475	13.35	1.05	13.35	0	0	0	52.475	30.978	0

Fig.6: The snapshot showing first page of occupants’ activity results



```
***SUMMARY***SUMMARY***SUMMARY***SUMMARY***SUMMARY***

Simulation:            untitled
Version:               2019.3.1204
Mode:                  Steering
Total Occupants:       2340


Completion Times for All Occupants (s):
  Min:                   3.7         "00064"
  Max:                 918.8         "00015"
  Average:             452.4
  StdDev:              263.5

Completion Times by Behavior (s):
       Behavior Count    Min      Min_Name        Max    Max_Name         Avg    StdDev
  Goto Any Exit  2340    3.7       "00064"      918.8     "00015"       452.4     263.5
*all behaviors*  2340    3.7       "00064"      918.8     "00015"       452.4     263.5

Completion Times by Profile (s):
        Profile Count    Min      Min_Name        Max    Max_Name         Avg    StdDev
        Default  2340    3.7       "00064"      918.8     "00015"       452.4     263.5
 *all profiles*  2340    3.7       "00064"      918.8     "00015"       452.4     263.5

Travel Distances for All Occupants (m):
  Min:                   3.7         "00064"
  Max:                 419.5         "00060"
  Average:             174.0
  StdDev:               95.8

Movement Distance by Behavior (m):
       Behavior Count    Min      Min_Name        Max    Max_Name         Avg    StdDev
  Goto Any Exit  2340    3.7       "00064"      419.5     "00060"       174.0      95.8
*all behaviors*  2340    3.7       "00064"      419.5     "00060"       174.0      95.8
```

Fig.7: The snapshot showing first page of general summary of the results

SUVEK SALANKAR

EDUCATION:

1995-1998	B.E.(Fire Engineering), National Fire Service College, Nagpur University, Nagpur, Maharashtra
1993-1995	Bachelors in Science , Nagpur University, Maharashtra
2002 -2003	Advance diploma in Industrial Health Safety & Environment , Mumbai
2012	International certificate in occupational Health & Safety from the national examination board of safety & Health, UK

JOURNAL PUBLICATIONS:

1. Salankar S., Tauseef S. M., & Sharma R. K. (2018). “Need for better high rise building evacuation practices”, published in Springer Nature Singapore Pte Ltd. 2018 , N. A. Siddiqui et al. (eds.), Advances in Fire and Process Safety, Springer Transactions in Civil and Environmental Engineering, https://doi.org/10.1007/978-981-10-7281-9_16

2. Salankar S., Tauseef S.M., Sharma R.K. (2021) A New Method for Estimation of Staircase Evacuation Time in High Rise Buildings. In: Siddiqui N.A., Bahukhandi K.D., Tauseef S.M., Koranga N. (eds) Advances in Environment Engineering and Management. Springer Proceedings in Earth and Environmental Sciences. Springer, Cham. https://doi.org/10.1007/978-3-030-79065-3_25

3. “Investigating the best evacuation strategy for a high rise building” ready for submission.

4. “Study of various optimization methods and proposing the best staircase configuration for optimization of the building evacuation time” Ready for submission.