FIRE SAFETY ASSESSMENT OF HIGH-RISE RESIDENTIAL BUILDINGS

by

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To Baba and Inna, my strength and my courage

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ABSTRACT

FIRE SAFETY ASSESSMENT OF HIGH-RISE RESIDENTIAL BUILDINGS

In the present work, the risk of a high-rise residential building fire has been framed in terms of the safety of its occupants. The two parallel processes taking place during a building fire evacuation have been analyzed. The total escape time of occupants during a fire was evaluated based on multiple empirical sources collected worldwide and data specifically on Istanbul high-rise residential occupancy. The evacuation of occupants from a high-rise building was simulated using an agent-based model. Parametric studies were also carried out using a detailed description of the model in order to investigate the influence of certain egress variables on the total egress time and egress performance of high-rise residential buildings. The relative time the evacuees spent in queues on the stairs was used as the standard for measuring the effect of changing a variable on egress performance. Pre-flashover hazard assessment was also performed using a CFD model and the tenability limit was used to analyze the allowable safety egress time and threat posed by fire to the high-rise building occupants. Using the results, a framework for risk characterization of high-rise residential buildings has been presented. This approach can be useful as an aid in quantitative risk analysis of high-rise buildings under fire conditions as well as for other fire safety procedures and building design for fire safety.

ÖZET

YÜKSEK KATLI KONUT YAPILARIN YANGIN GÜVENİĞİ DEĞERLENDİRMESİ

Bu çalışmada, yüksek katlı toplu konut yapılarının yangın sonrası tahliye analizi yapılmıştır. Bir binanın yangın esnasındaki tahliyesi sırasında gerçekleşen iki paralel süreç analiz edilmiştir. Yangın esnasında bina sakinlerin toplam kaçış süresi ve her kattaki sakinlerin bekleme süreleri hesap edilmiş, elde edilen bulgular ile İstanbul'daki yüksek katlı toplu konutlarla ilgili varsayımlar öne sürülmüştür. Sakinlerin yüksek binalardan tahliyesi, ajan bazlı bir model kullanılarak simüle edildi. Tahliye esnasında, merdivenlerde kuyruklarda harcanan bekleme süresi, bir değişkenin çıkış performansı üzerindeki etkisinin ölçülmesinde standart olarak kullanılmıştır. Herhangi bir katta çıkan yangın CFD modeli kullanılarak yapılmış, yangından çıkan toksik gazların sakinlerin tahliye hızlarına etkisi araştırılmıştır. Çıkan sonuçlar kullanarak yüksek katlı konut binalarının risk karakterizasyonu için bir çerçeve sunulmuştur. Bu yaklaşım yangın koşulları altında yüksek binaların yanı sıra diğer yangın güvenliği prosedürlerinde ve yangın güvenliği için bina tasarımında nicel risk analiz yardımcı olarak yararlı olacaktır.

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LIST OF ACRONYMS/ABBREVIATIONS

ASET	Available Safe Egress Time
BYKHK	Binaların Yangından Korunması Hakkında Yönetmelik
CFD	Computational Fluid Dynamics
FLED	Fire Load Energy Density
FDS	Fire Dynamics Simulator
FED	Fractional Effective Dose
FSE	Fire Safety Engineering
FSG	Fire Safety Goals
FSO	Fire Safety Objectives
HRR	Heat Release Rate
OPS	Optimal Performance Statistic
PADM	Protective Action Decision Model
PBFD	Performance-Based Fire Design
PRA	Probabilistic Risk Assessment
RSET	Required Safe Egress Time
RTI	Response Time Index
V&V	Verification and Validation

1. INTRODUCTION

The continuous increase in population throughout the world has been accompanied by a corresponding increase in the number of high-rise buildings in modern and developing cities. In an emergency situation such as the event of fire, a high-rise building poses a safety problem for its occupants as travelling down a long vertical distance can be a complex and challenging task. Between 2007–2011, there have been a reported 15,400 structural fires in the U.S alone claiming an annual average of 46 civilian lives, 530 injuries and $219 million in direct property damage (Hall, 2013). On the other hand, research on fire injuries and deaths has shown that roughly two-third of the injured and half of the dead in building fires could have evacuated had they been given more time to escape (Hall, 2004). Although high-rise buildings account for a lower number of the total fatalities than low-rise buildings of the same type, the number of potential people involved in even a single high-rise building fire makes this a significant issue of interest. This is evident in some of the catastrophic fires in history such as the World Trade Centre terrorist attack of September 11, 2001, and more recently the Grenfell Tower fire of June 14, 2017 in London, which claimed the lives of 72 people.

A less unfortunate incident was the fire that broke out about five years before Grenfell Tower fire in Polat Tower, a 42-storey high-rise structure in Istanbul. It was an office building fire and according to reports, the fire-extinguishing system was activated automatically. Luckily, no lives were lost. However, the suppression of the fire was quite challenging. Also, the construction materials of some of the present-day high-rise buildings allow for fast spread of fire, thus affording relatively little time for the occupants of those buildings to evacuate. The large amount of combustible material in Joelma Building fire in Brazil in 1974 is said to have contributed to the rapid spread of the fire killing 179 people and injuring another 300 (Craighead, 2009). The MGM grand fire which occurred in Nevada in 1980 also killed at least 87 people and injured 650 others (Dailymail, 2012). The need to provide safe spaces for evacuees by understanding their behavior and their environment is therefore crucial, and the safety of these high-rise buildings with regard to the survival of the occupants needs to be evaluated in order to assess the risk and also to plan for safe and innovative future designs.

The field of fire safety engineering (FSE) has grown significantly over the past decades and notable progress has been made in enabling safer structures to be built. Because FSE analysis is an integrated process in which the fire, building uses, and users are considered simultaneously, a multi-disciplinary knowledge from different fields like fire science, architecture, and human physiology and psychology are being synthesized. Engineering tools such as risk assessment and probabilistic methods have also been applied. On the other hand, every building poses a unique challenge due to difference in architecture, construction and occupancy, and research carried out on low-rise buildings does not necessarily extend to high-rise building structures which have become ever more ubiquitous in more and more places. This research aims to contribute to the work done in fire safety taking into account the distinguishing features of high-rise buildings and utilizing the sophisticated computational power that has now become accessible.

According to NFPA, a high-rise building is "a building where the floor of an occupiable story is greater than 73ft (23m) above the lowest level of fire department vehicle access." (Hall, 2013) has categorized building types into three based on their uses – office buildings, residential buildings and health-care facilities. All of these different building categories exhibit different building characteristics from the point of view of infrastructure and population. In this thesis, high-rise residential buildings will be studied. And since the primary fire safety goal of residential buildings, or the ultimate safety goal of any structure for that matter, is life safety, it will be the focus of the study.

1.1. Background

Over the past couple of decades, there has been a shift towards a performance-based design approach in quite a number of countries including the Unites States, the United Kingdom, Australia, New Zealand, Japan and China. In 1985, the British Regulations became completely performance-based, and in the year 2000 a performance-based option was included in NFPA 101. This has allowed for the accommodation of complexity and innovation in design all the while rooting for optimum solutions. Other advantages notwithstanding, this method requires more expertise and careful assessment of the variables involved.

As one of the fastest growing and industrializing nations in the world, Turkey has seen tremendous increase in the number of high-rises built in recent years especially in cities like Istanbul. The fire safety regulation in Turkey, however, still offers a prescriptive approach to fire safety design. The application of performance-based approach to evaluating the life safety of high-rise building occupants in the event of fire will require taking into account the social culture and legislative framework in the Turkish context. While differences in social and fire culture has been shown by (Özkaya, 2001) to influence the amount of time necessary to evacuate people to safety, the majority of available published data used in fire engineering application comes from a small number of countries with broadly similar cultural backgrounds (Galea *et al.*, 2010). With this in mind, fire safety assessment of high-rise residential buildings will be carried out from first principles using the available data on high-rises in Istanbul, and also with occasional resort to fire safety codes when necessary.

Figure 1.1. Grenfell Tower fire (BBC, 2018).

1.2. Scope and Objectives

The aim of this research is to utilize the available concepts of FSE and performance-based approach in order to evaluate the life safety of the occupants of a typical high-rise residential building. Because of the large expected range of evacuation time due to the significant occupant loads and diverse age groups in high-rise residential buildings, the demonstration of a pre-planned evacuation strategy for a building design requires detailed analysis of data. Important variables will be identified, and scenarios will be analyzed from the point of view of the fire incident and residential building occupancy. Using state-of-the-art computational models and data on Istanbul high-rise buildings, the life safety of the occupants will be evaluated. The topic of fire safety in buildings is a complex and vast one ranging from structural integrity to systems design. The major concern here will be the means of egress, i.e. ensuring a reliable and safe escape for people from the fire affected zone to a safety zone, with the assumption that the regulations on other active and passive physical components and systems for ensuring fire safety such as proper compartmentation and use of appropriate building materials are in place. To achieve this, the fire envisaged to occur in a high-rise residential building is modelled using an advanced computational technique – CFD. Likewise, the evacuation time of occupants from this building is also measured considering their interaction with the fire – FED. In the end, the results are used for risk-based analysis which is intended to provide a framework for other fire safety procedures for high-rise residential buildings.

In Chapter 1, the motivation, background and general structure of the thesis is outlined. Chapter 2 then reviews some of the relevant literature available on the topics pertinent to fire safety evaluation. The methodology and theoretical approach as well as the safety assessment criteria used for the study are detailed in chapter 3. In Chapter 4, the analyses and results of the case study residential building are provided. Lastly, Chapter 5 presents the conclusions of the study and general suggestion for fire safety design along with some recommendations for areas of future research.

2. LITERATURE REVIEW

The survival of building occupants from fire is dependent upon two parallel processes:

(i) The developing hazard of the fire; and

(ii) The process by which the occupants escape.

The first process depends on a range of variables such as the fire load and the ventilation the fire receives. Assessment of these processes for any particular scenario is aimed at calculating the time from ignition of the fire to the time when occupants will receive an incapacitating dose to the fire effluent. The duration of this period is known as the available safe egress time (ASET). The second process depends on the provision of warnings, escape routes, behavior of the occupants, and the psychological and physiological effects of heat, smoke and other toxic gases from the fire on their behavior. This is known as the required safe egress time (RSET).

Research on fire safety has focused on the complexities that entail these two processes. In the first section of this chapter, the former process is briefly explored while in the section that follows it, the activities that are involved in the latter are investigated. The subsequent sections then examine the behavioral aspect of evacuation especially the malicious and lethal effect of fire effluents on the evacuees along with methods, strategies and the underlying uncertainties in the evaluation of RSET.

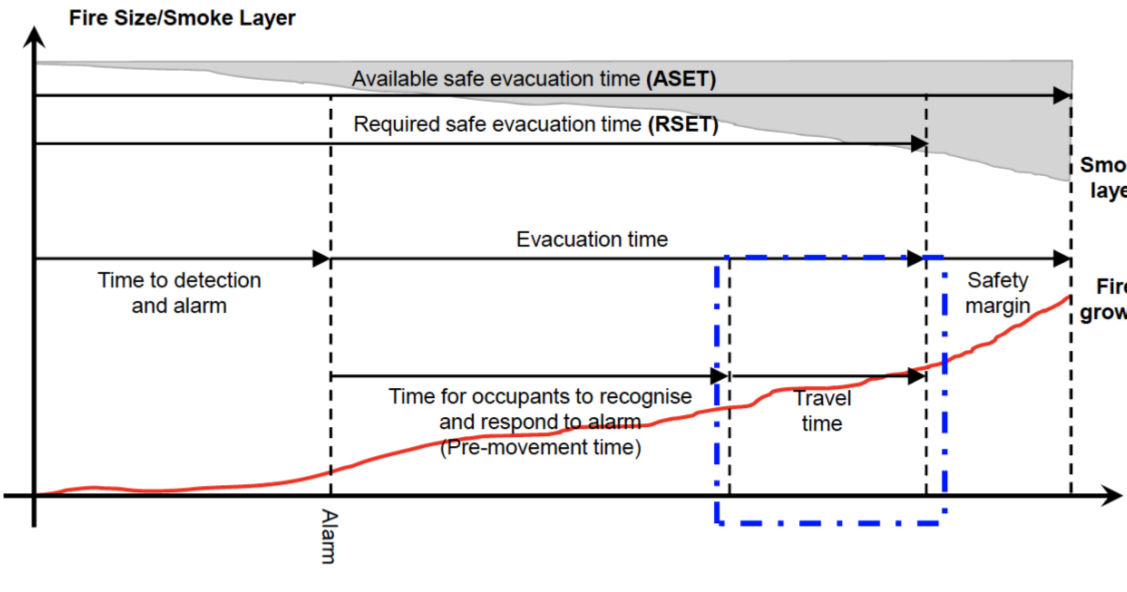


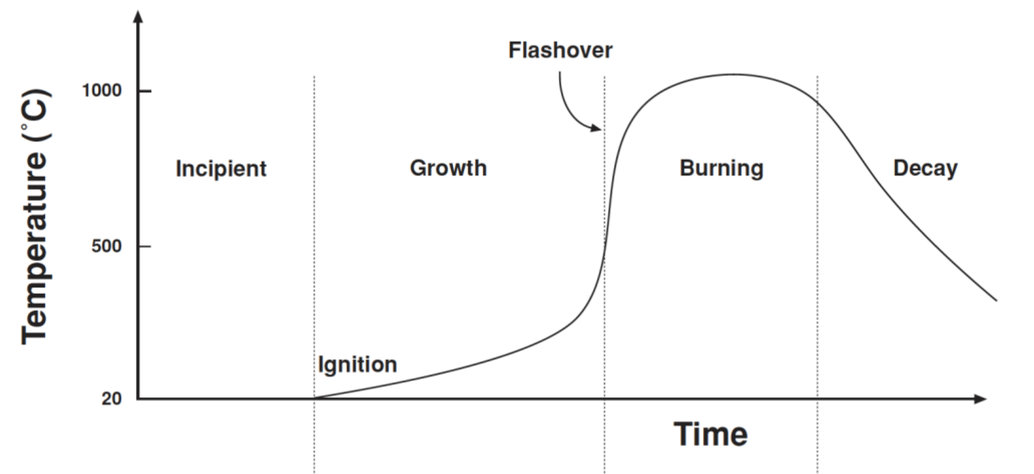
Figure 2.1. Components of fire evacuation analysis (Selamet, 2018).

2.1. Fire Evolution

The development of fire is dependent upon the ventilation it receives, and the fuel load burnt. Ignition is said to begin with the heating of a flammable or combustible material above its fire point. This categorical distinction between combustible and non-combustible materials, however, lacks technical definition for a scientific measure and reflects the fire knowledge of the nineteenth century (Babrauskas and Janssens, 2016). A more useful yardstick for hazard analysis is the Heat Release Rate (HRR) of surface materials. This is the rate at which a combustion reaction produces heat. Measured in kilowatts (kW), HRR is the essential characteristic of the fire fuel that quantitatively describes the magnitude of a fire. It also varies from material to material with higher HRR materials producing faster growing fires.

Over the recent decades, fire science has advanced from simple qualitative descriptions to detailed quantitative measurements of an otherwise complex process. The process of quantifying fire and its impact on life safety and property for each fire scenario is called *hazard analysis*. This involves the calculation of the full process of fire development which includes its initiation, growth and decay. The methods for these calculations can range from low levels of abstraction such as one zone models to the complex mathematical field models. Despite the fact that the governing equations for fluid dynamics, heat transfer and combustion were written down over a century ago, modelling fire is inherently complex and until recently, impractical due to the sheer number of scenarios possible, the computational power required to perform the calculations of all the processes involved and unintended fuel in most fires (NIST, 2013). In large-scale fire applications, convection is the primary mode of transport of heat and combustion products while diffusive processes may play a significant role in the flames and near the boundary layers. Also, due to the computational demand, turbulent models are used in fire modelling, but more detail on this will be delved into in the next chapter.

As Figure 2.2 indicates, all life safety measures must be carried out before the advent of *flashover*, which is the point at which the fire is fully developed, and occupants become either incapacitated by the acrid smoke or trapped within the building to await their inevitable demise. Since all occupants must be saved before flashover occurs, the full fire need not be quantified for life safety evaluation. Pre-flashover fire quantification is very important in ensuring the safe evacuation of occupants. The rate of burning during the growth of the fire is controlled by the surface area of the fuel. With the advancement of computational models, the conditions in a building during fire can be determined using a number of available computer models. Also, one of the measures taken for fire safety is *passive control*, i.e. systems built into the structure not requiring operation or any automatic activation to control the spread of fire. One method of passive control is *compartmentation* where each *fire cell* is completely isolated from another in order to contain a potential fire from spreading for a certain amount of time. In residential flats, each property is enclosed as a separate compartment (Rasbash *et al.*, 2004). The spread of the fire is therefore slowed down, and the fire can be contained within a compartment to allow occupants to escape the hazard. The first component of ASET and RSET from the start of the fire until its detection by the fire alarm or by people/staff is largely determined by the fire detection and alarm systems design. After the fire is detected, the processes that follow will determine the survivability of the potentially threatened occupants.



Stage	Incipient	Growth	Burning	Decay
Fire behaviour	Heating of fuel	Fuel-controlled burning	Ventilation -controlled	Fuel-controlled burning
Human behaviour	Prevent fire	Extinguish by hand, escape	Death	
Detection	Smoke detectors	Smoke detectors Heat detectors	External smoke and flame	
Active control	—	Extinguish by sprinklers or Fire Service. Smoke control	Control by Fire Service	
Passive control	Control of materials	Flammability, surface spread of flame	Fire resistance, containment, prevent collapse	

Figure 2.2. Typical fire development curve (Buchanan, 2001).

2.2. Evacuation Process

The process of transporting building occupants from their position at the time of fire occurrence to safety can be divided into two broad phases namely: the pre-evacuation phase and the evacuation movement phase. The pre-evacuation phase for an occupant is the period after the fire incident before which he/she makes the decision to move to a place of safety. At the beginning of this period, the notification of the occupants of the fire incident marks the beginning of what is known as the recognition phase during which the occupants decide whether or not to evacuate. After this decision is made commences the response phase which ends when the evacuation movement begins.

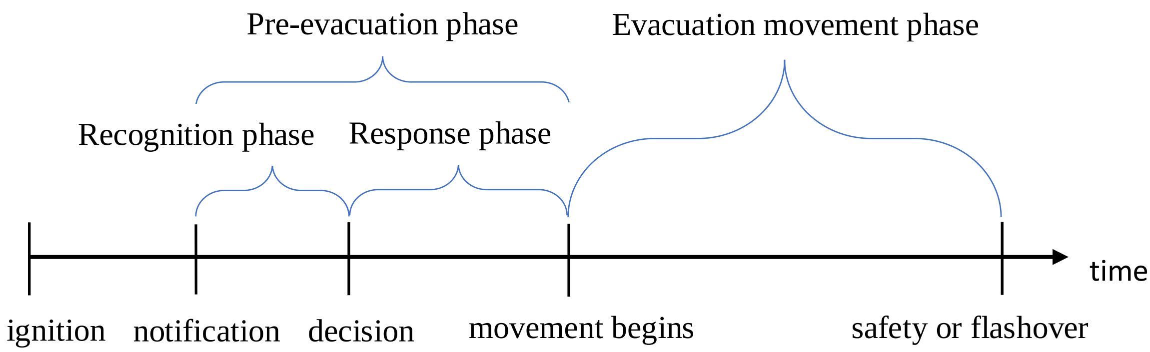


Figure 2.3. Fire evacuation timeline.

During an environmental hazard or disaster, the decision to take action after the acknowledging and comprehending a cue can go in one of three ways:

(i) Re-engage in previous activity;

(ii) Seek additional information; or

(iii) Proceed toward protecting oneself or others.

This model outlined in Figure 2.4, as adapted in (SFPE Task Group, 2019), is based on what is known as the Protective Action Decision Model or PADM (Lindell and Perry, 2012). The PADM is based on several empirical studies on people's response to social and environmental cues. The perception of the fire cues be it from heat or smoke from the environment, or from other sources like alarm, staff or fellow occupants will determine one's decision to protect oneself. (Galea *et al.*, 2010) also employed a similar model in developing a framework for representing the impact of culture on response phase behavior. The stages of evacuation are not one step processes and they do not necessarily occur sequentially. There may be overlap but for simplicity all actions carried out from the start of the fire, cognitive or otherwise, before the activity of moving oneself toward the path of egress is categorized in the pre-evacuation phase. The physical activities in preparation for egress after responding to fire cue are called pre-evacuation actions.

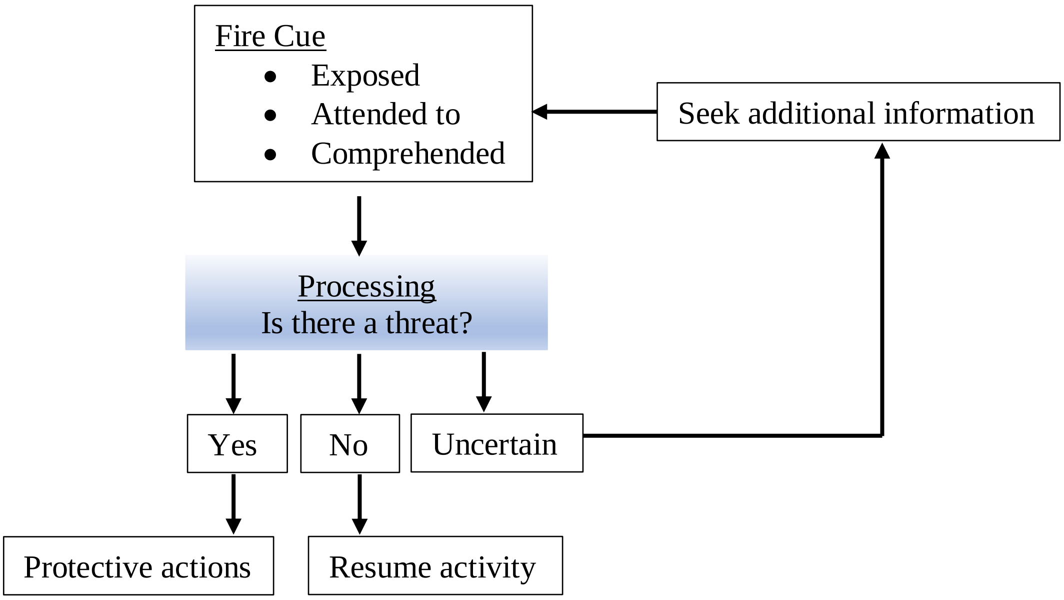


Figure 2.4. Protective Action Decision Model for building evacuation.

Pre-evacuation times are generally higher in residential buildings than in other building types for the reason that the occupants in these buildings may be asleep or in a state not ready for evacuation. Occupants in residential buildings also exhibit re-entry behaviors or reluctance to leave the structure due to emotional ties with the it (Proulx, 1995). Moreover, compartmentation makes information spread and communication of warning slow. (Kuligowski and Mileti, 2009) studied the pre-evacuation delay by occupants in World Trade Centre Towers 1 and 2 on September 11, 2001 using a quantitative method of data analysis known as path analysis. This method seeks to highlight correlations – not necessarily causations – between variables by identifying significant paths of influence among two variables while controlling all other variables in the model. The factors that influence pre-evacuation delay from community disaster evacuation theories were identified. The six variables influencing the pre-evacuation delay relate to the characteristics of the crisis situation and of the people who experience the event. They are as follows:

(i) environmental cues (e.g. smoke, heat, etc.);
(ii) proximity from safety (i.e. floor level of the occupant);
(iii) obtaining information (receiving information without seeking e.g. from other occupants);
(iv) perceived risk (perception of the seriousness of the event);
(v) seeking additional information (milling behavior to make sense of the situation); and
(vi) pre-evacuation actions (number of actions performed before evacuating).

It was found that the three factors with the strongest direct influence on pre-evacuation delay were environmental cues, floor level and obtaining information. Also, across both towers, floor level and environmental cues were the strongest predictors of perceived risk. But most importantly, the strongest predictor of pre-evacuation actions in both towers was the floor level of the occupant. This means that people on the lower floors tended to underestimate the risk involved more than those on the higher floors. In short, occupants on different floors exhibited different pre-evacuation behaviors, with higher floor occupants having a higher normalcy bias. An evacuation like this one will tend to produce congestion and bottlenecks at the escape stairs.

The movement phase is the stage in which human physiology and the egress system is taken into account. Data on the demography and speed of the population are applied to track the movement of individuals through the egress paths. Means of egress in the US codes consists of three components namely: the exit access, the exit itself and the exit discharge. The exit access leads to the exit; rooms, doors and corridors lead to the exit doors, stairs and/or evacuation elevators. In the Turkish fire regulation, however, emergency lifts are only used for fire-fighting procedures while escape stairs are used as egress exits. The exit to the public way or the housing precinct where safety is sought is fulfilled with the exit discharge. This is illustrated in Figure 2.6. These paths provide the surrounding in which movement of escaping evacuees takes place. Turkish fire safety code, BYKHY, also requires the exit stairs to be at least 120cm in high-rise buildings. The escape route, according to BYKHY, is defined as the “entirety of continuous and unobstructed way from any point inside of a building to the street at ground level.” The escape is divided into the following components:

(i) Escape from rooms to independent areas;

(ii) Hallways and similar passages in each floor;

(iii) Floor exits;

(iv) Stairs to the ground floor;

(v) In the ground floors, the ways from the stair head in each floor to the final exit at the same floor and;

(vi) Final Exit.

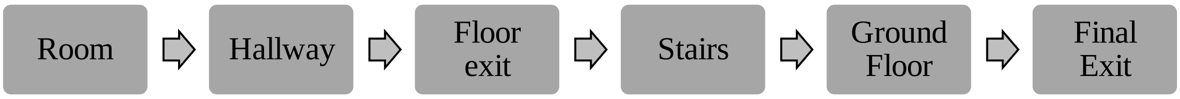


Figure 2.5. Egress components in the Turkish Code.

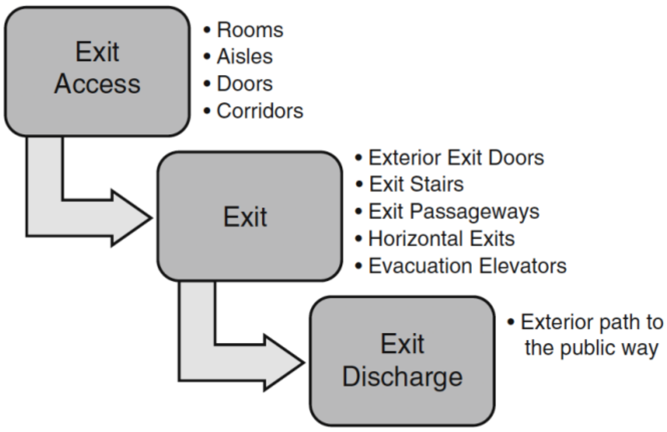


Figure 2.6. Egress components in the US codes (Gwynne and Rosenbaum, 2016).

The movement response parameters of evacuation are largely determined by the behaviors the evacuees exhibit. Understanding the behavior of people and their coping strategies at different stages of the evacuation taking into account the circumstance and environment from which they are trying to escape is therefore necessary in order to properly plan the means by which they can escape in case of such an emergency. The view that people will panic for instance, will influence the notification procedures employed. People need information to act. In Grenfell Tower fire, for instance, the residents were asked to 'stay-put' but due to the fast spread of the fire, the fire brigade were not able to handle the rapidly diffusing blaze. The social science discipline of ergonomics, also known as human factors, can help in incorporating the behaviors people exhibit in fire. Human behavior is undoubtedly a key factor in determining the nature of the evacuation process and it is to this we turn to the next section.

2.3. Human Behavior in Fire

Human behavior in fire is one of the most challenging areas of FSE in part because its study is highly multi-disciplinary. It is also one of the key determinants of egress performance and more emphasis is given to it nowadays (Kobes *et al.*, 2009). A comprehensive review is therefore well beyond the scope of this project. From the time research in human behavior in fire began some decades ago, several theories have since been developed from both quantitative and qualitative data to explain how people will react in fire. Over the years, some of the claims made were subsequently refuted and are now labelled as disaster myths. These myths, sometimes applicable for some a small minority of the population, when generalized for the entire population do not hold true (Kuligowski, 2016a). One characteristic misattributed to people in fire is panic or selfish competition. In his review of human behavior in fires in the U.K., (Ramachandran, 1990) concluded that “people often act inappropriately but rarely panic or behave irrationally.” Another discarded myth is that fire emergency immobilizes people with fear and shock rendering them unable to cope with the situation. Furthermore, the idea that the population as a group exhibit response which is the sum of individual responses has also been shown to be an oversimplification (Kuligowski, 2016a). The population is more likely to manifest a division of labor based in their experiences and relationship in the group in order to facilitate the evacuation process.

Also, building occupants seldom head directly toward the exit after the perception of a cue to evacuate. In fact, it is now widely accepted that pre-evacuation behavior is a key factor in determining the success of an evacuation (Galea *et al.*, 2015). The manner in which the population responds as a whole depends on many factors including whether they are alone or with others upon the reception of the cue, especially if it is an ambiguous one (Proulx, 2001). Other factors include age and gender distribution. According to (Oven and Cakaci, 2008), men are more likely to fight the fire while women are more likely to engage in protecting families and calling fire department. (Purser and Bensilium, 2001) have shown that pre-evacuation times can be represented using a log-normal distribution. Numerous data-sets also support this theory. Data of 51 students collected by (Galea *et. al.*, 2011) from an unannounced evacuation trial in a library in Izmir Turkey, for example, confirms this as shown in Figure 2.7. The length of pre-evacuation time may also depend on the alarm notification system since some alarms are less ambiguous than others.

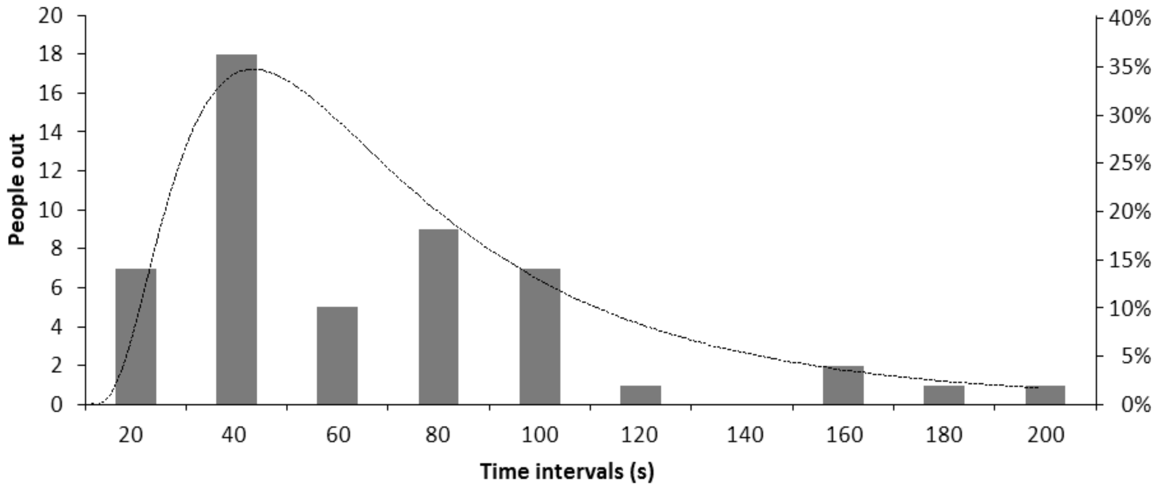


Figure 2.7. Response Time distribution of a Turkish sample (Galea *et al.*, 2011).

From the point of view of occupant physical abilities, movement time is a function of only the occupant travel speed and the distance to the exit discharge – see Figure 2.13. However, the process of evacuation is a more complex one. Since other evacuees need to be taken into account and due to congestion, queue will be formed especially in densely populated areas. (Galea *et al.*, 2008) posits that floors linked to the landing on sides adjacent to the incoming stair rather than on the more common opposite side as shown in Figure 2.8 can maximize the flow efficiency of high-rise building evacuations. It was observed that connecting the incoming stair to the adjacent stair favors the merging process of the floor population.

One model used to represent the flow of people through the egress components is the *hydraulic model*. According to the hydraulic analogy, the rate of flow of people is a function of the width of the component and the density of people moving through. The determinant of the speed at which evacuation occurs is the density of the population. As will be discussed later in this chapter, this simplistic model, although handy, assumes the egress components will be used at a maximum capacity and do not take into account other factors such as human behavior. Recent computer programs, on the other hand, allow the conversion of architectural drawings into a network of nodes and the traverse time between the nodes is calculated from the speed of movement based on lattice-gas model (Oven and Cakici, 2009). This mesh of individual cells makes possible the incorporation of human behavior on the evacuation movement as well as the effect of the dynamic environment resulting from the developing fire.

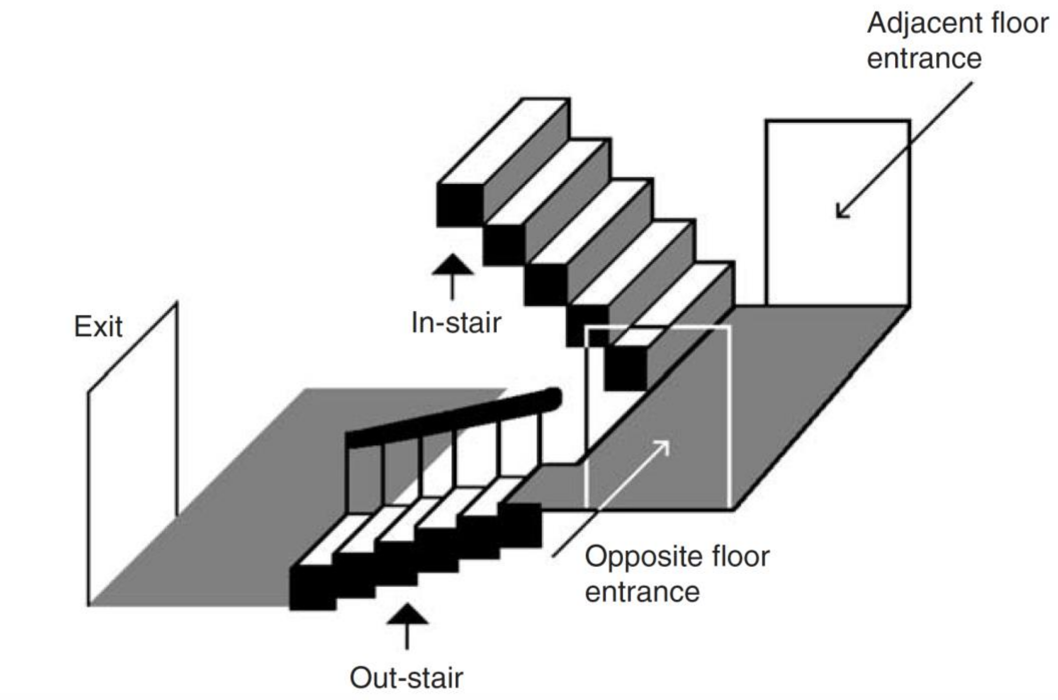


Figure 2.8. Adjacent and opposite floor-stair interface connections (Galea *et al.*, 2008).

Factors arising from the development of the fire contribute to deterioration in speed. The effluent resulting from fire have effects on the occupants' visibility and movement abilities. At a certain point, some occupants' movement is completely stagnated. The tenability limits for these occupants is the time of incapacitation at which these occupants are unable to escape (Purser and McAllister, 2016). Not much research is available on the effect of these gases, but the gases identified to influence movement are discussed next.

2.4. Psychological Effects of Fire Effluents

Fire produces heat, smoke and toxic gases which when inhaled up to a sufficient dose that may cause one to become confused or lose consciousness. The depletion of Oxygen due to fire and flame spread may also lead to conditions known as asphyxiation or hypoxia causing suffocation. RSET is said to end when conditions within the building exposed to fire become untenable. At this point, occupants are unable to escape either due to death or incapacitation. The two major asphyxiants are carbon monoxide (CO) and Hydrogen Cyanide (HCN). CO in blood is expressed as a percentage of carboxyhemoglobin (%COHb), the combination of carbon monoxide and hemoglobin, while the rate of HCN uptake into the brain is the main determinant of HCN incapacitation (SFPE, 2017). Across a population, the tolerance of lethal agents is different. The distribution shown in Figure 2.9 is based on data from the SFPE Handbook. Another important effect of fire is the Carbon dioxide (CO_2) present which increases the rate at which these toxic gases are taken in, thus shortening the time to incapacitation. Although not toxic at concentrations up to 5%, CO_2 stimulates breathing; at 3%, the respiratory rate is approximately doubled and at 5% it is tripled (SFPE, 2017).

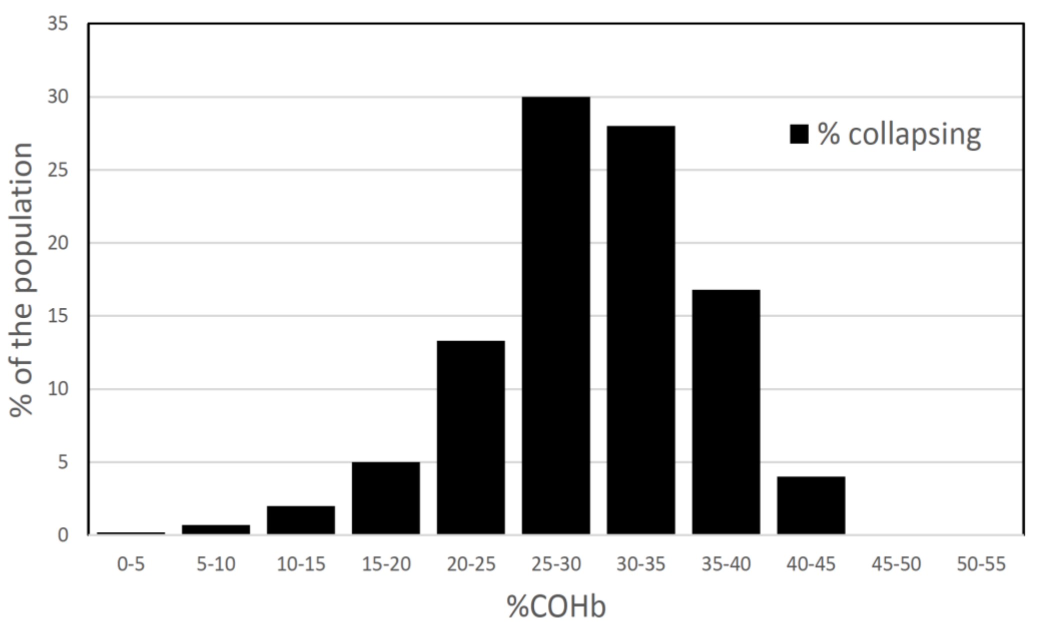


Figure 2.9. Population distribution of CO sensitivity to cause incapacitation (Purser and McAllister, 2016).

Furthermore, exposure to the convective and radiative heat generated by the fire influences the speed and mobility of evacuees. Heat exposure may also lead to burns, heat stroke or some form of damage to the body. In addition to the rise in temperature, fire produces irritant gases harmful to the skin and a limiting exposure to will also scorch the skin and cause irritation. Irritant gases include Hydrogen Chloride (HCL), Hydrogen Bromide (HBr), Hydrogen Fluoride (HF), acrolein (CH_2CHO) and formaldehyde (HCHO).

Smoke layers in the early stage of fire reduce the visibility of evacuees. As the visibility in smoke is decreased, people are less likely to move through an exit route (Hurley and Rosenbaum, 2015). However, the lack of visibility does not incur a direct physiological effect, nor does it totally prevent evacuees from moving (SFPE, 2017). Several visibility distances have been suggested from as low as 1.2 m to as high as 20 m and fixed visibility threshold cannot provide certainty that an evacuee will use a route (SFPE, 2017). In a recent study, however, (Fridolf *et al.*, 2019) proposed three methods for representing evacuation in smoke-filled transport systems all of which assume a visibility threshold of 3m at which evacuees move with unobstructed speed and a minimum speed of 0.2m/s. Visibility distance may be derived from a CFD solution using the predicted concentration of soot particles. This is currently implemented in CFD models and is expressed as follows.

$$S = \frac{K_1}{K_2 m_s} \tag{2.1}$$

where K_1 is a constant usually set to 3 for illuminating signs and 8 for reflected ones

K_2 is the specific extinction coefficient, often taken as 7.6 m^2/g for flaming combustion

m_s is the mass concentration of soot particles in g/m^3.

Using the above formulation, the threshold visibility will occur at a mass concentration of 2.85 g/m^3 of the soot particles for reflected signs and 7.6 g/m^3 for illuminated signs. (Hurley and Rosenbaum, 2015) have given the table of the visibility distances for British and U.S. populations from the data collected by Bryan J. As Figure 2.10 and Figure 2.11 show, the visibility distance at which people moved through smoke or initiated a turn-back behavior is different for different populations. It can also be observed from both figures that more people initiate a turnback behavior than move through smoke for when the visibility distance is very low.

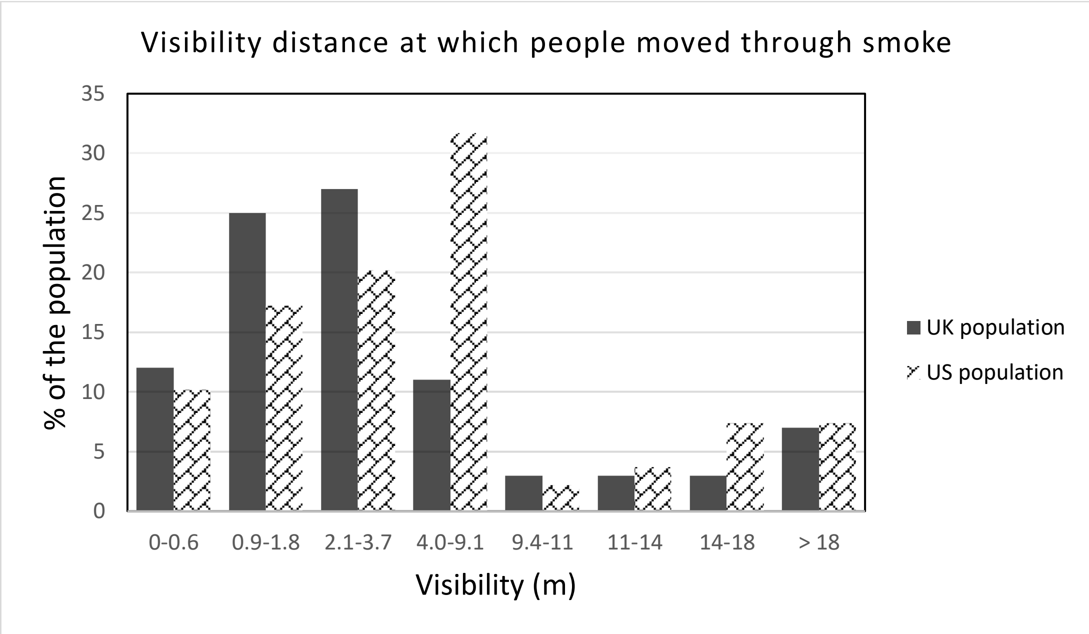


Figure 2.10. Visibility distances at which people moved through smoke.

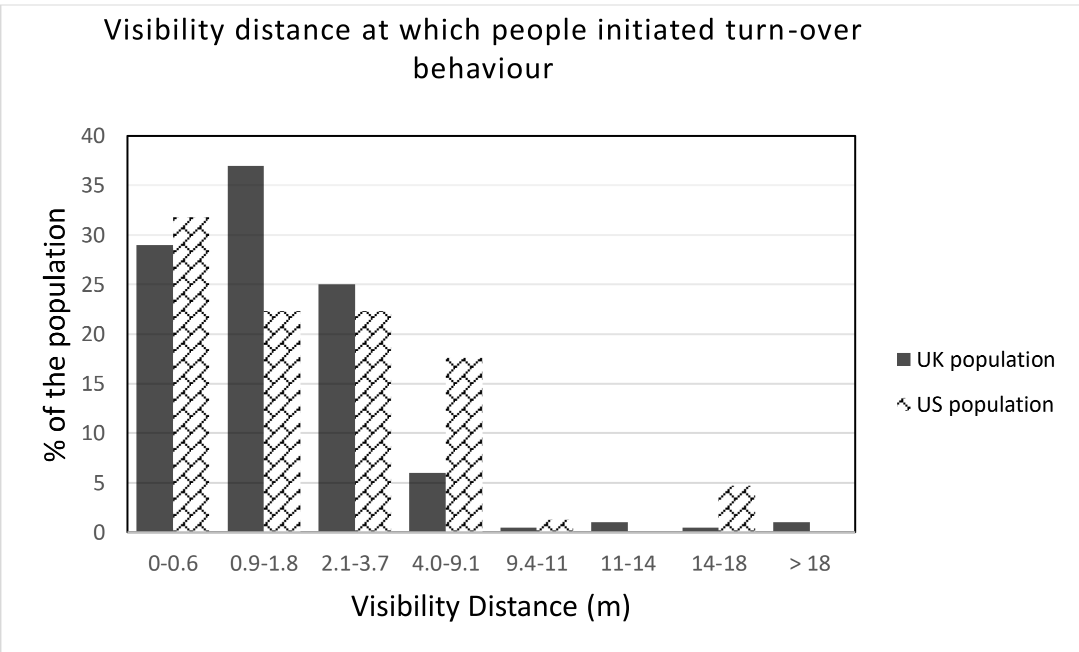


Figure 2.11. Visibility distances at which people initiated a turn-back behavior.

As the fire grows in size, the probability of escape diminishes. Analysis of life safety is made by envisaging probable scenarios and evacuation strategies planned for these events before tenability limits are reached. Using either a deterministic method of analysis which describes hazards in terms of their consequences, or a probabilistic method which takes into account the distribution of the input variables, safety can then be demonstrated or, more appropriately, quantified. (Oven and Cakici, 2008) have investigated the impact of fire on the lives of occupants on different floors. Fire on lower floors is said to have more devastating consequence on the occupants of upper floors especially on congested stairs.

Before the discussion of uncertainty and randomness, the method for modelling egress strategies are reviewed next. There are several ways of approaching the issue, but it is worth noting that evacuation is not deterministic even if deterministic models are used to represent it and so a perfect model may not exist but taking into account ergonomics, group behaviors and the rest of the factors affecting the process can produce helpful results that can be used in studying egress in fire. A numerical example is also given within the next section. The effect of these toxic agents on evacuees is presented in detail in the next chapter.

2.5. Egress Modelling Methods

As with any model, egress models are an approximation of the real world. The methods used to model the egress performance of buildings as well as other structures can range from qualitative descriptions of the egress performance to mathematical models of several egress variables. These methods can be grouped into three categories: empirical method, manual engineering method and computer modelling method (Gwynne and Rosenbaum, 2016). Although, they do not all have the same level of accuracy, each one has its own set of advantages. They are also sometimes applied in conjunction with one another. In the empirical approach, data collected from a built structure comparable to the one to be modelled is extrapolated to predict the building's egress performance. In situations where comparison needs to be made between the egress performance of different structures, this method is quite useful. For example, two buildings with similar geometry and number of floors having similar occupancies will be said to produce similar egress characteristics in case of similar fires. The main concern is that careful deductions must be made based on the available information and the similarity of the buildings. Results produced through other means can be applied elsewhere and sometimes certain aspects can even be generalized for buildings of similar use. For detailed analysis of egress variables, however, other modelling methods are used. Like other scientific methods, empiricism is the basis for other egress modelling methods and egress trials performed on previous structures are used as basis for developing the models of future structures.

2.5.1. The Hydraulic model

The hydraulic model is used to represent the egress from people from an environment. According to the model, the population moves from one egress component (e.g. a room or corridor) to another. The data collected on the movement characteristics of people in fire is applied at the component level by means of sets of equations. All the evacuees are assumed to start evacuating at the same time and all exit paths are continually used at maximum capacity from the moment of alarm to the time of total evacuation. For this reason, this method is an inherently optimistic estimate of the evacuation time since human behavior is such that the interaction of many occupants produces delays and the use of the egress components is not completely efficient. For each evacuee, RSET is divided into a number of time intervals that define different phases of egress. This method can be extended to account for the delays caused by human decisions, notifications and so on.

Although not all the factors influencing the egress performance are represented in this model, the core components that make up RSET are, and each one constitutes a different phase of process.

$$RSET = t_d + t_n + t_{p-e} + t_e \quad (2.2)$$

where t_d is the time from ignition to detection, i.e. the detection phase

t_n is the time from detection to notification, i.e. the notification phase

t_{p-e} is the time from notification until movement starts, i.e. the pre-evacuation phase

t_e is the time from the start of movement until safety is reached, i.e. the evacuation phase.

The first two phases are related to the fire detection system and/or staff, if available, in the building. Properly designed flame, heat or smoke detection systems with early warnings will produce less time during these phases. In the design of heat detection systems, the detectors are spaced at intervals specified by codes, NFPA 72 for example, so that the fire can be noticed at an early stage. The time it takes these passive systems to detect heat from fire relate to the time it takes for the fire to produce a certain temperature. This, of course, is directly related to the HRR of the fuel. The sensitivity of the detector or sprinkler can be expressed in terms of a heat transfer function known as Response Time Index (RTI) which assumes that height is proportional to the gas velocity ($h = Cu^{1/2}$) (Schifiliti *et al.*, 2016).

$$RTI = \frac{t_r u_o^{1/2}}{\ln\left[(T_g - T_a)/(T_g - T_r)\right]} \tag{2.3}$$

where RTI is the response time index in $m^{1/2}s^{1/2}$

t_r is the response time of the detector

u_o is the reference velocity of the gas in m/s

T_g is the temperature of the gas heating the detector in ˚C

T_a is initial (ambient) temperature of the detector in ˚C

T_r is response temperature of the detector in ˚C

The above equation is derived from the lumped thermal approximation of the energy equation. The energy equation in lumped approximation is as follows.

$$\frac{\mathrm{dT}}{\mathrm{dt}} = -\frac{h_c A}{\rho V_c}(T - T_\infty) \tag{2.4}$$

where $h_c A(T - T_\infty)$ is the heat transfer rate to a body from Newtons' law of cooling; $\frac{h_c A}{\rho V_c}$ is defined as the characteristic time which provides an estimate of the time required for the non-dimensional temperature to reach its steady value.

To put this formulation into perspective, with a sprinkler head with a diameter of 4 mm and length of 12 mm, it will take about 243 seconds for the fuse to open if the activation temperature is 80˚C (Ezekoye, 2016). (Heskestad and Bill, 1988) have shown that this relatively simple solution of the characteristic time is important for estimating the temperature of the sensing element (or "link") of an automatic sprinkler.

For t-squared fires in which the increase in HRR is proportional to the squared of time from ignition, (Evans and Stroup, 1985) have devised methods to calculate the detection time comparable to NFPA 72. For HRR of 1MW and a detector RTI of 370.34 $m^{1/2}s^{1/2}$, the detection time was computed to be about 300 seconds. The type of alarm system also affects the pre-evacuation time. According to (Shi *et al.*, 2008), a single-stage central alarm system located on corridors and stairs generate more than three times the pre-evacuation time as a two-stage fire alarm system in every apartment. The former produced a pre-evacuation time of 502 seconds while the latter produced only 150 seconds.

The pre-evacuation phase is evaluated from data on human behavior in fire. It is a function of the nature of the building occupants. The last phase, the evacuation phase, is when the evacuation movement takes place, and this essentially is what is model equations describe. The sum of the two evacuation phases is known as the escape phase.

$$t_{esc} = t_{p-e} + t_e \tag{2.5}$$

Given the varying conditions present at different locations in the building, the different levels of information available and the differences in the abilities of the evacuees, these two phases occur non-sequentially and there may be significant overlap.

The equations of the hydraulic model used in the calculation of the evacuation time (t_e) relate the following parameters: the effective width, population density, speed flow characteristics (specific flow and calculated flow), time for passage through a component and transitions between components. Although the expressions indicate absolute relationships, there is considerable variability in the data. For example, one can observe in Figure 2.12 variability in the data relating speed of evacuees to the density on stairs. In summary, the movement of evacuees is dependent upon the travel speed, the distance to the exit discharge and the effective width of the egress component. The latter two are aspects of the egress component and the former, travel speed, is a physiological attribute of the evacuee. Travel speed is a function of the population density which is a function of the total population of the occupants. This relationship is summed up in Figure 2.13.

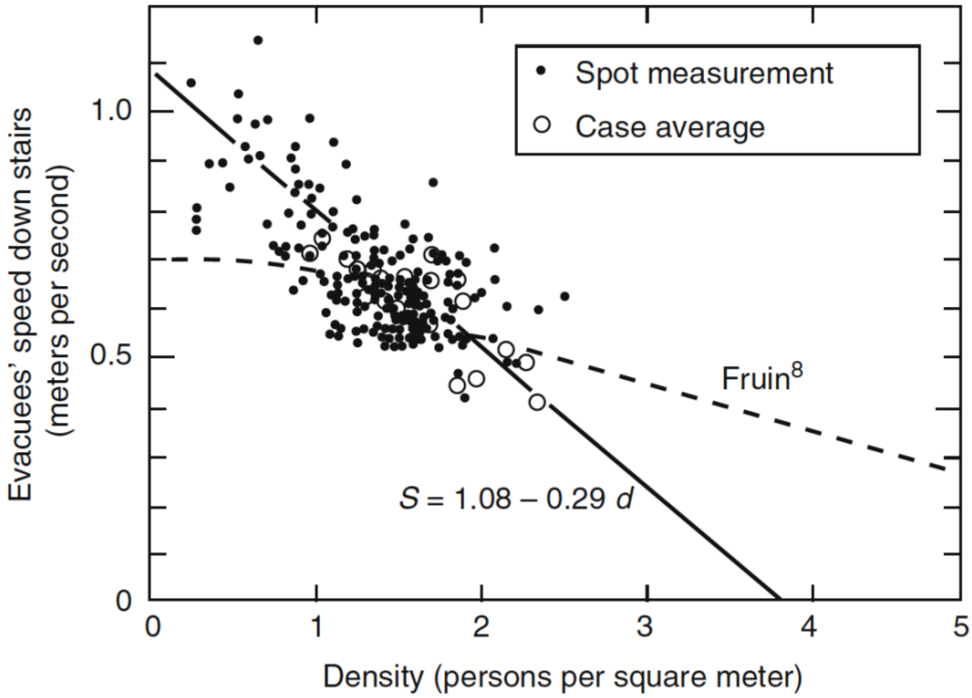


Figure 2.12. Relation between speed and density on stairs in uncontrolled total evacuation derived from Fruin (Pauls, 1987).

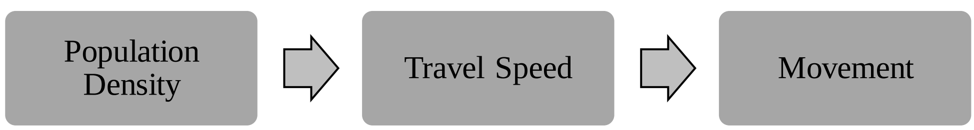


Figure 2.13. Relationship between evacuee movement characteristics.

Effective Width, W_e, is the usable width of the component. Evacuees maintain a boundary layer clearance between themselves and other objects as the pass. This clearance is needed to accommodate lateral body sway and assure balance. The useful effective width of an exit path is the clear width of the path less the width of the boundary layers. Figure 2.14 illustrates the effective width of stairs in relation to walls and handrails, and Table 2.1 gives the boundary layer widths of different egress components.

Population density, *D*, is the degree of crowdedness in an evacuation route. Expressed in person per square meter, it is dependent upon size of the individuals present. However, for simplicity the sizes are averaged across the population. The relationship between the speed of an evacuee and the population density is based on the data shown in Figure 2.12.

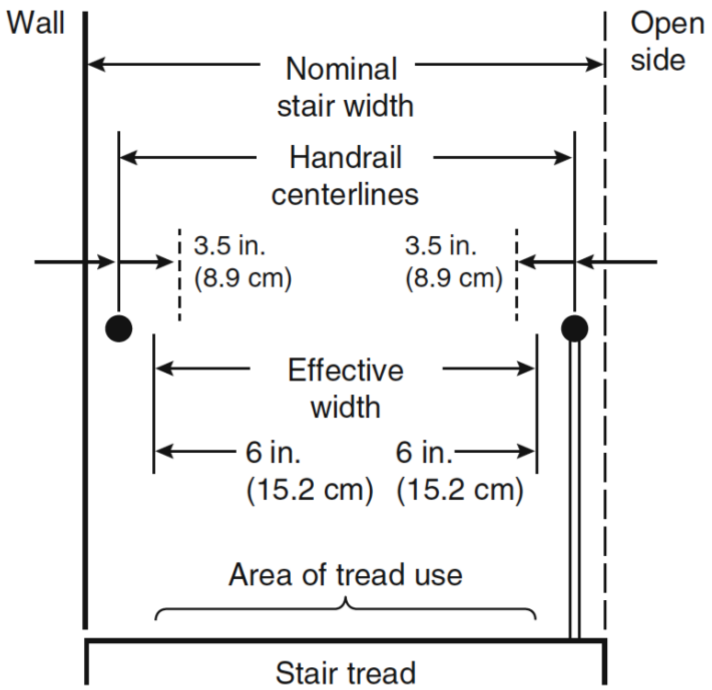


Figure 2.14. The effective width of stairs in relation to walls and handrails (Gwynne *et al.*, 2016).

Table 2.1. Boundary layer widths (Gwynne *et al.*, 2016).

Exit Route Element	Boundary Layer (cm)
Stairways – wall or side of tread	15
Railings, Handrails	9
Corridors	20
Obstacles	10
Door, archways	15
Wide concourses or passageways	46

Speed, *S*, is the movement rate of the exiting individuals. As Figure 2.13 shows, this parameter is dependent on the population density. Furthermore, it is assumed that when the population density is less than approximately 0.54 person/m^2 of the exit route, individuals move at their own pace. If the population density exceeds 3.8 persons/m^2, it is assumed that no movement will take place until enough crowd has passed and the population density is reduced (Gwynne *et al.*, 2016). In between these two values, the speed is represented by the linear function given in equation 2.6.

$$S = k - akD \tag{2.6}$$

where k is a constant dependent on the height and width of the stairs

a = 0.266 for speed in m/s and density in persons/m^2.

Table 2.2. The k constant for evaluating evacuation speed (Gwynne *et al.*, 2016).

Exit Route Element		k
Corridor, aisle, ramp, doorway		1.40
Stairs		
Riser (in.)	Tread (in.)	
7.5	10	1.00
7.0	11	1.08
6.5	12	1.16
6.5	13	1.23

It can be observed from Figure 2.15 that at a population density of about 3.8 persons/m^2, no movement occurs. Increase in population density beyond 4 persons/m^2 may lead to crush conditions (Pauls, 1987).

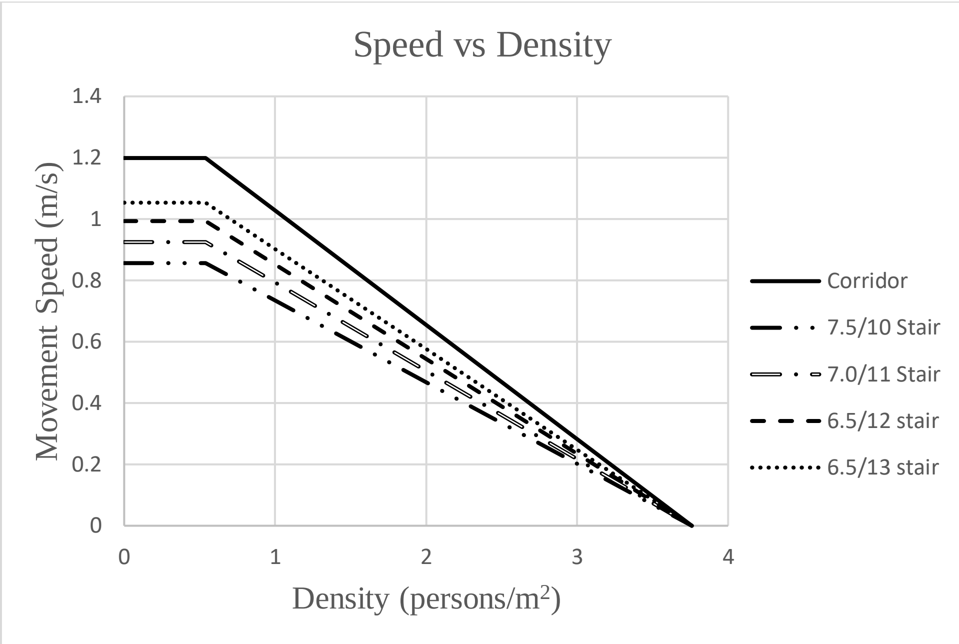


Figure 2.15. Speed vs density relationship for various egress components.

Specific flow, F_s, is the flow of the evacuating persons past a point in the exit route per unit of time of W_e. Specific flow is expressed in person/s/m of the effective width.

$$F_s = SD \tag{2.7}$$

$$F_s = (1 - aD)kD \tag{2.8}$$

From equation 2.8, it can be observed that the second order quadratic equation yielded will produce a maximum specific flow at a certain density. Solving equation 2.9 using the k values of each egress component, the maximum specific flow occurs at a density of about 1.9persons/m^2. For the corridors, this value is around 1.33 person/s/m. This is shown in Figure 2.16.

$$F_s = -0.266kD^2 + kD \tag{2.9}$$

Calculated Flow, F_c, is the predicted flow rate of persons passing a particular point in an exit route. It is expressed in persons/s.

$$F_c = F_s W_e \tag{2.10}$$

$$F_c = (1 - aD)kDW_e \tag{2.11}$$

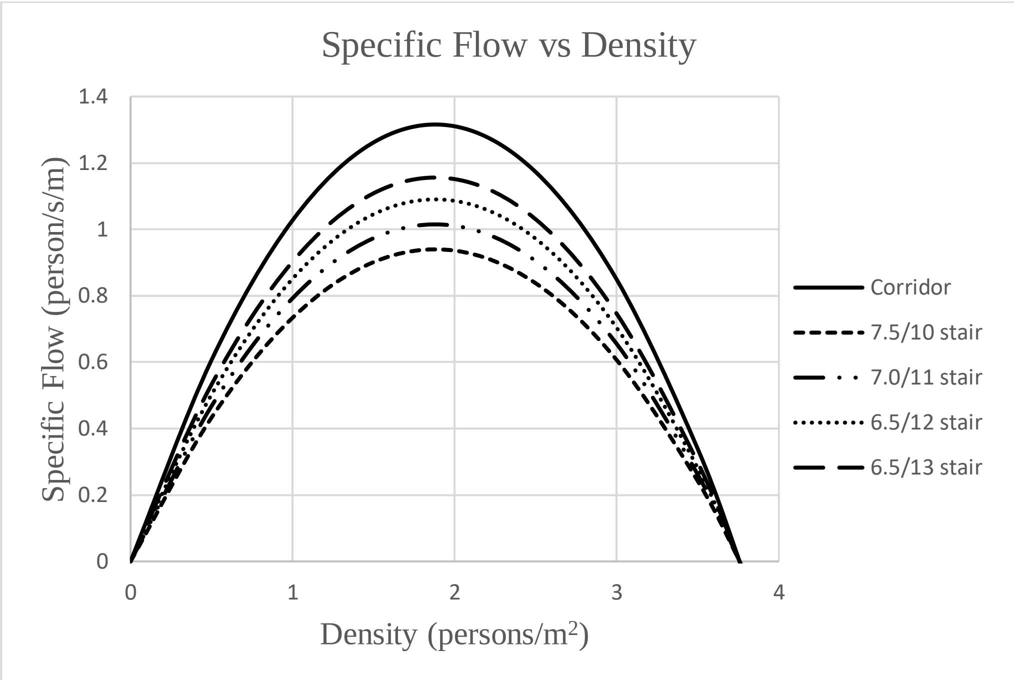


Figure 2.16. Specific flow vs density relationship for various egress components.

Time for passage, t_p, is the time for a group of persons to pass a point in an exit route.

$$t_p = P/F_c \tag{2.12}$$

$$t_p = P/(1 - aD)kDW_e \tag{2.13}$$

where P is the population size in persons.

Transitions are any points in the exit system where the character or dimension of a route changes or where routes merge or branch. After this point, the same set of equations are applied with the different variables. Flow out of a transition point can be calculated using equation 2.14.

$$F_{s(out)} = \frac{F_{s(in)} W_{e(in)}}{W_{e(out)}} \tag{2.14}$$

where $F_{s(out)}$ is the specific flow departing from transition point

$F_{s(in)}$ is the specific flow arriving at transition point

$W_{e(out)}$ is the effective width prior to transition point

$W_{e(out)}$ is the effective width after passing transition point

For cases involving two incoming flows and one outflow from a transition point, equation 2.15 can be used.

$$F_{s(out)} = \frac{F_{s(in-1)} W_{e(in-1)} + F_{s(in-2)} W_{e(in-2)}}{W_{e(out)}} \tag{2.15}$$

where the subscripts $(in - 1)$ and $(in - 2)$ indicate the values for the two incoming flows. The summation in the numerator applies also for cases involving more than two incoming flows.

As mentioned previously, different evacuation scenarios are examined in fire safety analysis. (Purser *et al.*, 2007) have identified two base scenarios that can be modified through the manipulation of model variables in order to produce a set of scenarios for analysis. In sparsely populated spaces, the escape time produced is more sensitive to the time taken to traverse the distance to the place of safety and the time taken to respond, than the time for congestion. So, it is unlikely that queues will dominate the egress performance will be generated. On the other hand, in densely populated spaces, it is more likely that congestion will be produced. Therefore, the time to reach a point of safety is likely to be highly sensitive to the clearance of congestion along the egress routes. As shown in Figure 2.17, scenario 1 assumes that congestion dominates the results produced. In such situations, the egress time depends on the pre-evacuation time and unrestricted walking time of the first few occupants; these determine the time for congestion to develop. Moreover, due the non-sequential nature of the evacuation processes, it is only logical that a computer model be used to represent egress for a high-consequence event like a tall residential building fire. But first, numerical example to illustrate these concepts also utilized by the computer models is provided next.

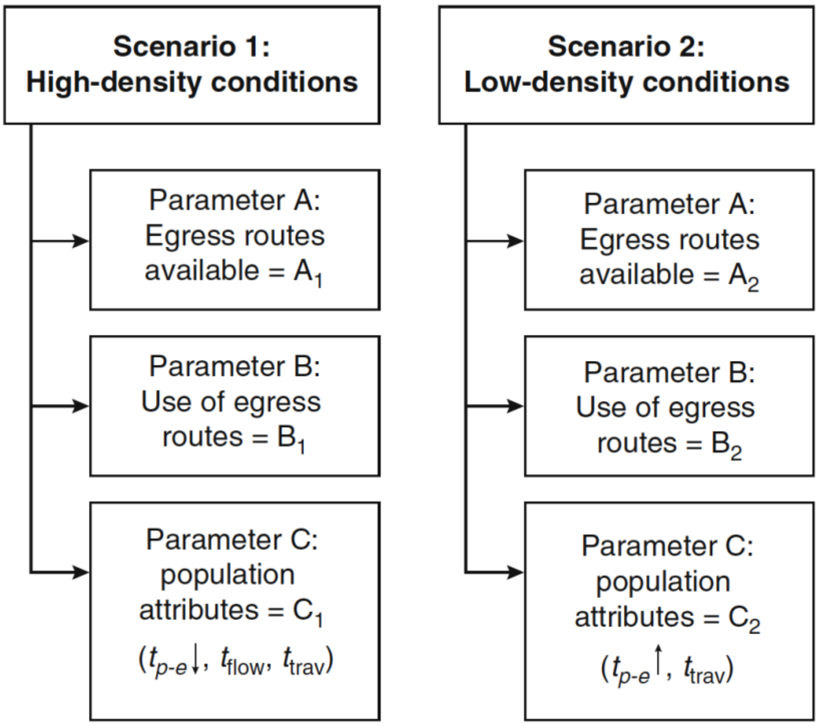


Figure 2.17. Generation of scenarios by manipulating parameters (Gwynne *et al.*, 2016).

2.5.2. Numerical Example

Assume a simple two-floor building in which only the top floor is occupied and with egress components as shown in Figure 2.18. Two aisles connect the apartments to the escape stairs, one coming from the south, the other from the east as shown. The width of the corridor is 2m. The total length of the side of the corridor leading from compartment B is 15m and the other side is 16m. The door leading to the 7/11 escape stair is 1m wide and is situated 3.5m away from the compartment A. Therefore, those coming from B will have to travel 14m and additional 10m to reach the escape stairs while compartment A occupants will have to walk only 4m to reach the escape door. The stair has bounded by a wall on one side and a railing on the other, with a total of 10 risers to the ground floor. If there are 20 occupants in each compartment starting at an initial density of 1.5person/m^2, the time it will take to reach the bottom of the stairs can be calculated as follows.

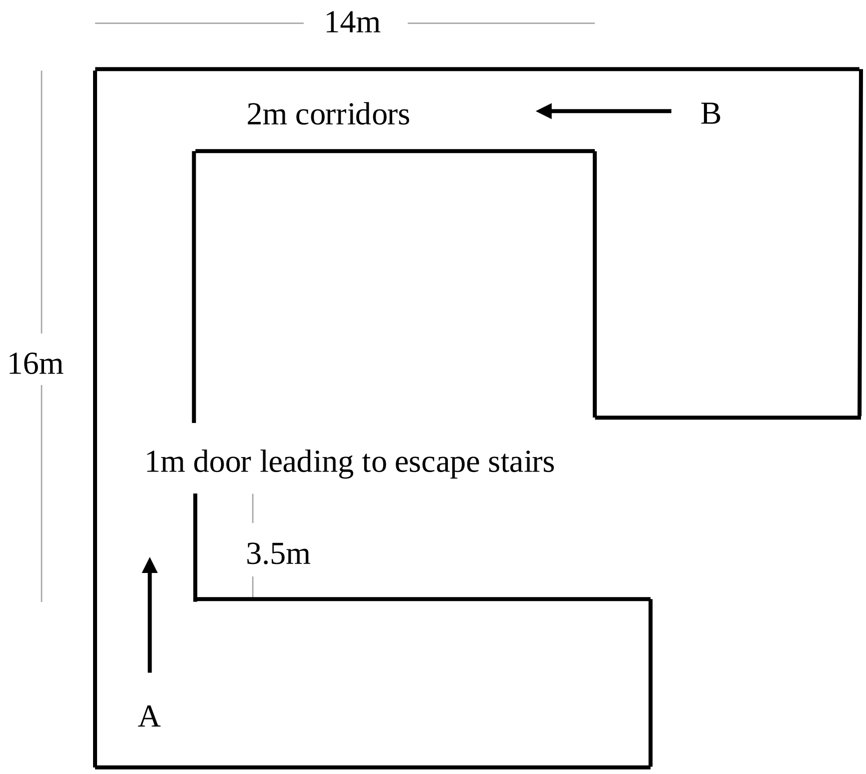


Figure 2.18. Egress components of a typical high-rise residential building.

For the corridor,

Effective width,

$$W_e = 2.0 - 0.4 = 1.6m$$

Speed,

$$S = k - akD$$
$$S = 1.4 - (0.266)(1.4)(1.5)$$
$$S = 0.84m/s$$

Time for the first person to reach the stair exit from compartment A is

$$t_A = \frac{distance}{speed} = \frac{4m}{0.84m/s} = 4.76secs$$

For compartment B

$$t_B = \frac{distance}{speed} = \frac{14 + 10m}{0.84m/s} = 28.6secs$$

Specific flow,

$$F_{s-1} = SD = 0.84 * 1 = 0.84person/s/m$$
$$F_{s-2} = SD = 0.84 * 1 = 0.84person/s/m$$
$$F_c = F_s W_e = 0.84 * 1.6 = 1.34person/s$$

The value of the specific low rate is less than the maximum value of 1.3p/s/m of the effective width. Therefore, it can be used for the calculation.

The time for the queue to dissipate for compartment B can be determined by calculating the time delay for the last person to start on stair,

$$t_{pB} = \frac{P}{F_c} = \frac{40}{1.34} = 29.85secs$$

Given that those on compartment B start evacuating after 28.6secs, the total queuing dissipation time will be

$$t_p = 29.9 + 28.6 = 58.5secs$$

On the transition between the corridor and the stair,

$$F_{s(out)} = \frac{F_{s(in-1)}W_{e(in-1)} + F_{s(in-2)}W_{e(in-2)}}{W_{e(out)}}$$
$$F_{s(out)} = \frac{0.84 * 2 + 0.84 * 2}{1}$$
$$F_{s(out)} = 3.36person/s/m$$

This flow rate, however, is greater than the maximum flow rate. Therefore, the flow rate on the stairs is

$$F_s = 1.01 person/s/m$$

For the stair,

Effective width,

$$W_e = 1.0 - (0.09 + 0.15) = 0.76m$$

Density,

$$0.266D^2 - D + F_s = 0$$
$$0.266D^2 - D + \frac{1.01 * 0.76}{1.4} = 0$$
$$D = 3.09 p/m^2$$

Speed,

$$S = k - akD$$
$$S = 1.08 - (0.266)(1.08)(3.09)$$
$$S = 0.19 m/s$$

Specific Flow,

$$F_s = SD = 0.19 * 3.09 = 0.59 person/s/m$$
$$F_c = F_s W_e = 0.59 * 0.76 = 0.45 person/s$$
$$t_p = \frac{P}{F_c} = \frac{40}{0.45} = 88.6 secs$$

Therefore, the total amount of time it will take for the occupants of this building to reach the ground floor is the sum of the queuing dissipation times.

$$t_{p_{total}} = 147 secs$$

This is a somewhat conservative number considering the fact that the compartment A occupants will have evacuated before the occupants in compartment B reach the stairs. In a scenario in which the fire has started to spread before these occupants began evacuation, the percentage of %COHb the last person to exit will have inhaled as calculated from the equation in chapter 3 is about 3%. Though this will probably not lead to incapacitation as Figure 2.9 indicates, it is easy to see that in a tall building, exposure to heat effluents during the vertical evacuation can lead to casualties. The use of computer to model these and more complex geometries is therefore appropriate.

2.5.3. Computer modelling method

This is by far the most widely used method in research due to its sophistication in representing occupant behaviors. Applications can range from simply automating the manual process to complex refined representation. An exclusively manual approach does not explicitly consider behaviors that distract from movement and the results can only be determined in a deterministic way. Computer models, on the other hand, provide the option of introducing randomness and the identity and individual attributes of evacuees can be considered. More detailed understanding gained in the field of human behavior in recent years has allowed the behavioral component to be accounted for, albeit imperfectly, when trying to establish the egress performance. An evacuation decision model can be implemented for pre-evacuation behavior (Lovreglio *et al.*, 2016). The level of detail to which the structure and population are represented is referred to as the level of refinement. Chapter 3 gives more detail on this.

Computer models also use different methods to calculate the evacuation times (Kuligowski, 2016b). Models that concentrate on the simulation of occupant movement are known as movement models. Other models calculate the occupant movement but also simulate some behavior like pre-evacuation, overtaking behavior and smoke effects on occupants to some extent. These are called partial behavior models. Models partial incorporate actions and decision making to movement are called behavior models. (Gwynne *et al.*, 1999) have investigated the capabilities of evacuation models in use. More recently, (Ronchi and Nilsson) have given a more detailed review of these models taking into account the three types of buildings which account for the most significant part of high-rise building evacuation as categorized by (Hall, 2013).

2.6. Egress Strategies

To ensure the safety of building occupants potentially exposed to fire, they are either protected in place, moved to a place of safety within the building or provided paths to exit the building completely. These protected spaces and paths of travel needed to ensure safety are known as egress components and the system and features facilitating such safety measures are the egress strategies. The traditional means of egress has been the use of stair. Alternative vertical means of egress like the use of elevators has not gained acceptance in all codes. NFPA 101 conditionally allows the use of elevators for egress. (Kuligowski and Bukowski, 2004) have investigated the usefulness of elevators for evacuation especially for the disabled. In some situations, horizontal means of egress like the sky-bridge in Petronas Tower in Malaysia are also used. In the event of fire, these means of egress can be mixed together as an egress strategy or the efficient use of stairs can be sought. The number of stairs and their layout will determine the optimal escape strategy. The possible application of each strategy is dependent upon the characteristics and use of the building, the population involved, the staff/rescue operators or alarm system and the nature of the scenario involved.

2.6.1. Full building evacuation strategy

While there may not always be a need for full building evacuation especially in buildings with properly designed fire suppression systems, a scenario in which the fire has spread through the whole building or a terrorist attack will necessitate full building evacuation. Evacuating a large number of people simultaneously from a high-rise building requires a performance-based engineering approach. This strategy also tends to be the most common strategy for life safety in tall buildings (Bukowski and Tubbs, 2016). (Ronchi and Nilsson, 2013b) modelled full evacuation strategies of a 50-floor office building using the computer evacuation models Pathfinder and STEPS to investigate the effectiveness of total evacuation strategies. Using a designed generic model case study which was mostly code-compliant, seven combinations of full evacuation strategies were analyzed in Pathfinder and their effectiveness were compared with one another. According to the results, the use of two stairs and occupant evacuation elevators with a waiting time of 10 minutes for the use of elevators produces similar evacuation times which are significantly lower than the use of only two stairs. The model case study was a 50-story building which provides a justification for use of an additional stair for buildings above 128m where no occupant evacuation elevators are not used. As a hypothetical strategy, the use of only occupant evacuation elevators was simulated which shows that evacuation time for a high-rise building is reduced by an increase in the number of elevator users.

2.6.2. Protect-in-place and relocation strategies

In certain scenarios, full building evacuation may not be practical due to untenable conditions on the lower floors or higher risks involved down the egress path. Because of compartmentation in residential buildings, protect-in-place strategy where occupants are allowed to remain in a place of safety within the building during the fire event can be an egress strategy option. This allows a portion of the population especially the disabled to seek shelter in a safety zone. However, owing to the ravaging unfolding of recent fire events, the appropriateness of this ‘stay put’ strategy has received reconsiderations (Hopkin *et al.*, 2019). A variation of this strategy is Relocation. Relocation strategies play a fundamental role in the safety design (Tubbs and Meacham, 2009). People may evacuate to the roof; however, such a strategy is not advisable due to limited space in the roof and difficulties in the rescue procedures using helicopter (Ronchi, 2013b).

(Hong Kong, 2011) prescribes the provision of refuge floors for all buildings exceeding 25 stories. The staircases on these non-usable floor spaces are designed to separate the upper and lower parts of the building to prevent smoke spread from the staircase to the whole building. (Ma *et al.*, 2012) conducted experiments on Shanghai World Financial Centre to investigate the process of ultra-high-rise building evacuation in China. Evacuee characteristics like speed characteristics, merging and transit behavior in stairwells and the combined used of lifts were analyzed on the 470m tall building. A mean vertical speed of 0.28 m/s was resulted, relatively lower than the range 0.33 – 0.38 m/s suggested by (Pauls, 1984). This may be indicative of fatigue apparent in the long-distance high-rise evacuation. Transit on these floors also adds to the evacuation time in case of full-building evacuation.

But if the evacuees can be provided safety in these areas, protect-in-place strategy may be viable.

2.6.3. Phased or partial evacuation strategy

Based on the synchronization of the evacuation period, egress can be either simultaneous or phased; based on the percentage of the population evacuated, egress can be either total or partial. In phased and partial evacuation strategy, individuals intimate with the fire incident are relocated or evacuated while those not intimate with the event are protected-in-place.

2.7. Uncertainties

Discussion of fire safety concepts is not complete without the acknowledgement of uncertainties. Uncertainty is a general term describing lack of knowledge and the randomness, indeterminacy, and variability inherent in real world idealization. Uncertainties associated with randomness can be referred to as *aleatory uncertainties* while those stemming from lack of knowledge as *epistemic uncertainties*. Though this distinction may not always be important (Winkler, 1996), it is worth noting that the selection of a scenario to deal with automatically eliminates some of the epistemic uncertainties. Both fire models and evacuation models have inherent uncertainties. To account for these, a margin of safety is often added implicitly in the components of the design or explicitly in the critical analysis parameters (Natarianni and Parry, 2016). Classical statistical techniques for quantifying uncertainty include the use of confidence intervals and standard deviation. Since fire in high-rise buildings is a high-consequence phenomenon and the fact that life safety in fire involves both physical and social processes makes the identification of knowns and unknowns important. A language to deal with such is the use of probability and this is implicitly or explicitly in the form of risk.

Probabilistic Risk Assessment (PRA) methods have been developed to describe the future performance of systems. (Paté-Cornell, 1996) proposed six levels of sophistication in the treatment of uncertainties depending on the level of the outcome. On one side of the extreme is a categorical affirmation of the existence or non-existence of the hazard, moving to the worst-case approach without any notion of probability, to quasi-worst-case involving 'plausible upper bounds', up until full probabilistic risk analysis with multiple risk curves. For a reasonable treatment of uncertainty in our context given the risk involved and the limited data available, a quasi-worst-case scenario is appropriate (Grandison *et al.*, 2017).

2.7.1. Modelling uncertainties

The simplifying assumptions of engineering models gives rise to epistemic uncertainties. V&V models, as described in the next chapter, can help in understanding the limitations and applicability of the simulation results obtained from software(s) used. It is left to the discretion of the user of the software to look out for what in the evacuation modelling community has come to be referred to as the *user effect* (Ronchi and Nilsson, 2013b). It is enough to acknowledge the existence of this uncertainty as further treatment of it is beyond the scope of this project.

2.7.2. Data uncertainties

The parameters involved in egress modelling, like the number of occupants assumed to be in the building or the movement and pre-movement characteristics of the occupants, are by their nature uncertain. The behavior these occupants exhibit is also unpredictable. The input data collected as a basis for the future expectations in a fire event therefore exhibit variability as mentioned previously in this chapter. Using a Monte-Carlo technique, (Lord *et al.*, 2004) generated Cumulative Distribution Functions that represent the effect of adjusting different input pre-movement and movement variables of a 6-story office building on the evacuation time. The results suggested that variables like patience, walking speed, and door floor rate have fairly insignificant impact on the total evacuation time. It was postulated that the lack of significance of walking speed on the total evacuation time was due to the limited range of the age of office building occupants. Other variable however, such as occupant load, pre-movement times, queuing coefficient and Locks Solver Depth (the maximum number of iterations that will be used to find a solution when a circular lock occurs in the simulation) have a significant impact on the total evacuation time. Investigation into these issues in high-rise residential buildings will be performed using the accepted engineering methods.

3. METHODOLOGY

The complexity of high-rise residential buildings demands high safety criteria to be established to avoid unwanted consequences that may arise from the potential low-probability high-consequence events such as an earthquake or a fire which necessitate occupants to evacuate the building entirely within a limited amount of time. In the design of a building, the approach employed to ensure that the safety criteria are met should accommodate its uniqueness and produce the desired level of performance. Hence the development of performance-based approach.

Before the development of performance-based building codes, building design relied upon the specifications of the prevailing prescriptive building codes to achieve ‘safety.’ These are strict definitions of minimum dimensions and other features of a building that need to be provided for a structure to be considered safe, even though the meaning of ‘safe’ is not itself clearly defined. These codes also allowed ‘equivalency’ and the use of ‘alternate methods and materials’ in their specifications. However, the method by which the equivalent level of safety can be achieved was not specified. With the formalization of key authoritative references in some countries such as the SFPE Handbook of Fire Protection Engineering in the U.S., performance-based methodology has become a widely used and continues to gain acceptance as a superior method of ensuring a safe design. The more elaborate quantitative understanding of fire gained in the last decades has also facilitated the adoption of this method of ensuring fire safety.

Performance-based fire design (PBFD) describes the desired level of safety in a building in the event of fire. This is achieved through the implementation of agreed upon fire safety goals (FSG) and fire safety objectives (FSO). FSG identifies the desired overall fire safety outcome expressed in qualitative terms while FSO defines the maximum tolerable damage in case of fire. Since in the context of this thesis the FSG is specifically the life safety of occupants in tall residential buildings, the FSO will be to afford reasonably enough time for them to evacuate the building or reach a place of safety without detriment to their health or life: simultaneous full building evacuation. To evaluate the life safety of building occupants, the predicted development of fire and its effluents is compared against the time required to move occupants to a place of safety within or outside the building. In other words, ASET is compared against RSET. The performance criteria by which life safety is evaluated can be assessed using egress modelling tools. A state-of-the-art software will be used here as a tool to model the egress of people from tall residential structures.

There are two sets of information needed to assess the acceptability of a design. One is the performance criteria and the other is the design fire scenario which describes the fire for which a design is intended to provide protection. Analogous to the selection of design fire scenario envisaged to produce undesirable consequence is the designation of design occupant scenario (Nilsson and Fahy, 2016). If the goal of the FSE analysis is life safety for occupants, the two must be used hand in hand. In the evaluation of RSET, the evolving fire scenario will have physical and psychological effects on the evacuating occupants. As we shall see, the heat, smoke and gases, termed fire effluents, can be modelled in the environment from which the evacuees are escaping. A flexible framework for performance-based design is summarized in Figure 3.1. The relevant steps are used as guide for the fire safety evaluation of high-rise residential buildings covered in this study.

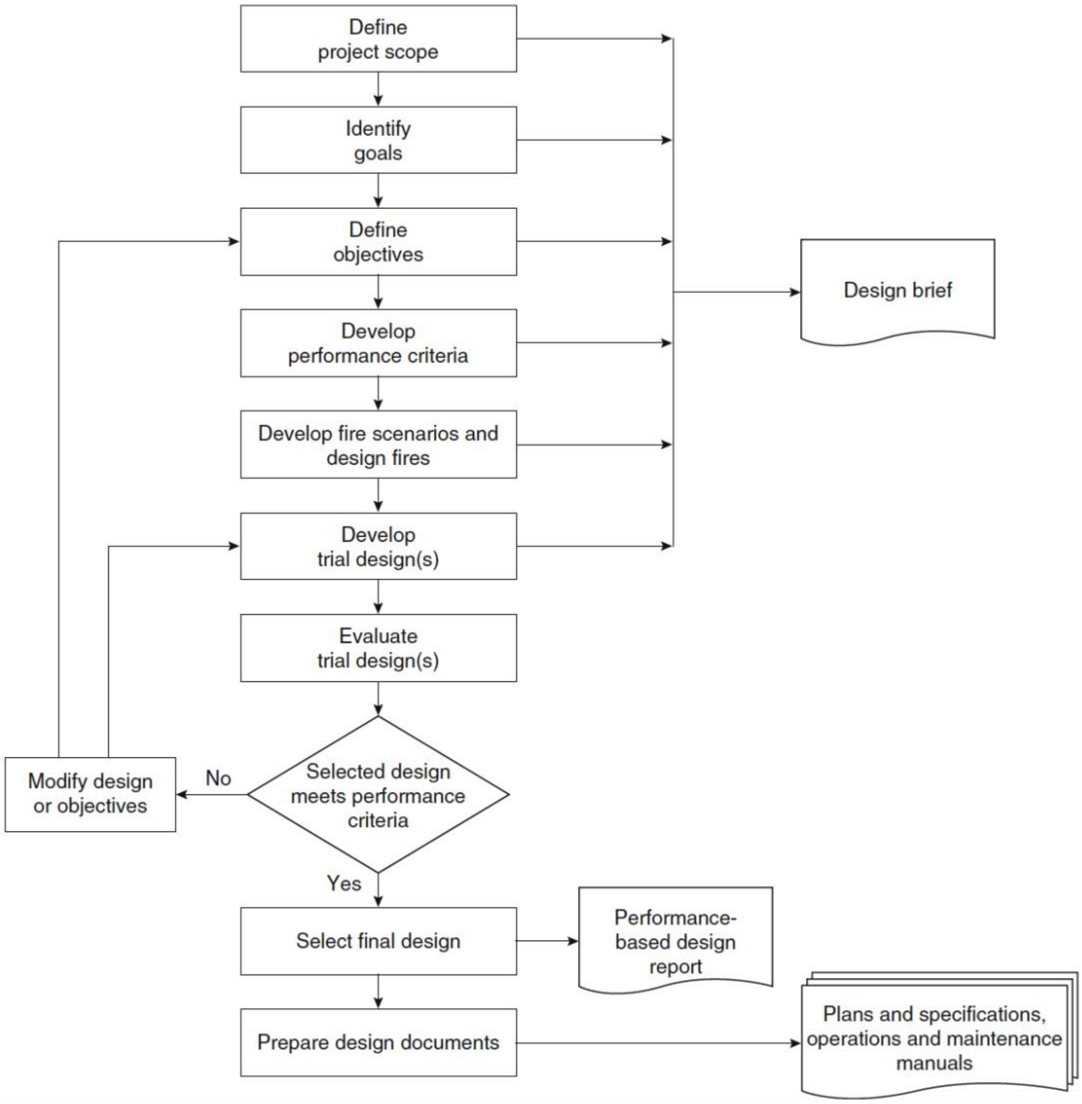


Figure 3.1. Performance-based design process (Hurley and Rosenbaum, 2015).

3.1. Fire Modelling

As mentioned before, field models such as CFD models provide accurate means of predicting the temperature, smoke and toxic gases produced by fire using sophisticated mathematical techniques. One such model developed at NIST in the US is the Fire Dynamics Simulator (FDS). The FDS approach is flexible allowing for the simulation of small-scale to large-scale fires and ventilation in buildings (Thunderhead, 2018). The graphical user interface for the FDS used to create the fire models in this thesis is called PyroSim, a product of Thunderhead Engineering. This software is used to predict the smoke, temperature, CO and the other substances generated by the fire models used in this study.

The starting point for CFD models is the set of partial differential equations for the conservation of mass, momentum and energy within the fire and throughout the space surrounding it. The solution of these equations on a 3-D mesh of each of the thousands of controlled volumes that spans the geometry yields a time-varying prediction of the temperature and other characteristics of the fire. In fire modelling, the fire is defined by pyrolysis, the rate at which a solid or liquid generates fuel vapor, and combustion, the chemical reaction of fuel vapor and oxygen.

3.1.1. Governing equations

The conservation of mass, i.e. that matter can neither be created nor destroyed can be stated mathematically as follows.

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \boldsymbol{u} = 0 \tag{3.1}$$

In other words, the change in the density, ρ, at a given point in the flow field is equal to the net mass flux, $\rho\boldsymbol{u}$, across the boundary of a small control volume surrounding the point.

The conservation of momentum, on the other hand, is essentially Newton's Second Law of Motion where the forces that drive the fluid consists of the pressure gradient, ∇P, friction, τ, external forces terms, **f**, such as buoyancy,

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla . (\rho \boldsymbol{u}\boldsymbol{u}) = \nabla \mathrm{p} + \mathbf{f} + \nabla . \tau \tag{3.2}$$

Finally, the conservation of energy states that the sensible enthalpy, h, at a given point changes according to the net energy flux across the boundary of a small control volume surrounding the point. The terms on the right-hand side of equation 3.3 are related to pressure, combustion heat release rate, radiation and conduction, and kinetic energy dissipation respectively.

$$\frac{\partial \rho h}{\partial t} = \nabla.(\rho h \boldsymbol{u}) = \frac{\mathrm{DP}}{Dt} + \dot{q}''' - \nabla.\mathbf{q} + \varepsilon \tag{3.3}$$

The numerical technique for approximating these governing equations are roughly categorized according to their spatial and temporal fidelity: Direct Numerical Simulation (DNS), Reynolds-averaged Navier-Strokes (RANS) and Large Eddy Simulations (LES). DNS is the direct numerical solution of the governing equations and because it demands very fine spatial and temporal resolution, it is impractical for large-scale fire simulations. On the other hand, RANS solves a statistically time-averaged form of the conservative equations while LES solves a space-averaged form of the conservation equations. FDS is based on LES of the turbulent convective motion (Rehm and Baum, 1978) and this approach requires a combustion model.

3.1.2. Heat combustion

The reaction of hydrocarbon fuel with oxygen to produce carbon dioxide and water is the most basic description of the chemistry of fire. However, since fire involves an inefficient combustion of more than one carbon and hydrogen atom, the number of fuels is simplified to one and the number of reactions to just one or two, also leaving the possibility that the reaction may not proceed due to lack of oxygen. At least six gas species (fuel, O_2, CO_2, H_2O, CO, N_2) and soot particles are kept track of by considering the fuel as a single gas species and other gases as "lumped species."

$$\mathrm{Fuel} + \mathrm{Air} = \mathrm{Products} \tag{3.4}$$

The combustion model determines the mean chemical mass production rate of species per unit volume and HRR per unit volume. Prior to that, pyrolysis determines the desired energy release from the HRR on a surface by using the heat of combustion defined by the reaction to calculate the fuel vapor mass release rate. For a complex solid-state pyrolysis, a "layered" surface is used so that a heat transfer calculation can be performed. The temperature is then used to calculate the solid-state pyrolysis rate. The HRR is determined by summing the mass production rate for each species times their respective heats of formation.

$$\dot{q}''' = \sum_{\alpha} \dot{m}_{\alpha}''' \, \Delta h_{f,\alpha} \tag{3.5}$$

An upper bound for HRR is used to maintain code stability. In FDS, the value is 200kW/m^2 of flame sheet.

$$\dot{q}'''_{upper} = \frac{200}{\delta x} + 2500 \text{ kW}/m^3 \tag{3.6}$$

where δx is the characteristic cell size.

The parameters and form of the so called "simple chemistry" combustion model are given in equation 3.7. The simple chemistry combustion model assumes that the reaction of fuel and oxygen is infinitely fast and controlled only by mixing. This approach assumes a single fuel species composed of C, H, O and N that reacts with air to form products H_2O, CO_2, CO, soot and N_2.

$$C_xH_yO_zN_v + v_{O_2}O_2 \longrightarrow v_{CO_2}CO_2 + v_{H_2O}H_2O + v_{CO}CO + v_sSoot + v_{N_2}N_2 \tag{3.7}$$

where v represents the stoichiometric coefficient of the respective gas species.

3.1.3. Smoke and temperature distribution

The distribution of temperature and soot particles of the smoke can be determined for a particular height using 2D slices of the geometry. A thermocouple can also be installed at a location to monitor its temperature. The thermal boundary conditions of the materials and the surrounding walls are utilized to perform the numerical calculations needed to generate the distribution of fire effluents. The aim of fire modelling in this project is to capture the range or order of magnitude of the fire effluents. As a result, a detailed fire model is not the interest and approximate results are deemed acceptable.

3.1.4. Verification and validation

The process by which a numerical model is independently evaluated for reliability is termed Verification and Validation (V&V). This has become essential in the fire engineering community for advancing evacuation models. According to ASTM 1355, verification is defined as the process of determining that the implementation of the calculation method accurately represents the developer's conceptual description of the calculation method and the solution of the calculation method. Validation, on the other hand, is defined as the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method.

The basic assumptions and limits of applicability of FDS have been mentioned. In this work, since a detailed fire analysis is not the main aim, a basic description is used to perform a fire engineering analysis. The so-called zoned data have been approximated to provide a basis for the FED analysis.

3.2. Egress Modelling

The models designed in this thesis to study the evacuation behavior of building occupants were created in EXODUS. This is a software suite developed by Fire safety Engineering Group (FSEG) at the University of Greenwich in the UK, and it currently consists of three models designed to simulate the evacuation of individuals each from a different type of structure: aircrafts, marine structures and buildings. The modelling tool in the EXODUS family designed for simulating the evacuation of people in the built environment is called buildingEXODUS.

Within buildingEXODUS, sub-models operate and interact with each other in order to simulate real-life evacuation. Each of these sub-models control a specific aspect of the evacuation. The six factors known to influence the evacuation of people in fire are each handled by a sub-model:

(i) geometry sub-model defines the grid system enclosure;

(ii) occupant sub-model stores attribute of each individual;

(iii) hazard sub-model controls the physical and atmospheric nature of the environment;

(iv) toxicity sub-model evaluates the effect of fire hazard on each individual's attributes;

(v) behaviour sub-model evaluates an individual's response to the prevailing situation;

(vi) movement sub-model controls the motion of individuals from one node to another.

The results generated by these sub-models within EXODUS time are communicated with one another to result in emergent evacuation characteristics of the population. For instance, after the toxicity sub-model determines the effects of toxic hazards on the occupants, the information obtained is communicated to the movement sub-model which leads to a decrease in each individual's speed based on their attribute and location, resulting in a different egress performance.

Evaluating life safety in buildingEXODUS requires modelling physical environment in which the evacuating building occupants interact with each other, the behavior and attributes of these evacuees, and the atmospheric nature of the environment in which they are moving where the effect of the fire effluent on them is discerned. The subsections that follow describe the level of representation of each one of these aspects of the model.

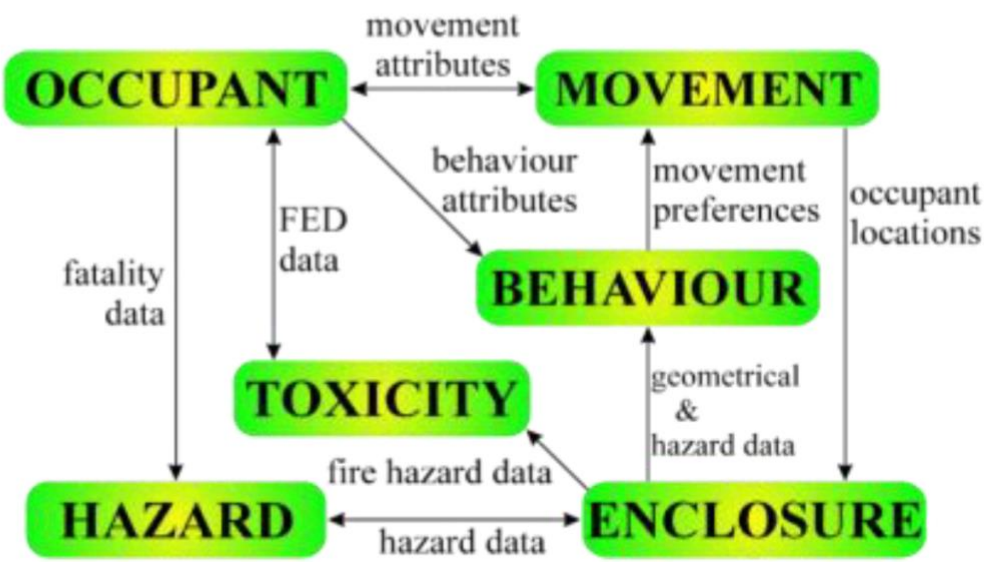


Figure 3.2. buildingEXODUS sub-model interaction (Galea *et al.*, 2017a).

3.2.1. Evacuation environment

Different computer evacuation models employ different levels of sophistication with which to represent the physical evacuation space. In terms of the level of refinement of the structure, computer models can generally be classified into three groups, namely: coarse network models, fine network models and continuous models. Coarse network models represent the simplest representation in which the floor plan is divided into compartments – rooms, corridors and so on. Unlike coarse networks where compartments can be of differing sizes, fine network models on the other hand utilize a series of small, uniform grid cells, known as nodes, typically the size of one person. This allows simulated occupants to move from one node to another based on their physical attributes. In continuous models, the structure is overlaid with the x-y coordinate points allowing occupants to travel through all possible space in the building. BuildingEXODUS utilises the fine network system. The space in which occupants move are represented in this system as two-dimensional nodes. Each node is connected to a neighboring grid with an arc – Figure 3.3. When the space region to be represented is an unobstructed horizontal terrain, the free-space node type is used. In cases otherwise, like a stair or a seat whereby movement is slowed down, other available node types or obstacles can be generated. This distinguishing feature of the nodes defines the terrain type of the evacuation space. Each node can be occupied by one occupant at a time and the length of each arc joining an adjacent node is 0.5m so that the maximum population density is 4 people/m^2 as Figure 3.4 shows. The environmental state of a space region is also associated with the nodes it encompasses. For each environmental variable, the values at head height and near floor height are stored for the node – 1.7m and 0.5m say – to then be used by the toxicity sub-model.

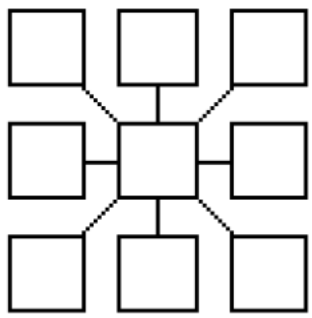


Figure 3.3. Connections between neighboring nodes using arcs (Galea *et al.*, 2017a).

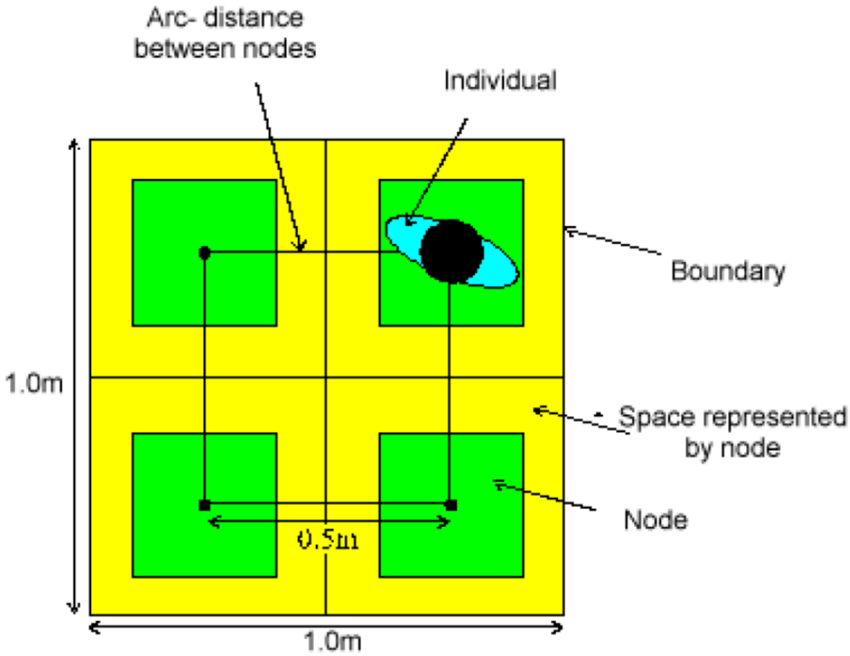


Figure 3.4. Node representation of a 1m x 1m enclosure (Galea *et al.*, 2017a).

3.2.2. Toxicity and heat effects

To calculate the effect of fire hazards on evacuees, the concept of Fractional Effective Dose (FED) is used whereby the dose received by an individual at any point during the fire is expressed as a fraction of dose predicted at a given endpoint. The dose of carbon monoxide, for example, at any time during the fire will be expressed as a fraction of the dose required to cause collapse and loss of consciousness. Time to loss of tenability from the effects of heat, narcotic gases, irritant gases or smoke is calculated as the time at which endpoint reaches a FED of 1. The general FED equation can be summed up in equation 3.1.

$$FED = \int_{t_1}^{t_2} \sum_{i=1}^{n} \frac{C_i}{(Ct)_i} \Delta t \qquad (3.1)$$

where C_i is the average concentration of a dose related toxicant i over the chosen time increment

Δt is the chosen time increment

$(Ct)_i$ is the specific exposure dose expressed as concentration x minutes that would produce a defined endpoint such as preventing an occupant's escape.

In simpler terms,

$$FED = \frac{Dose\ Recieved\ at\ time\ t}{Effective\ dose\ to\ cause\ incapacitation\ or\ death} \tag{3.2}$$

BuildingEXODUS utilizes a FED model developed by (Purser and McAllister, 2016) to model a fire scenario. This model assumes that the effects of toxic and physical hazards are associated with high temperature, HCN, CO, CO_2 and low O_2, and estimates the time to incapacitation. Table 3.1 gives the formulation used for the FED analysis of these narcotic agents. The personal incapacitating dose for the population follows normal the distribution discussed in the previous chapter. RMV is the volume inhaled in liters per minute. CO_2 has the effect of increasing an individual's RMV thus increasing his/her uptake of other gases. For the combined effect of narcotic agents, equation 3.3 is used.

Table 3.1. Fractional Incapacitating Dose of narcotic gases.

Narcotic gas	Fractional Incapacitating Dose
HCN	$FICN = HCN^{2.36}\ (\ RMV\ )\ \frac{t}{2.43\ x\ 10^{7}}$
CO	$FICO = 3.317\ x\ 10^{-5}\ (\ CO^{1.036}\ )(RMV)\frac{t}{PID}$
CO_2	$FICO_2 = \frac{t}{e^{(6.1623(0.5189-CO_2))}}$
O_2	$FIO = \frac{t}{e^{(8.13-0.54(20.9-O_2))}}$

$$FIN = (FICO + FICN + FLD)\ x\ VCO_2 + FIO \tag{3.3}$$

where FLD is the fractional lethal dose of the irritant gases; and

$VCO_2 = e^{(CO_2/5.0)}$ is a multiplicative factor which increases the gas uptake.

For heat exposure, the fractional incapacitating dose of convective and radiative heat flux contributes to hazard effect on evacuees. Table 3.2 gives their FED formulations. *t* represents the time and *T* the temperature. *q* is the radiative flux in kW/m^2 and D_r is the radiative denominator or the radiation dose required to cause the 'desired' effect of pain or incapacitation.

$$FIH = \int_{t_1}^{t_2} \left(\frac{1}{t_{I_{conv}}} + \frac{1}{t_{I_{rad}}} \right) \Delta t \tag{3.4}$$

Table 3.2. Fractional Incapacitating Dose of heat.

Heat Flux	Fractional Incapacitating Dose
Convection	$FIH_c = t\ x\ 2.0\ x\ 10^{-8}\ x\ T^{3.4}$
Radiation	$FIH_r = \frac{q^{1.33}}{D_r} x\ t\ x\ 60.0$
FIH	$FIH_c + FIH_r$

For irritant gases, the FED model is represented as Fractional Irritant Concentration (FIC). Another concept applied if the Fractional Lethal Dose (FLD) which represents the cumulative impact of irritant gases upon an individual (Galea *et al.*, 2017). The critical dose and tolerance factor of irritant gases.

$$FIC = \frac{Conc.of\ irritant\ to\ which\ subject\ is\ exposed\ at\ time\ t}{\begin{array}{c}Conc.of\ irritant\ required\ to\ cause\ impairment\ of\\ escape\ efficiency\end{array}} \tag{3.5}$$

As an example, consider a subject with a light activity level with RMW of 25 L/min exposed to 90 ppm HCN for 25 minutes, incapacitation is predicted between 23 and 24 minutes.

$$FICN = 90^{2.36}\ (\ 25\ ) \frac{20}{2.43\ x\ 10^7} = 1.05$$

Also, consider a subject exposed to a concentration of 10% oxygen for 5 minutes, loss of consciousness is predicted at 9.5 minutes.

$$FIO = \frac{10}{e^{(8.13-0.54(20.9-10))}} = 1.06$$

3.2.3. Occupant attributes

With regard to the refinement of the population, in some computer models the population is represented as individuals while in others it is considered homogenous represented by fluid models. The former category is classified as microscopic and the latter as macroscopic. A major drawback of the people-fluid analogy is that it does not create congestions (Korhonen *et al.*, 2005). BuildingEXODUS employs the microscopic approach, and the movement of occupants is agent-based with their behavior determined by an individual set of heuristics or rules. One of the advantages of using this approach is its flexibility in representing complex relocation strategies by allowing for behavioral changes during the evacuation process, typical of a real-world fire evacuation. Each evacuee is represented with many attributes which are then used in tracking his/her movement in time. There are four classes of attributes associated with each individual: physical, psychological, experiential and hazard.

Table 3.3. Range of occupant physical attributes.

Physical Attribute	Scale
Gender	Male or Female
Age	1 – 100 years
Weight	1 – 200 kg
Height	1.0 – 2.0 m
Mobility	0.0 – 1.0
Agility	0.0 – 7.0
Travel speed	0 – 10.0m/s (fast walk =1.5m/s)
Respiratory Minute Volume	0 – 50 litres/m

The first four attributes in Table 3.3 are given as input. Also, some of the physical attributes of individuals are dynamic and therefore change during the simulation. Mobility, for instance, is decreased from a value of 1.0 representing no disability or influence of toxicity to lower values representing either impairment or mobility degradation from the effects of narcotic gases, irritant gases and/or smoke. The instantaneous mobility of an occupant is calculated according to equation 3.6. Agility, a measure of prowess in tackling obstacles, is also degraded in a similar manner.

$$Mobility = Initial\ Mobility * Mobility\ Degradation\ Factor \qquad (3.6)$$

The mobility degradation factors of the effect of narcotic gases, irritant agents and smoke on an individual are each calculated separately, and their minimum is used in evaluating his/her mobility with time. Mobility degradation is employed ultimately to slow down the travel speed of the evacuees. The initial Fast Walk travel speed of the evacuees is the basis for other five levels of travel speed; Walk, Leap, Crawl, Stairs Up and Stairs Down travel speeds are fractions of the Fast Walk Speed. For the narcotic gases, as it is shown in Table 3.4, it is assumed that significant degradation only occurs at extremely high values of narcotic gas exposure. For irritant gases on the other hand, equation 3.7 approximates the sigmoidal function that represents their mobility degradation factor. This equation is also plotted in Figure 3.5.

$$MDF_{FIC} = \frac{\left(e^{-((FIC*1000)/160)^2} + (-0.2 * FIC + 0.2)\right)}{1.2} \qquad (3.7)$$

Table 3.4. Mobility Degradation Factor for narcotic gas exposure.

FIN	Mobility Degradation Factor (MDF)
0.00 – 0.89	1.00
0.90 – 0.95	0.90
0.95 – 1.00	0.80

The effect of smoke concentration on mobility can be assumed to be either by irritant or non-irritant smoke. The former is dubbed the simplified model and the latter the comprehensive model. Equation 3.8 expresses the effects of non-irritant smoke on MDF. For irritant smoke concentrations up to 0.1/m, MDF is kept constant after which it degrades according to equation 3.9. For smoke concentrations above 0.5 /m, escape abilities are severely limited, and the model assumes a maximum travel speed as Crawl speed or, as plotted in Figure 3.6, retains a value of about 0.36.

$$MDF_{NonIrritant\ Smoke} = -0.161K^2 - 0.488K + 1.105 \tag{3.8}$$

$$MDF_{Irritant\ Smoke} = -2.0814K^2 - 0.375K + 1.0648 \tag{3.9}$$

where K is the extinction coefficient.

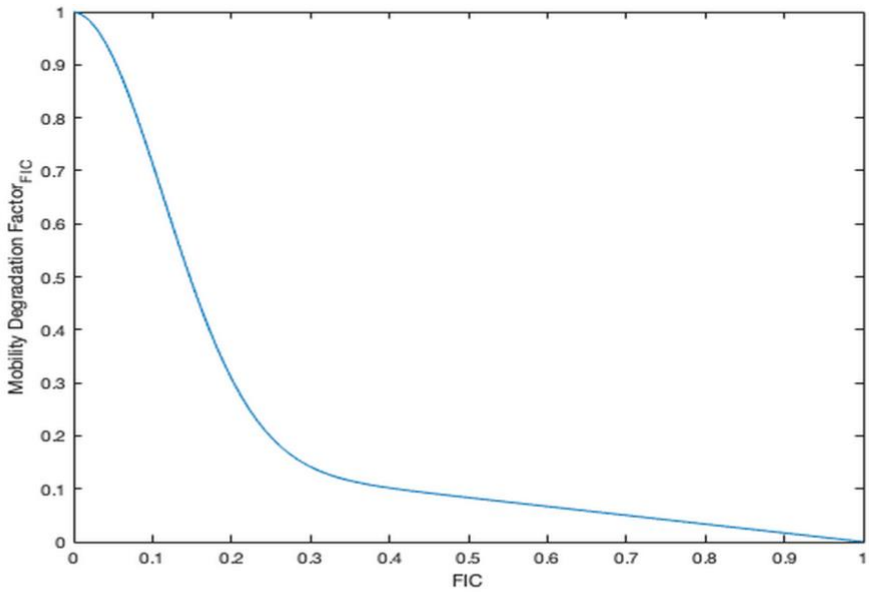


Figure 3.5. Mobility Degradation Factor for irritant gases.

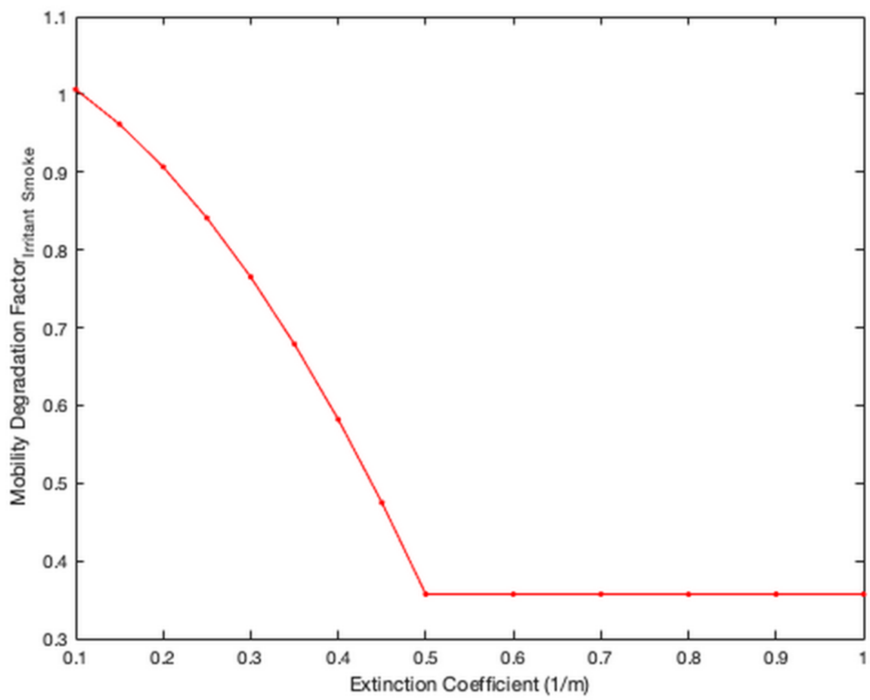


Figure 3.6. The impact of smoke upon $MDF_{Irritant\ Smoke}$

Table 3.5. Stair Travel Rate as derived from Fruin (Galea *et al.*, 2017a).

Gender	Age (years)	Down Avg. (m/s)	Up Avg. (m/s)
Male	< 30	1.01	0.67
Female	< 30	0.755	0.635
Male	30 – 50	0.86	0.63
Female	30 – 50	0.665	0.59
Male	> 50	0.67	0.51
Female	> 50	0.595	0.485

The rate of travel on stairs impose upon occupants is based on their ages. The data by Fruin is according to a range as shown in Table 3.5. The Walk, Leap and Crawl rates are 90%, 80% and 20% of the Fast Walk rate respectively.

Respiratory Minute Volume (RMV) is a measure of the air inhaled into the lung per minute, measured in liters/minute. This is used to calculate the effect of carbon monoxide dose which stipulates the incapacitation dose. The evacuees' gender and the type of activity involved at an instance are used to determine their RMV.

Drive, a measure of assertiveness of the individual, is used in conflict resolution. Young males typically have higher a drive, in contrast to old females. The survey by (Oven and Cakici, 2008) on office occupants in Istanbul, however, suggests the opposite: females have higher drive and agility in response to fire than their male counterparts. Compliant occupants have high patience values. When there is a queue, they wait long enough before attempting an alternative action. Response time is the time from the call to evacuation is issued to the time an occupant begins the evacuation movement. The Gene attribute determines the individual's ability to communicate with information. A Gene value of zero indicates that the person is not related to any other evacuee.

Table 3.6. Range of occupant psychological attributes.

Psychological Attribute	Scale
Drive	1 – 15
Patience	1 – 1000 seconds
Response Time	1 – 10000 seconds
Gene	Greater than 0

Among the experiential attributes, the first four in Table 3.7 are dynamic attributes changing during the simulation. Personal Elapsed Time, for example, measures the total time spent during the evacuation. Wait time is initially set to zero and then continuously compared with Patience. The total time an evacuee stays waiting is the Cumulative Wait Time. The remaining attributes are dependent on the intended scenario.

Table 3.7. Range of occupant experiential attributes.

Experiential Attribute	Scale
Personal Elapsed Time	0 – ∞ seconds
Distance Travelled	0 – ∞ metres
Distance Remaining	0 – ∞ metres
Wait	0 – ∞ seconds
Cumulative Wait Time	0 – ∞ seconds
Target Door	Nearest Door or List of Doors
Occupant Exit Knowledge	Nearest Exit – All Available Exits
Occupant Itinerary List	No task – Unlimited

Hazard attributes, as mentioned in the previous section, measure the effects of fire on the evacuees. Exposure to heat (conductive, convective and radiative), narcotic gases (HCN, CO, CO_2 and low O_2) and irritant gases (HCL, HBr, HF, SO_2, NO_2, acrolein and formaldehyde) along with their threshold and incapacitating dosed as measured by their respective governing equations described contributes to the evacuees' movement degradation. Tables 3.8 and 3.9 give the range of heat and narcotic gases. For the irritant gases, the instantaneous exposure and tolerance factor is stipulated. FIC represents an occupant's instantaneous exposure to all irritant gases and TF represents the tolerance factor of all irritant gases. The former has a range of 0 – 1 while the latter is based on the distribution of escape impaired values as shown in Table 3.3. The seven irritant gases measured are also given in Table 3.10. Aside from FIC and TF, the cumulative exposure to all irritant gases and their critical dose are measured, denoted by FLD and CD respectively. FIC, FC, FLD and CD for each individual gas is also measured. A subscript is used for notation e.g. CD_{HF}. See Table 3.10.

Table 3.8. Range of the effect of heat on occupants.

Heat	Scale
FIH (cumulative exposure to convection and radiation)	0 – 1
FIH_c (cumulative exposure to convection)	0 – 1
FIHr (cumulative exposure to radiation)	0 – 1
D_r (Pain Threshold)	∞
RHT (Radiant Heat Threshold)	∞

Table 3.9. Range of the effect of narcotic gases on occupants.

Narcotic Gases	Scale
PID (Personal Incapacitation Dose)	0 – 1
FICO (cumulative exposure to CO)	0 – 1
FICN (cumulative exposure to HCN)	0 – 1
FIO (cumulative exposure to low O_2)	∞
VCO_2 (hyperventilation effect caused by CO_2)	∞
$FICO_2$ (cumulative exposure to CO_2)	0 – 1
FIN (cumulative exposure to low O_2, HCH, CO, CO2)	0 – 1

Table 3.10. Dose notations of irritant gases.

Irritant Gas	FIC	TF	FLD	CD
HCL	FIC_{HCL}	TF_{HCL}	FLD_{HCL}	CD_{HCL}
HBr	FIC_{HBr}	TF_{HBr}	FLD_{HBr}	CD_{HBr}
HF	FIC_{HF}	TF_{HF}	FLD_{HF}	CD_{HF}
SO_2	FIC_{SO2}	TF_{SO2}	FLD_{SO2}	CD_{SO2}
NO_2	FIC_{NO2}	TF_{NO2}	FLD_{NO2}	CD_{NO2}
CH_2CHO	FIC_{CH2CHO}	TF_{CH2CHO}	FLD_{CH2CHO}	CD_{CH2CHO}
HCHO	FIC_{HCHO}	TF_{HCHO}	FLD_{HCHO}	CD_{HCHO}

3.2.4. Verification and validation

The process by which a software is independently evaluated for reliability is termed Verification and Validation (V&V). The main guidance for V&V of evacuation models provided by the International Maritime Organization (IMO) mainly for ships are used for evacuation models of other kinds of structures. The information in which a software is compared against can be in the form of qualitative expectations or quantitative experiment, or a routine checking of software sub-components and their inherent assumptions. Behavioral uncertainties are acknowledged, and standard procedures are used in the validation process.

The EXODUS suite of software has presumably undergone all forms of verification and have been verified (Galea *et al.*, 2017a). Like many evacuation models, the software has been validated against fire drills, past experiments, other models and by third party (Kuligowski, 2016). The utility of the results then lies in the hands of the user. Using scientific and engineering principles, analytical benefits which are not within the reach of hand calculations can be derived from computer model results.

3.3. Fire Safety Evaluation

The methodology utilized for the assessment of fire safety can either be deterministic or probabilistic. Deterministic methods of analysis quantify fire and its consequences on building occupants by providing the outcome of a single scenario. Usually, this is done by considering a conservative input data. There are two aspects to be considered with regard to the scenario evaluated: fire scenario and occupant scenario. A fire scenario is defined as "a set of conditions that defines the development of fire and the spread of combustion products throughout the building" (Hadjisophocleous and Mehaffey, 2016). The total possible scenarios that may occur in a building is obviously very large and the choice of both scenarios is therefore determined the likelihood of occurrence and consequence of the scenario. The building characteristics, function and materials used are necessary information for quantifying the fire and its consequence. For a particular scenario, the fuel load and the occupant load interact to produce the desired egress performance. The process of ensuring that the desire level of safety is achieved as summarized in Figure 3.7 is adapted from (Buchanan, 2001).

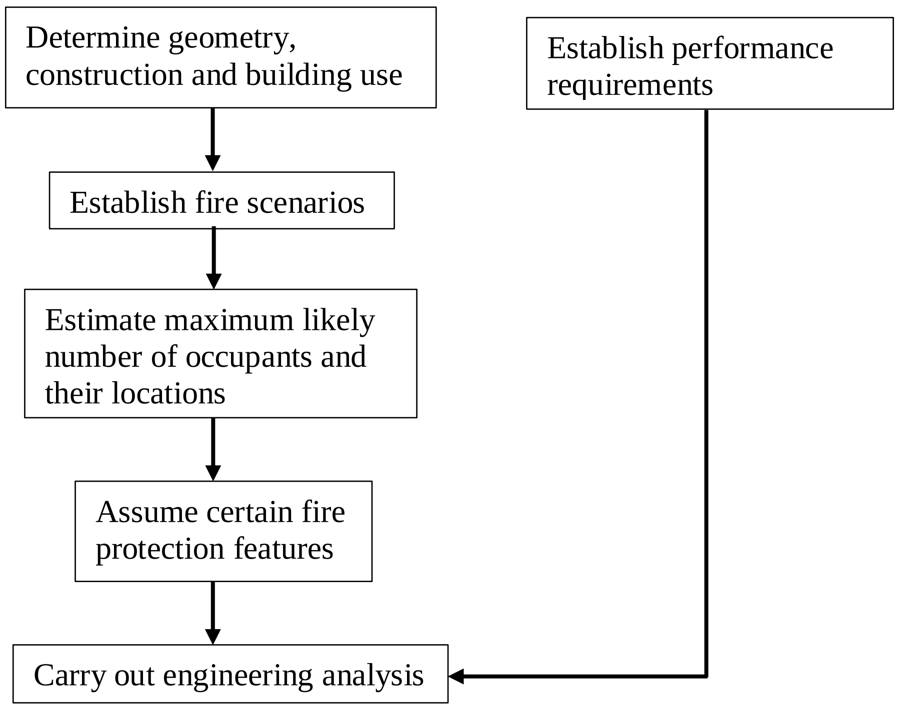


Figure 3.7. FSE Analysis procedure.

The term *occupant load* is used to describe "the total number of persons that might occupy a building or a portion thereof at any one time" and occupancy is "the purpose for which a building or other structure, or part thereof, is used or intended to be used" (NFPA, 2015). Residential buildings can be classified, based on occupancy, into dwellings, hotels, dormitories, tenements, flats or apartment buildings, etc. A single-family house up to three story high (Hong Kong, 2011) or a house for one or two families with maximum two independent units (TÜYAK, 2012) can be considered a dwelling. An apartment building is "a building or portion thereof containing three or more dwelling units with independent cooking and bathroom facilities" (NFPA, 2015). A high-rise residential building therefore consists of a collection of flats or apartments. The occupant load for any structure is evaluated from the occupant load factor or floor space factor. Several building fire safety guidelines specify the recommended values for residential building occupant load factor based on either the usable area or the number of bedrooms. Data also suggests that apartment buildings are more densely populated than dwellings (Hopkin *et al.*, 2019). Table 3.11 gives occupant load factors in select fire safety codes. The value for NFPA 101 and IBC is based on the 'gross leasable area' defined as "fifty percent of major tenant areas, and 100 percent of all other floor areas designated for tenant occupancy and exclusive use including storage."

Table 3.11. Occupant Load Factor for residential buildings.

Fire Safety Code	Occupant Load Factor
BYKHY	20 m^2/person (occupied area)
IBC and NFPA 101	18.6 m^2/person for (gross leasable area)
Approved Document B	8.0 m^2/person (bedrooms)
New Zealand C/VM2	Number of bed spaces and staff when appropriate
Hong Kong COP	4.5 m^2/person ($\geq$ 5 flats served by each staircase) 9 m^2/person (other flats)

It is evident from above that the distribution of the occupant load parameter is lacking and the source from which these values were derived may be dissimilar from the building of interest. To be in line with the modern PBFD, utilizing the occupant density distribution is more appropriate especially for probabilistic assessment. (Hopkin *et al.*, 2019) collected housing data in the UK for high-rise, low-rise and apartments, and generated a log-normal probability distribution of the occupant density in all the building types. A comparison between using number of occupants per bedroom against using occupant density per floor was also made. The former was described as more ‘reasonable’, as it better represents occupants who may be sleeping in a dwelling and the relationship between floor area and the number of bedrooms is subjected to a wide range of spread.

On the other hand, the selection of design fire scenario and design fires for a deterministic fire engineering analyses requires a qualitative description of a fire with time, identifying key events that characterize the fire and differentiate it from other possible fires (ISO/TS 16733, 2006). This accounts for the likelihood and potential for design fire scenario. This methodology is outlined in Figure 3.8.

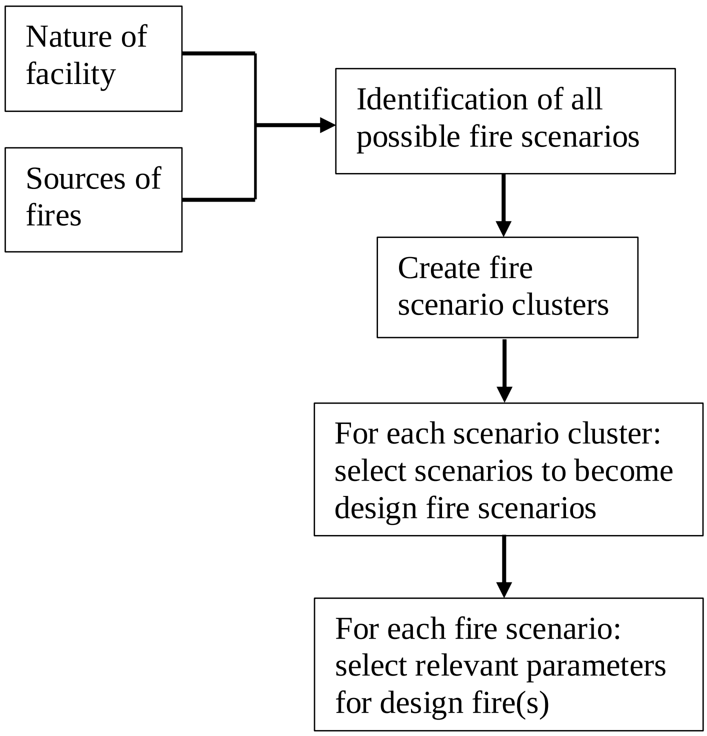


Figure 3.8. Fire scenario selection process.

According to (New Zealand, 2014), a fire in normally unoccupied room threatening the occupants of other rooms must satisfy the following:

(i) A FED of CO greater than 0.3;

(ii) A FED of thermal effects greater than 0.3; and

(iii) Visibility less than 10m except in rooms of less than 100m^2 where visibility may fall to 5.0m

Also, "for a building where vertical escape routes serve more than 250 people in a sleeping occupancy, visibility shall not be less than 5.0m in more than one escape route for the period of the RSET."

3.4. Probabilistic Risk Assessment

The two components of risk are exposure and undesired consequence (Watts and Hall, 2016). The former refers to the likelihood of experiencing a destructive event, i.e. fire. The latter is are a consequence of the former event. In an uncertain situation, the possibility of an unwanted outcome is a function of three factors:

(i) The loss or harm to something that is valued,

(ii) The event or hazard that may occasion the loss or harm, and

(iii)The judgement about the likelihood that the loss or harm will occur.

The term 'risk' has been defined by engineers as a numerical value that is a function of probability and consequences. In the context of this thesis, therefore, *fire risk* is defined as the possibility of loss of lives in an uncertain fire hazard. Building fire risk analysis refers to the process of understanding and characterizing fire hazard(s) in a building, the unwanted outcomes (loss of life) that may result from fire and the likelihood of fire and unwanted outcomes occurring. This is one of the main ways of assessing uncertainty, sensitivity and variability in unknowns (Meacham *et al.*, 2016). A mathematical representation of risk is given by equation 3.10.

$$Risk_i = \sum_{i}^{n} (Loss_i \; x \; P_i) \qquad (3.10)$$

where $Risk_i$ is the risk associated with scenario i

$Loss_i$ is the risk associated with scenario i

P_i is the probability of scenario i occuring

A concept which aims to provide a framework for the various aspects of risk is known as *risk* characterization (Meacham, 2004). These aspects of risk include risk identification, assessment, communication and analysis. Risk characterization suggests that coping with a risk situation requires a broad understanding of the relevant losses or consequences to the interested parties i.e. the building occupants. In the previous chapter, PRA methods have been described and the appropriate method for life safety assessment was identified. The objective of PRA for a system is to analyze the system by functions and compute probability of system failure as a function of the components accounting for the possibility of the external event, fire in this case.

The acceptable criteria for use in quantitative fire risk assessment developed by (Rasbash, 1984) is based on the following statistics:

(i) Fire loss statistics;
(ii) Statistics (and judgement) on the number of premises at risk; and
(iii) Statistics (and judgement) on the on the total number of occupants in each building type.

Table 3.12. Target probabilities for fire risks in buildings (Rasbash, 1984).

Maximum number at risk in a building	N number of fatalities			
	N > 5	N > 15	N > 100	N > 500
Less than 15	5×10^{-7}	-	-	-
15 – 100	1×10^{-6}	3×10^{-7}	-	-
100 – 500	2×10^{-6}	5×10^{-7}	6×10^{-8}	-
Greater than 500	4×10^{-6}	8×10^{-7}	1×10^{-7}	5×10^{-8}

From Table 3.12, in a building with more than 500 people at risk and where 5 or more people may be killed in a fire, target probability ranges from 10^{-6} to 10^{-8}. Based on that, one could establish target probabilities for fire risks in buildings based on the number of fatalities and the number of people at risk in the building as summarized in Table 3.12. This safety criteria can be considered as the ‘tolerance level’ rather than the more ambiguous ‘acceptable risk’. These concepts will be applied in the next chapter to determine the safety of rise residential building occupants in specific fire and occupant scenarios.

4. CASE STUDY

The evaluation of an FSE design for life safety involves developing scenarios that will test the ability of the building features to meet the safety goals. From a life safety point of view, this will require comparing the predicted ASET scenarios against the RSET scenarios of the design. The fire with the fastest growth rate or highest peak HRR is not necessarily the scenario that poses the greatest challenge to the FSG of occupant life safety. It is easy to see that a fire which blocks an egress path in which more occupants must pass through or stay longer poses a greater threat to the occupants of the building than one from which it is easy to move away. Also, given the randomness and uncertainty associated with people's response and behavior, a risk analysis is needed to analyze the consequence of the worst-case or quasi-worst-case scenario. In this chapter, the fire safety of a typical high-rise residential building in Istanbul will be evaluated. Given the available data on the population demographics and building characteristics, the evacuation of high-rise residential building occupants during fire has been simulated and the results have been analyzed.

4.1. Data: Istanbul

The map of Istanbul with the locations from which the data on floor size and number of 1167 high-rises were extracted is shown in Figure 4.1. These buildings vary in height and cross-section ranging from 15 floors to more than 55 floors and a few buildings exceeding 2000 square meters. A lognormal distribution approximates the floor number with a mean of approximately 17.7 floors and a standard deviation of 29 floors. The floor area also follows a lognormal distribution with a mean of $632m^2$ and a standard deviation of $278m^2$. These distributions are shown in Figure 4.4 and Figure 4.5. Moreover, only a few buildings exceed 45 floors, and this puts it in the 99.4^{th} percentile.

In order to perform a study on the fire safety of Istanbul high-rise residential buildings, the maximum floor height (99.4^{th} percentile) and average floor area (50^{th} percentile) will be used as basis in selecting the case study model. This will serve as a benchmark and the effect of increasing the floor area will also be studied in the parametric study of occupant load. Also, based on (Oven and Cakici, 2008) and other previously mentioned sources, the demographic attributes of Istanbul building occupants have been represented by the values in Table 4.1. The range of age distribution was divided in such a way as to coincide with the travel speed data in Table 3.5.

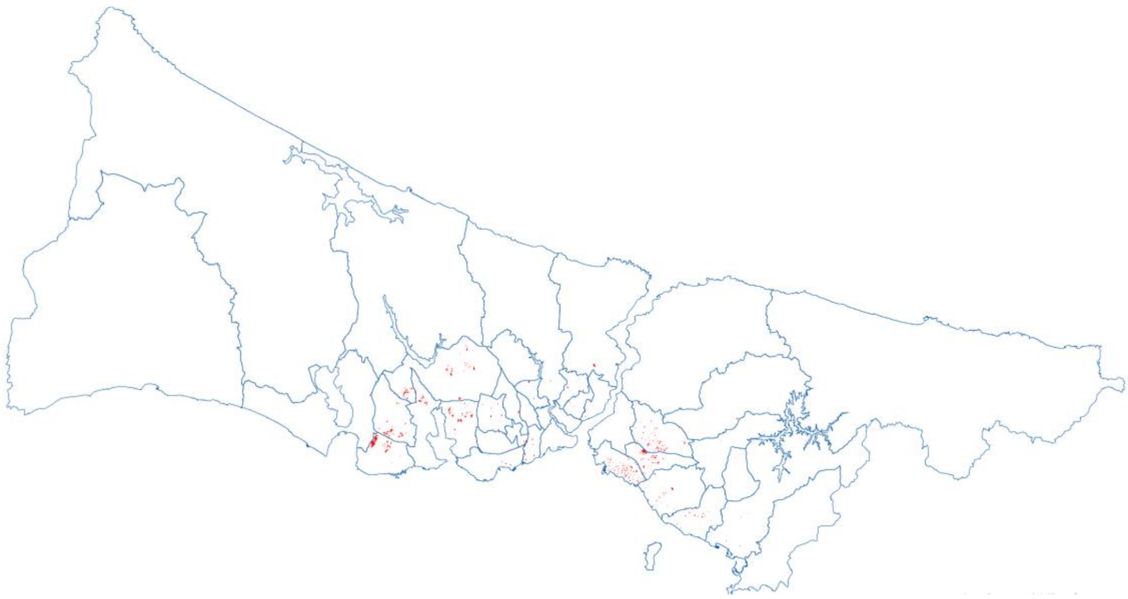


Figure 4.1. Map of high-rise buildings in Istanbul.

Table 4.1. Attributes of building occupants in Turkey.

Attribute	Males	Females
Age groups and their weights	12 – 29 years (20%, 40 – 80 kg) 30 – 50 years (20%, 60 – 90 kg) 51 – 80 years (10%, 60 – 80 kg)	12 – 29 years (20%, 40 – 80 kg) 30 – 50 years (20%, 60 – 90 kg) 50 – 80 years (10%, 60 – 80 kg)
Height	1.65 – 1.85 m	1.55 – 1.75 m
Agility	4 – 6	5 – 7
Drive	9 – 11	11 – 13
Patience	160 – 200 seconds	180 – 220 seconds
Response Time	11 – 181 seconds, mean = 3.78, S.D = 0.72 (lognormal)	11 – 181 seconds, mean = 3.78, S.D = 0.72 (lognormal)

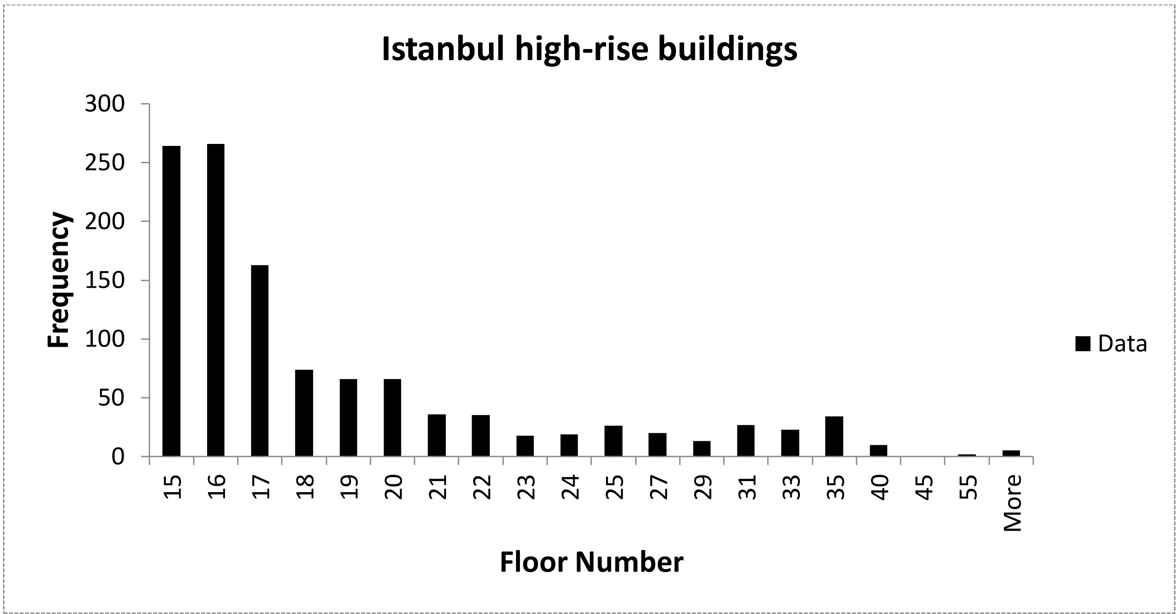


Figure 4.2. Distribution of floor number of Istanbul buildings.

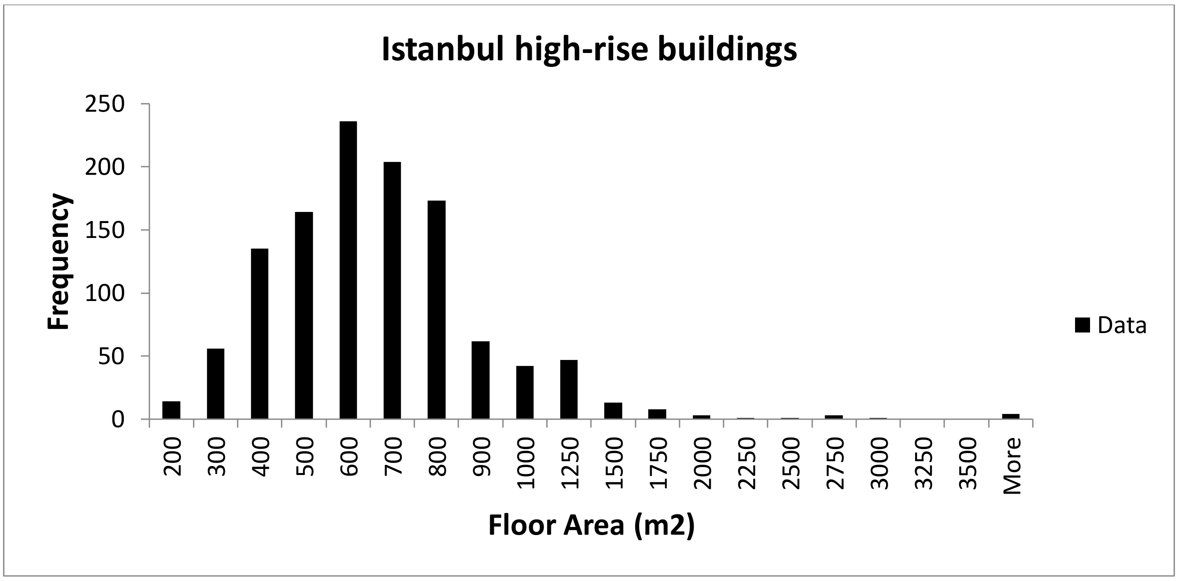


Figure 4.3. Distribution of floor area in Istanbul buildings.

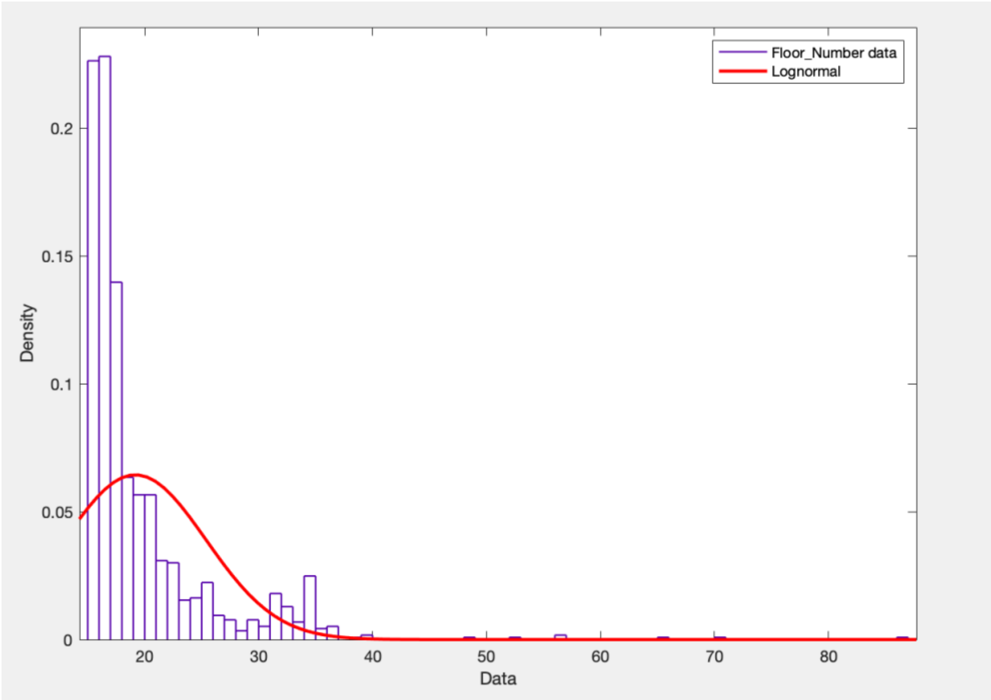


Figure 4.4. Probability density function of Istanbul high-rise floor number data.

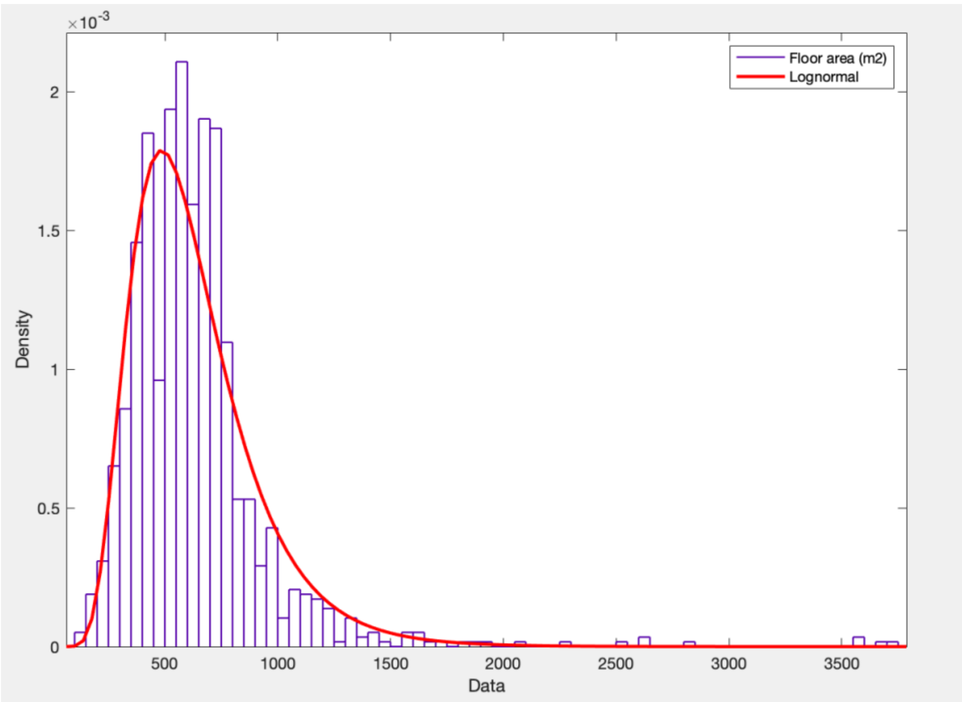


Figure 4.5. Probability density function of Istanbul high-rise floor area data.

4.2. Case Study Model

A typical high-rise residential structure consists of separate apartments with a common corridor to access the stairs and elevators on each floor. A protected entrance hall is recommended for fire safety as escape through this configuration is safer than one through an accommodation room from open plan flats. Furthermore, for full building evacuation strategy, the stairs should have a capacity for storing the occupants. And since lifts are not used for evacuation, two or more stairs are appropriate. Not all codes adopt the same standard. And as mentioned in chapter 2, the adoption of a third stair may be appropriate for high-rise buildings exceeding a certain height as is the case in IBC. As a result, a two-stair tower deemed sufficient has been chosen without the consideration of the need to satisfy all codes or any one particular code. The floor model in EXODUS is shown in Figure 4.6 and the case study model building with randomly placed occupants on each floor is represented as shown in Figure 4.7.

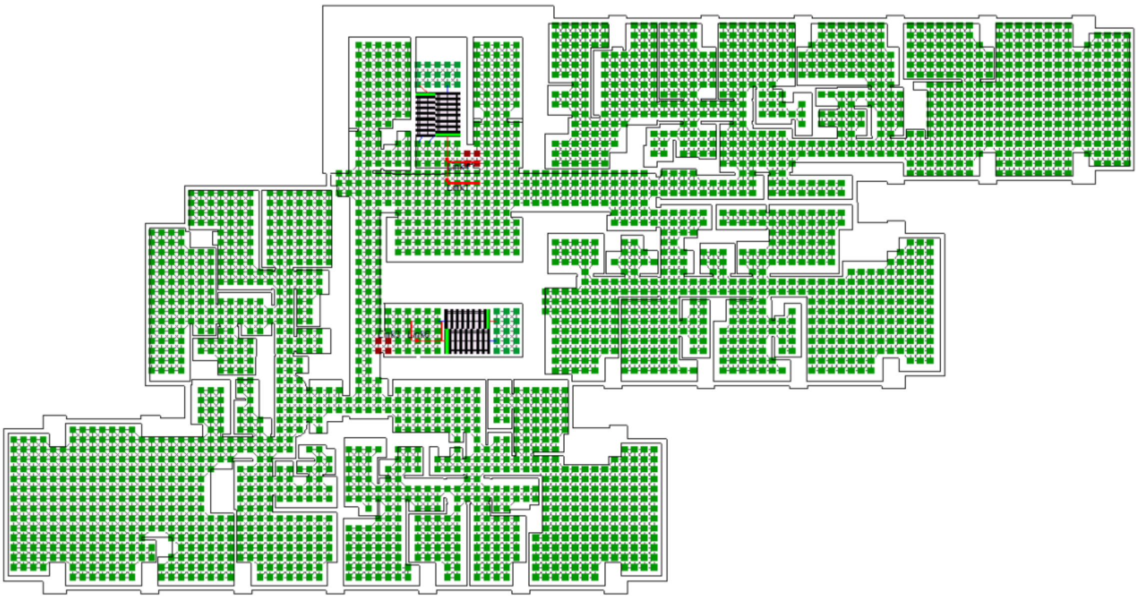


Figure 4.6. EXODUS Nodal Representation of Case Study Model Floor Geometry.

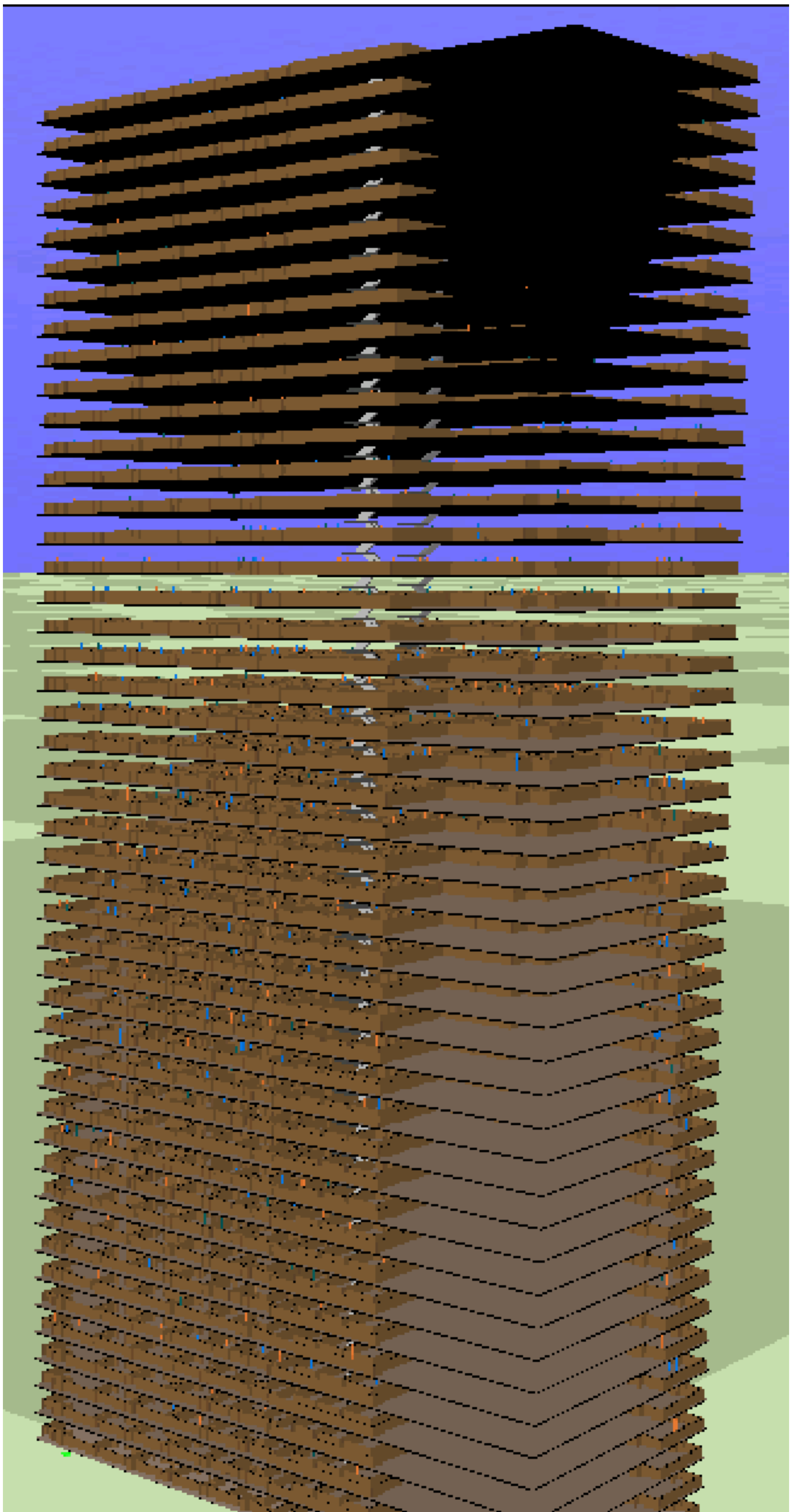


Figure 4.7. Case Study Model.

4.2.1. Benchmark Model Description

The case study model is a 180m high model structure consisting of 45 floors above ground level. Non-occupiable areas for technical services are on 12th and 29th floors of the tower. Four separate compartments make up each floor as shown in Figure 4.8 and their sizes are given in Table 4.2. The occupants travel through nodes represented in Figure 4.5 to the stairwell and then move downwards to the exit discharge. The flow rate assumption for exits in the Turkish fire code is identical to the HMSO flow rate of 1.33 occupants/m/s. Each floor is connected opposite the incoming stair so the evacuee entering the door leading to the staircase lands on the stair immediately after accessing the door. The elevators and lift are not used for the evacuation. The staircases each has a width of 1.22 m with 9 risers that spread evenly across a length of 2.25 m. The height between floors is 3.85 m and the staircases are dog-legged; each flight of stair is 1.95 m in height with a connecting half-landing 1.5 m by 2.5 m. The width 1.22 m of the stairs has two lanes accommodating an individual on each and therefore a maximum capacity of 16 people for each rising staircase. On each boundary of the stair, a 0.1 m handrail intrudes by 0.087 m. As a result, the total number of people that can be stored in each of the fire escape enclosure is 62 and 72: each stairwell has a capacity for storing 16 evacuees, each landing 15 evacuees and at the entrance of the fire escape area, 15 and 30 occupants can be stored as the nodes in Figure 4.6 show.

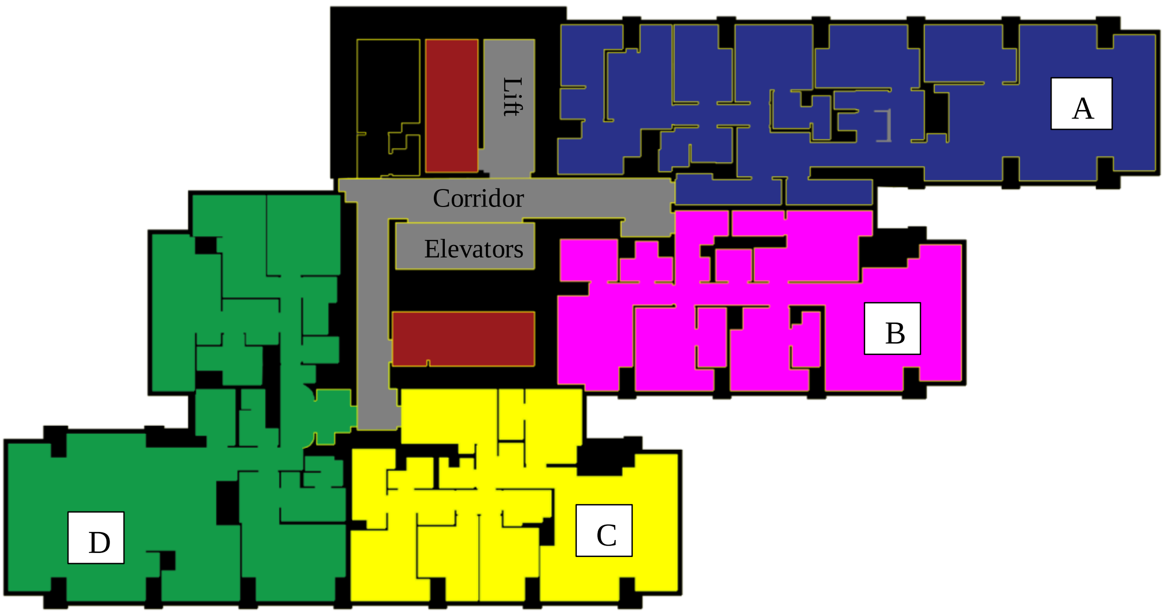


Figure 4.8. Compartmentation of Model Tower.

Table 4.2. Total Useable Area and Occupants of Model Tower Compartments.

Compartment	Area (m^2)	Number of Occupants
A	250.6	13
B	175.5	9
C	159.9	8
D	252.9	13
Total	838.9	43

4.2.2. Fire scenarios

NFPA 101 (chapter 5) and C/VM2 (part 4) both give several fire locations required to challenge a fire safety design. As a residential building, the source of fire in the present case study building is likely an outbreak in one of the compartments leading to the burning of a household item and eventual spread of the fire. Upholstered furniture, for example is known to have an ultrafast fire growth rate. Pre-flashover design fire has been assumed to grow as a fast t^2 fire with a growth rate of $0.0469t^2$ up to a peak HRR of 1,000kW/m^2 with a radiative fraction of 0.35 (New Zealand, 2014). A couch made of polyurethane foam is burnt with a heat of combustion of 4,460 kJ/kg. The combustion is represented by the stoichiometric reaction given in equation 4.1.

$$C_1H_{1.7}O_{0.3}N_{0.08} + (0.930)O_2 \longrightarrow (0.649)CO_2 + (0.832)H_2O + (0.029)CO + (0.357)Soot + (0.040)N_2 \tag{4.1}$$

It is also assumed that the temperature of the surface will stay constant and as a result, a fixed temperature boundary condition of 1000˚C has been prescribed to the burner surface. For the wall and floor surfaces, thin obstructions have been used to represent them, meaning that the heat transfer on these surfaces is not considered. The heat of reaction of the by-products used as fuel for the combustion model is 1000kJ/kg.

Table 4.3. Thermal Properties of foam.

Property	Value
Density	27 kg/m^2
Specific heat	1 kJ/(kg.K)
Conductivity	0.05 W/(m.K)
Emissivity	0.9
Absorption coefficient	50000 1/m

Both reactions are endothermic and take place within a mesh of size 0.1m with a design *Fire Load Energy Density* (FLED) of 400 MJ/m^2 (New Zealand, 2014). The Fire Load Density concept implicitly assumes a uniform distribution of combustibles in compartments (Hadjisophocleous and Mehaffey, 2016). The path in the building through which the fire is assumed to spread is shown in Figure 4.9 and Figure 4.10. Two thermocouples were installed to measure the head height and near floor height temperature on the stair area.

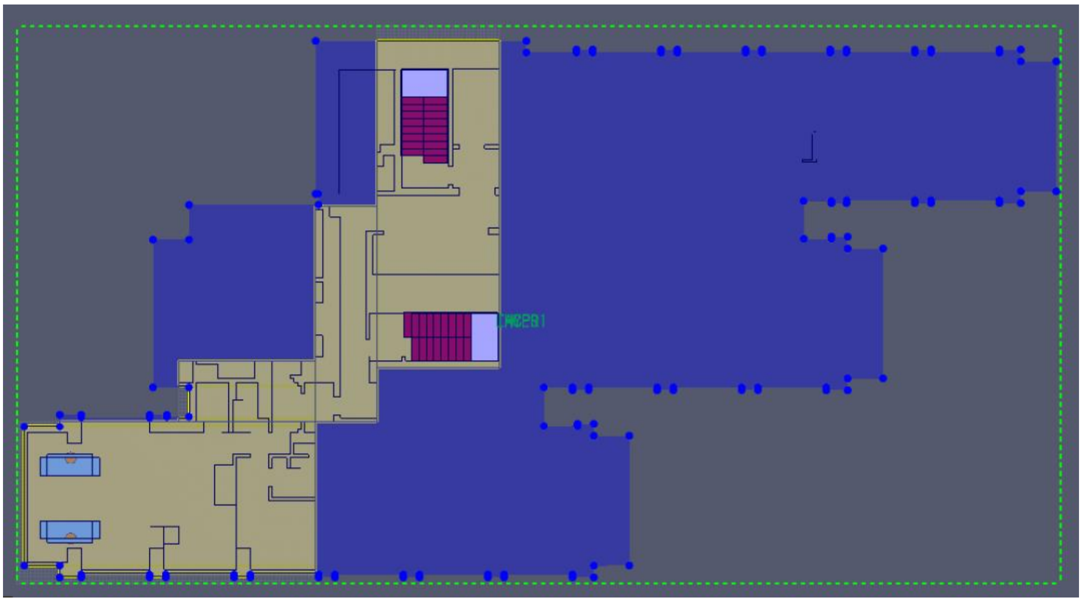


Figure 4.9. Meshed area of the floor.

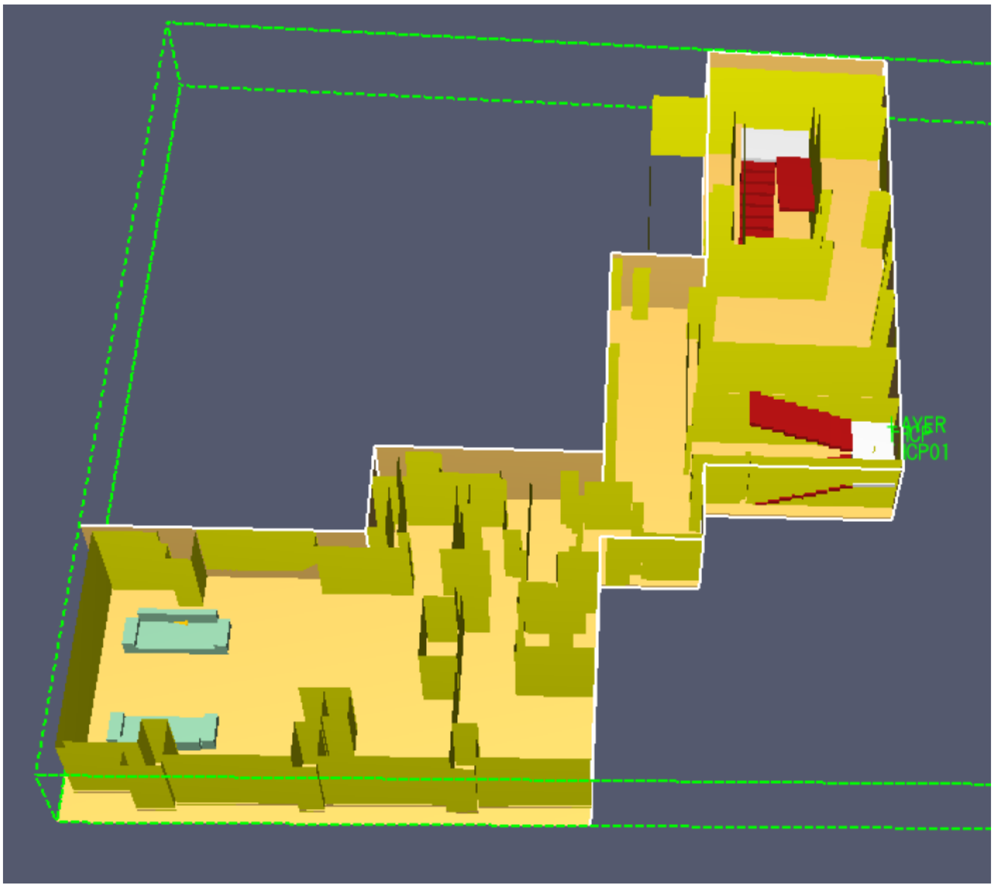


Figure 4.10. Volume of fire spread in the building.

4.2.3. Occupant scenarios

As per BYKHY, the number of occupants expected to occupy the floor areas are given in Table 4.2. The alternative approach of using number of bedrooms expected also gives a similar number. Aside from the size and distribution of the population, the location of the occupants of each floor are distributed randomly across the area and therefore the evacuees have no stated location at the start of the evacuation. Since it is more likely that occupants use the nearest known exit, the population can be divided into two: occupants of compartment A and B use one of the stairwells while those of compartment C and D use the other. This means that for each floor, a slight difference in the number of occupants using a stair may expected. They also have no given itinerary list; they simply head to the nearest exit at the start of their movement phase. The total population is distributed evenly between males and females. The physical attributes (age, weight and height) and psychological attributes (mobility, agility, RMV, drive and patience values) of these occupants are stated in Table 4.1. The response of the occupants is also random but follows a log-normal distribution with mean and standard deviation according to Table 4.1. Lastly, since elevators are not used for the evacuation, people with disabilities were not represented.

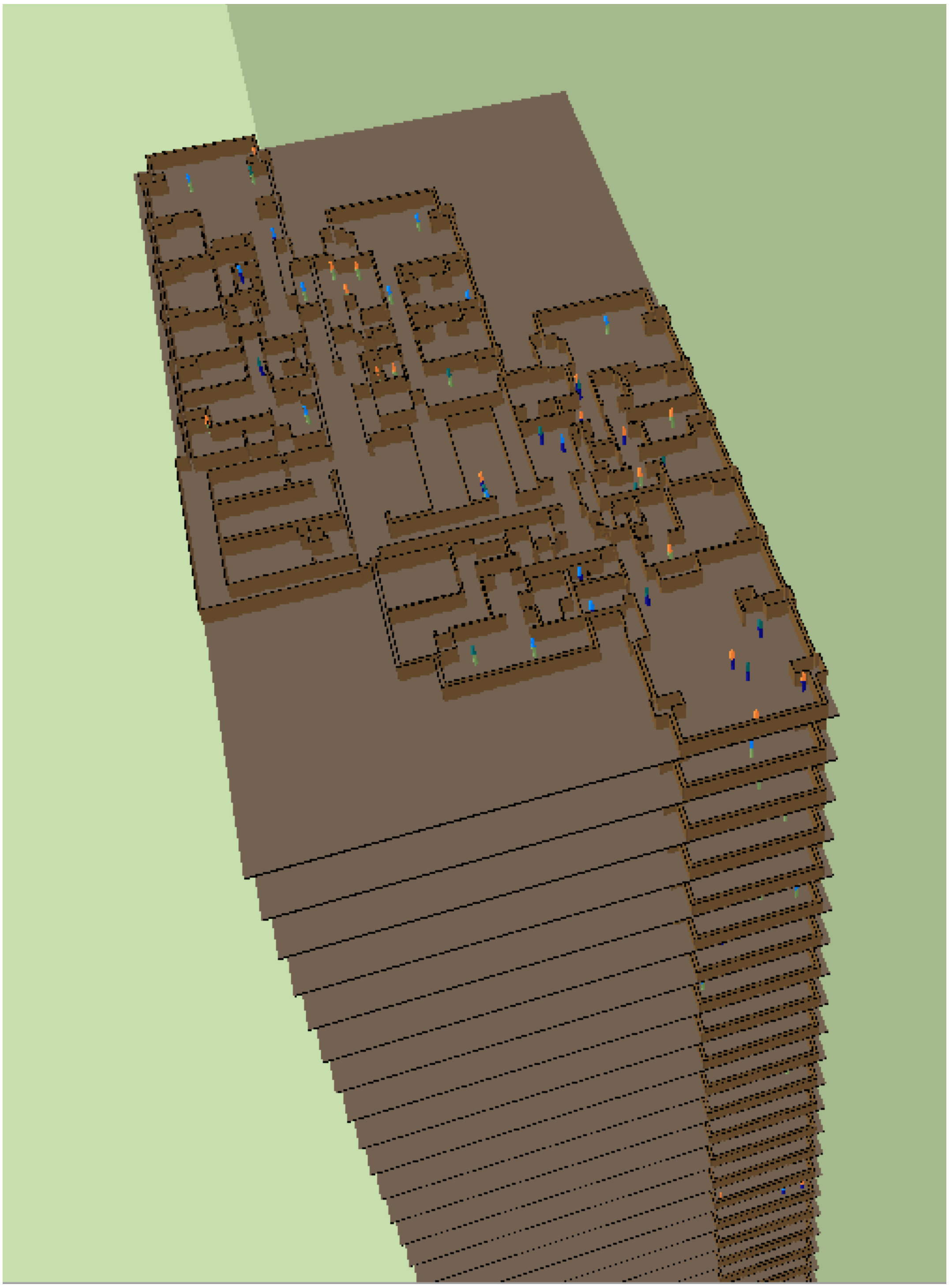


Figure 4.11. Orthographic view of Case Study Model.

4.3. Benchmark Model Studies

The analyses of the results generated from simulating the benchmark model in buildingEXODUS are presented in this section. The results obtained here will also serve as the basis for the parametric study conducted in the next section. As highlighted by (Ronchi and Nilsson, 2014), there are different levels to performing egress model simulations based on the degree of information available about the scenario to be simulated. *Blind calculations* are based on a basic description of the scenario and the additional details are decided by the user. A detailed model description is required for *specified calculations* and actual evacuation data is necessary for *open calcula*tions. For a benchmark model with actual evacuation data, open calculations may be viable. However, since the evacuation variables are objects of study in this project and no trials have been conducted, details of the benchmark model inputs are derived from available data and the rest of the inputs are reasonable assumptions that are made. As a result, specified calculations have been carried out and the details of this model are as described above.

After simulating the model, a MATLAB code was written specifically to analyze the egress performance of the evacuees on different floors using the generated results. A general version of this code has been made available in the appendix. Since an agent-based model was used, the evacuation time of each occupant starting at a particular floor was tracked and plotted side by side with the other floors. Also, the time they spent in queues before completely evacuating the building is plotted on a separate graph. And since the queuing time represents how dense or saturated the population is, a scenario which generates more queuing time produces a negative effect on the egress performance. This graph has been normalized to express the relative change in the queuing effect for a scenario or a variable change.

The Exit Time graph produced for the benchmark model is shown in Figure 4.12. The first person to leave the building from the first occupied floor exits after 70 seconds while the first to leave from the second occupied floor exits after 79 seconds. This increase for the first occupant to evacuate the building from each floor is fairly linear with the rise in floor level as the lower line indicates. This, however, cannot be said of the last person from each floor to exit the building. A curve fit of the last person out on each floor suggest a nonlinear regression. The rise of evacuation time of the last person on each floor to fully evacuate the building is steeper than the rise in evacuation time of the first person reaching a maximum when the last person on the 28th of the 43 occupied floors. It can also be observed that some of the evacuees do not fit within the linear and nonlinear curves fitted to the start and end of the evacuation of each floor respectively. The number of these outliers are considered to be a variance resulting from the non-homogeneous nature of evacuee attributes. From the result of a single simulation, out of the 43 people on the first floor, 42 were able to fully evacuate the building in 276 seconds leaving one occupant struggling until 1449 seconds before evacuating, perhaps due to a low drive. Neglecting the outliers, the upper curve suggests that the time it takes the occupant from each floor increases reaching a maximum when the occupants from the bottom two-third of the floors have fully evacuated. Also, a curve with a similar slope as that of those first to exit on each floor reaches a peak at around two thirds of the total evacuation time. In other words, the time it takes occupants from the bottom two-third of the building to evacuate is the total evacuation time taking into account the effect of queuing.

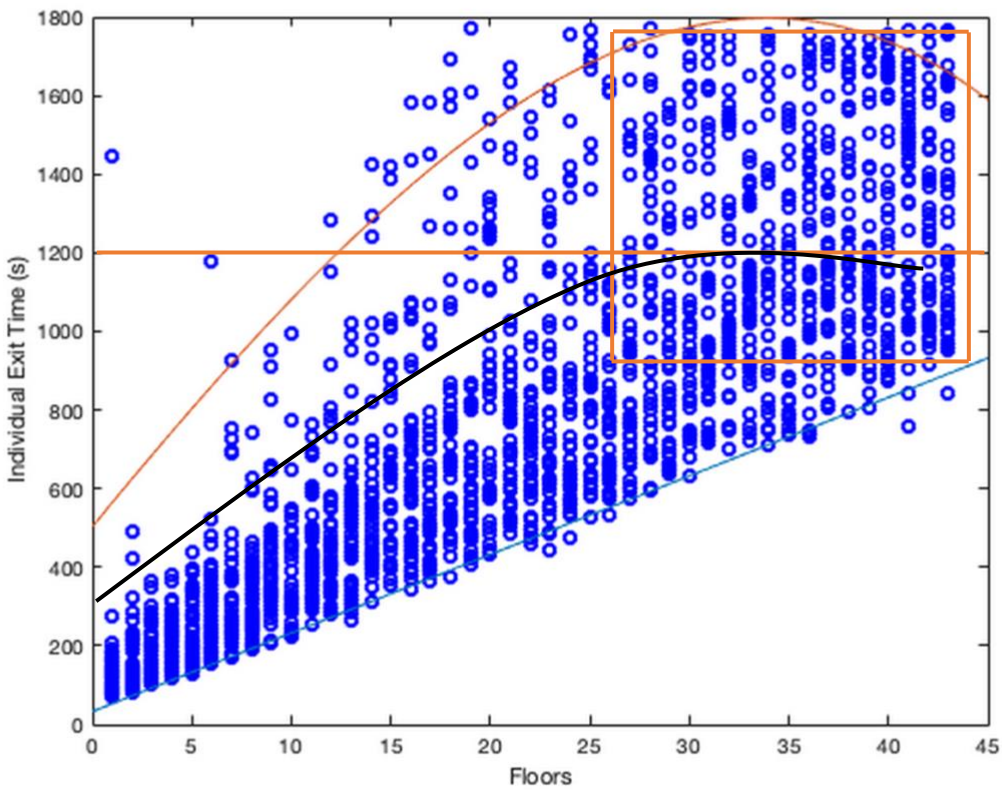


Figure 4.12. Exit Time of all evacuees on different floors.

Taking the evacuation of the occupants assuming the two thirds the height of the building i.e. 28 floors with 26 occupied floors, the evacuation also produces a similar graph as seen in Figure 4.13. In a similar manner, the top third of the building occupants finish evacuation at around the same time and also the time when the occupants from the bottom two-third have finished evacuation. We can take from this observation that a fire in the top third of the building height poses a greater threat to far more occupants than one below. Since evacuees from these floors may be subjected to additional psychological effects of fire effluents, this may be said to be a suitable threshold for additional fire safety measures.

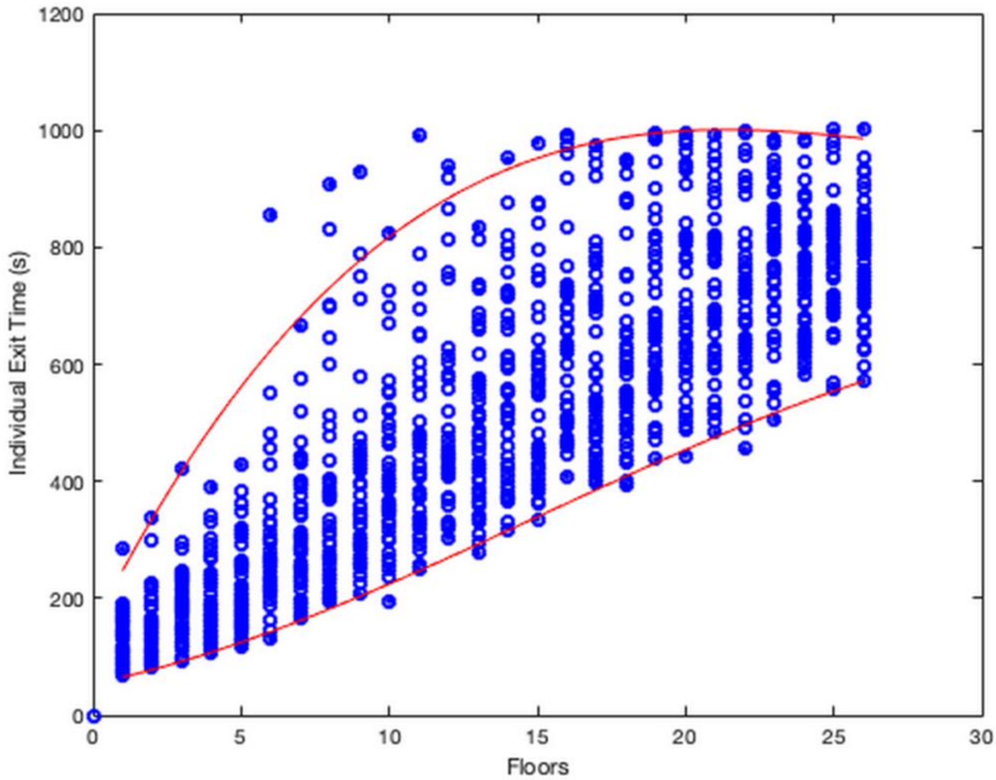


Figure 4.13. Exit Time of the evacuees on different floors (29 floors).

Moreover, although the number of occupants has been reduced by a third, the total evacuation time has more than halved: the floor numbers have increased from 28 to 46 and population from 1118 to 1849 but the total evacuation time has increased from 1038 seconds to 1770 seconds. This implies that as the height of a building increases the total time it takes to fully evacuate the building also increases with a higher proportion, i.e. a nonlinear increase.

The Exit Time graph of the benchmark model indicate that some of the occupants on the upper floors overtake evacuees on the lower floors during the evacuation. It has also been mentioned before that when evacuees have different attributes, particularly drive attribute, overtaking will occur by those with higher attributes. Figure 4.14 shows the exit time graph of a population assuming everyone has exactly identical attribute in every sense. It can be observed that unlike the benchmark model, the last person to exit increases almost as steady as the first person to exit the building. One can conclude that the nonlinear curve in Figure 4.12 is a result of the non-homogeneous nature of evacuees and that overtaking does take place in a case where evacuees have different characteristics.

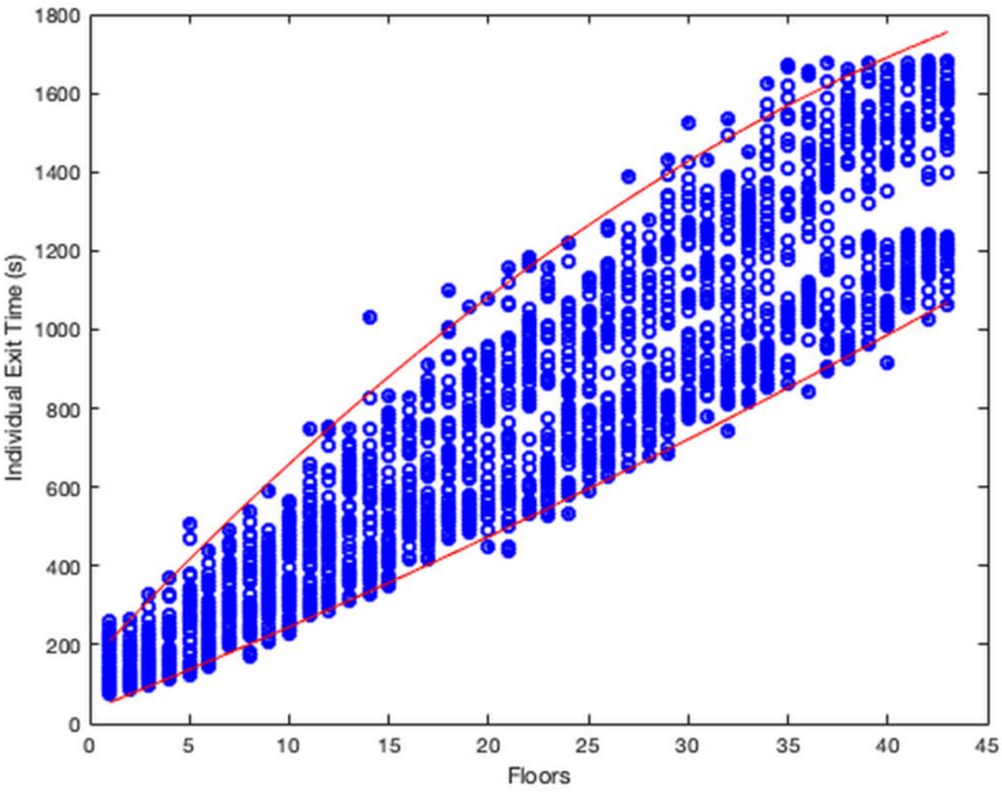


Figure 4.14. Exit Time graph of a homogeneous population.

On the other hand, Cumulative Wait Time of each occupant shows, for each evacuee, the total amount of time spent in queues before eventual exit out of the building. As Figure 4.15 indicates, this queuing effect is nonlinear in high-rise buildings. The Cumulative Waiting Time of each occupant was ordered on the basis of the time at which one exits the building. One can observe that the relative difference between time spent in queues for occupants evacuating at about the same time increases as the evacuation progresses.

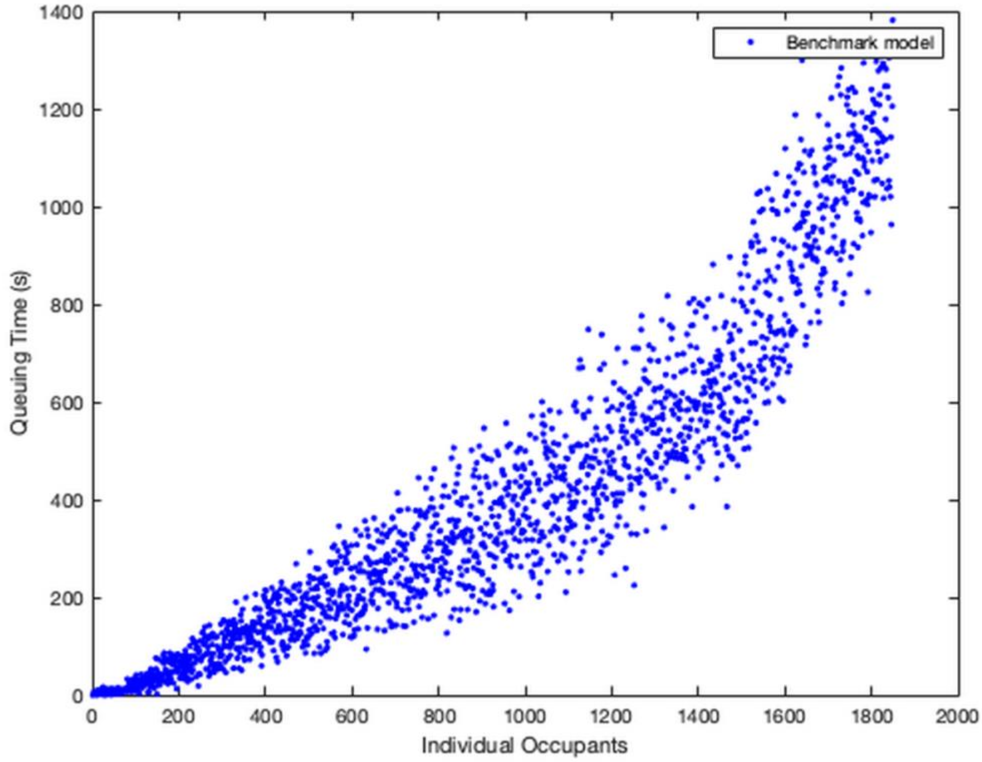


Figure 4.15. Cumulative Waiting Time of benchmark evacuees.

To investigate the effect stair have on the queuing time and as a result on the total evacuation time, a normalized graph of Figure 4.15 has been drawn to compare the total time each occupant spends in queues for the same number of occupants but with and without the use of stairs, i.e. the benchmark model with occupants on each floor and a fully saturated occupancy all on the same floor. As Figure 4.17 indicates, there is a linear progression in the effect of queuing for an evacuation without the use of stairs and a nonlinear increase for an evacuation in which stairs are used for many floors. Similarly, for Figure 4.18, those placed on the ground floor and those placed on the 2nd floor to use four flight of stairs are compared with each other. A difference of two floors has resulted in an increase in evacuation time by 50% (from 842 seconds to 1642 seconds). The Cumulative Waiting Time Graph of homogeneous evacuees is shown in Figure 4.16.

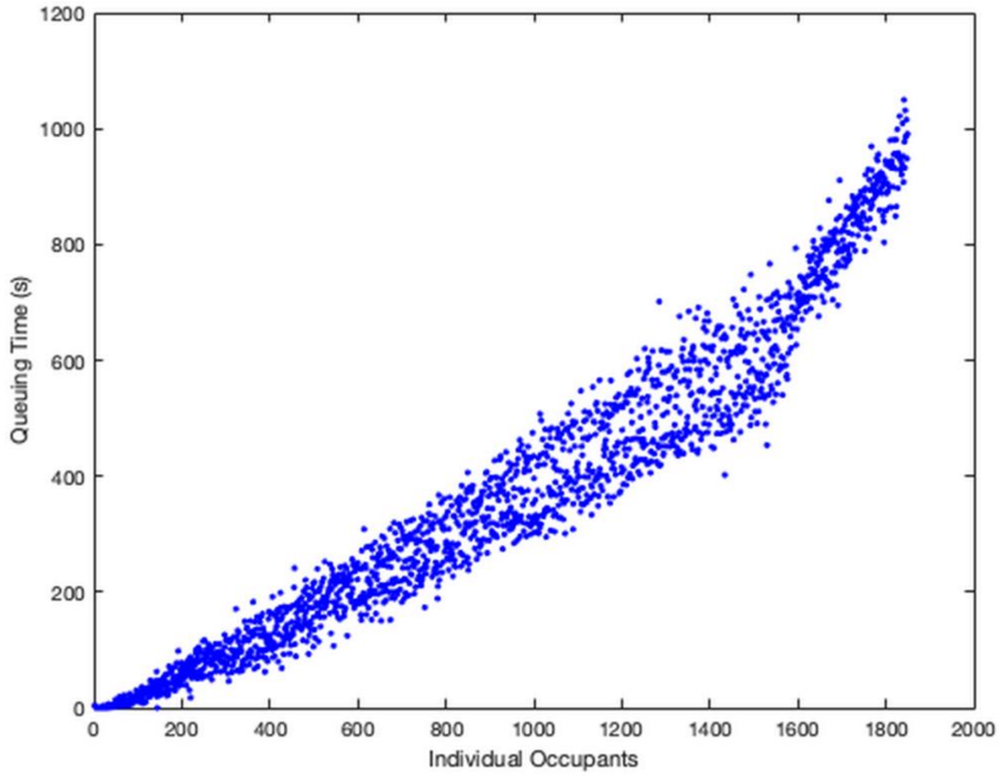


Figure 4.16. Cumulative Waiting Time of homogenous evacuees.

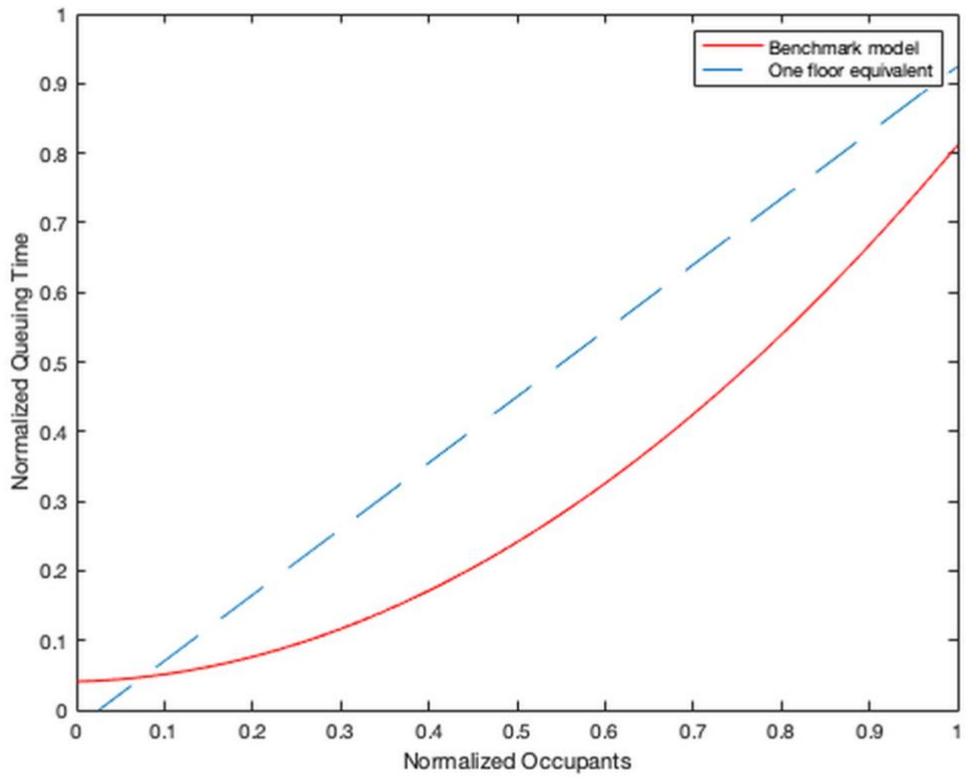


Figure 4.17. Vertical vs horizontal effects of queuing.

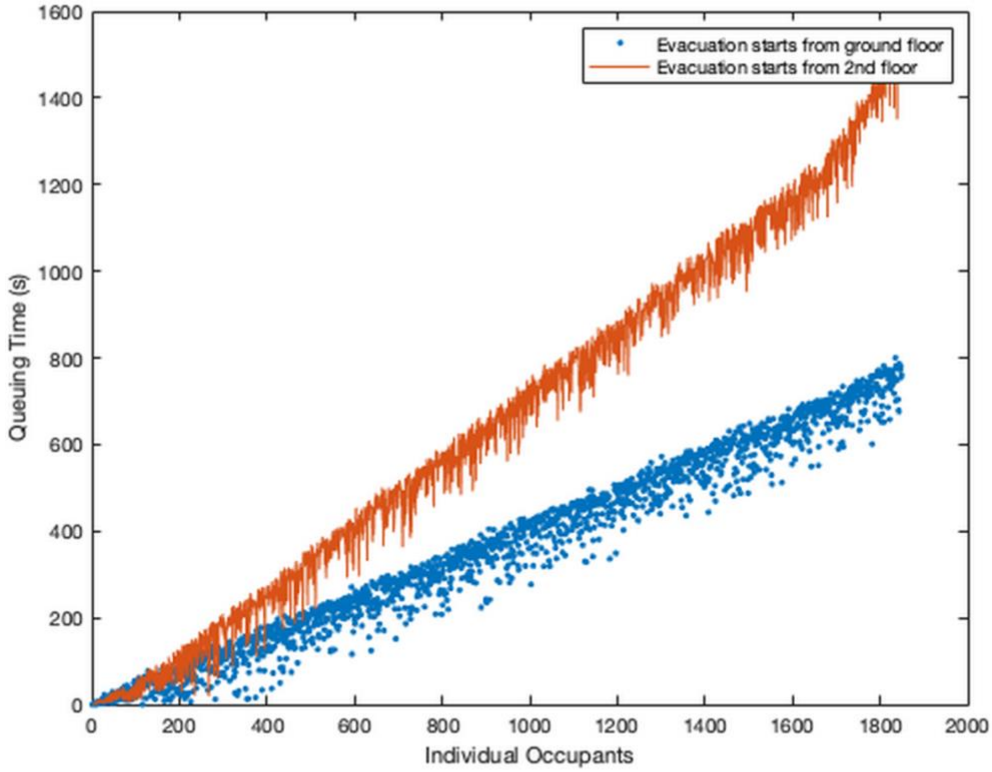


Figure 4.18 The effect of stairs on the egress.

Different floor numbers have also been compared with one another. In Figure 4.19, it can be observed that high-rise buildings as low as 15 floors and as high as 46 floors exhibit a similar egress characteristic with regard to the queuing effect on the stairs. On the other hand, a 3-storey building behaves differently, and using a straight line to represent this regression shoes that the waiting time flattens to a constant value indicating a lack of queueing effect. This behavior is also checked for a horizontal type of evacuation where a queue is expected to be formed immediately after the start of the evacuation. In a stadium evacuation, for example, all evacuees move toward an exit with a fixed flow rate and those behind are forced to wait for the people in front. For tall buildings, even the most assertive individuals on upper floors take relatively longer evacuate the building, while in short buildings, people with higher drive on upper floors can evacuate as fast as some evacuees on the lower floors.

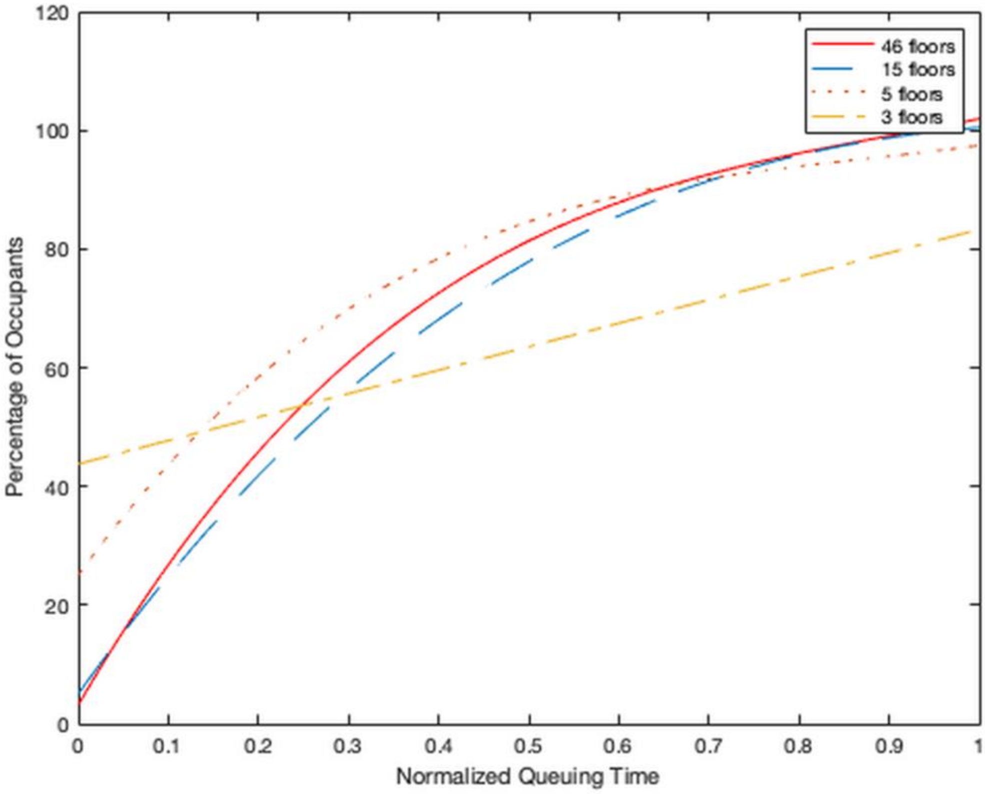


Figure 4.19. Evacuation behavior of buildings of different heights.

4.4. Parametric Studies

The effect of the different egress variables on the queuing effect and hence total evacuation time has been studied in the previous section. Evacuation from a building with more than one stair will produce different results in different simulations depending on how many evacuees use each stair, the attributes of these evacuees and their locations with time. From the geometry of the building, an almost identical performance is expected. However, a slight variation should be expected since the number of occupants in the apartment are not exactly identical. On the ground floor, occupants using each stair head toward a particular door leading out of the building while on other floors occupants use the stairs closest to their location. Optimal Performance Statistic (OPS) will be used to compare the issue. This is a measure of evacuation efficiency, 0 representing the most efficient evacuation and 1 signifying that at least one of the exit doors was not used at all. Mathematically,

$$OPS = \frac{\sum TET - EET_i}{(n-1) * TET} \tag{4.1}$$

where n = number of exits used in the evacuation

EET_i = Exit Evacuation Time (last person out of exit n in seconds)

TET = Total Evacuation Time (max. EET in seconds)

Figure 4.20. Flow of occupants out of the building.

4.4.1. Occupant Load

The first egress parameter studied here is the number of occupants assumed to be present in the building. As mentioned in the previous chapter, the data collected contains variability in the occupant density of residential buildings. According to the UK EHS data, the NFPA101/IBC recommended occupant load factor of 18.6m^2/person equates to approximately 87th percentile for all dwellings and 88th percentile for apartments (Hopkins *et al.*, 2019). To investigate the influence of a change in occupant density, three simulations were run for 21 occupants/floor, the benchmark model (43 occupants per floor) and 64 occupants/floor. The maximum queuing times are 454 seconds, 1312 seconds and 2046 seconds respectively. This indicates a tripling of queuing time with the halving of the recommended values and an increase of queuing time by 50% with a doubling of the recommended occupant load density.

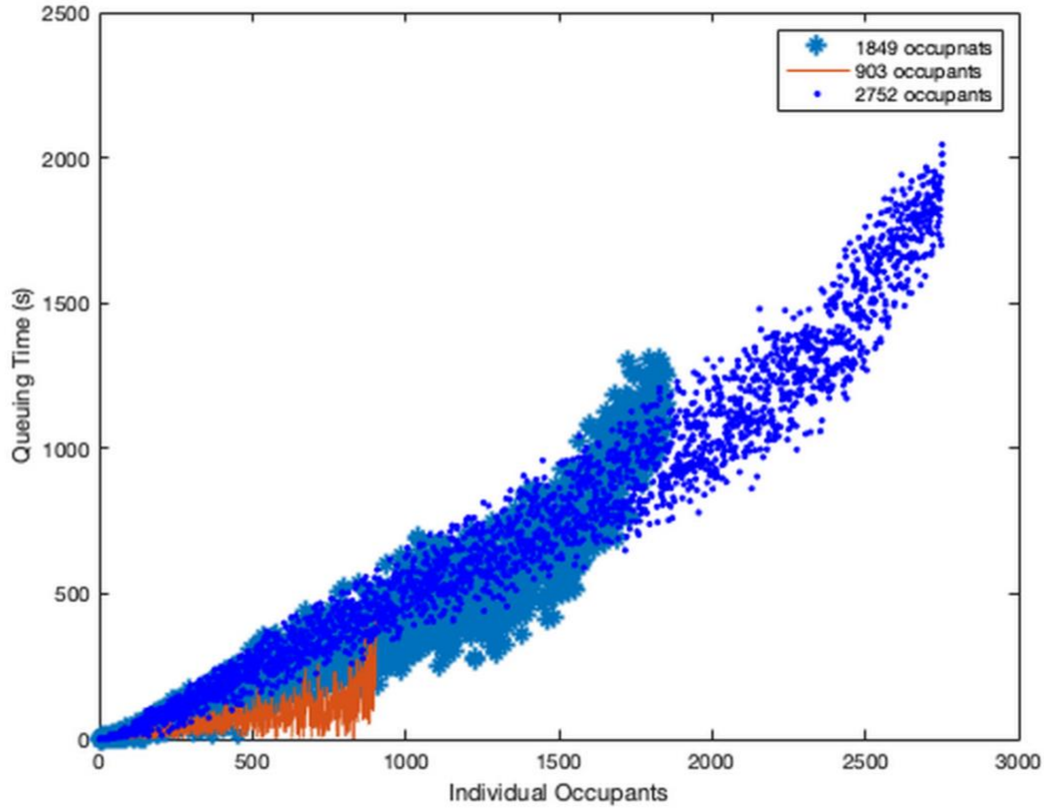


Figure 4.21. Evacuation time for different occupant loads.

The total escape time, on the other hand, increased by approximately 50% in both cases (832 seconds, 1728 seconds, 2474 seconds for 903, 1849 and 2753 occupants respectively). This suggest that occupant density has linear impact on the evacuation time in high-rise buildings. As Figure 4.22 also indicates, an increase in density by 50% does not significantly impacts the egress behaviour. The lines do not end at the full range of the queuing time due to approximation. In any case, the graph only compares the behaviour of different scenarios.

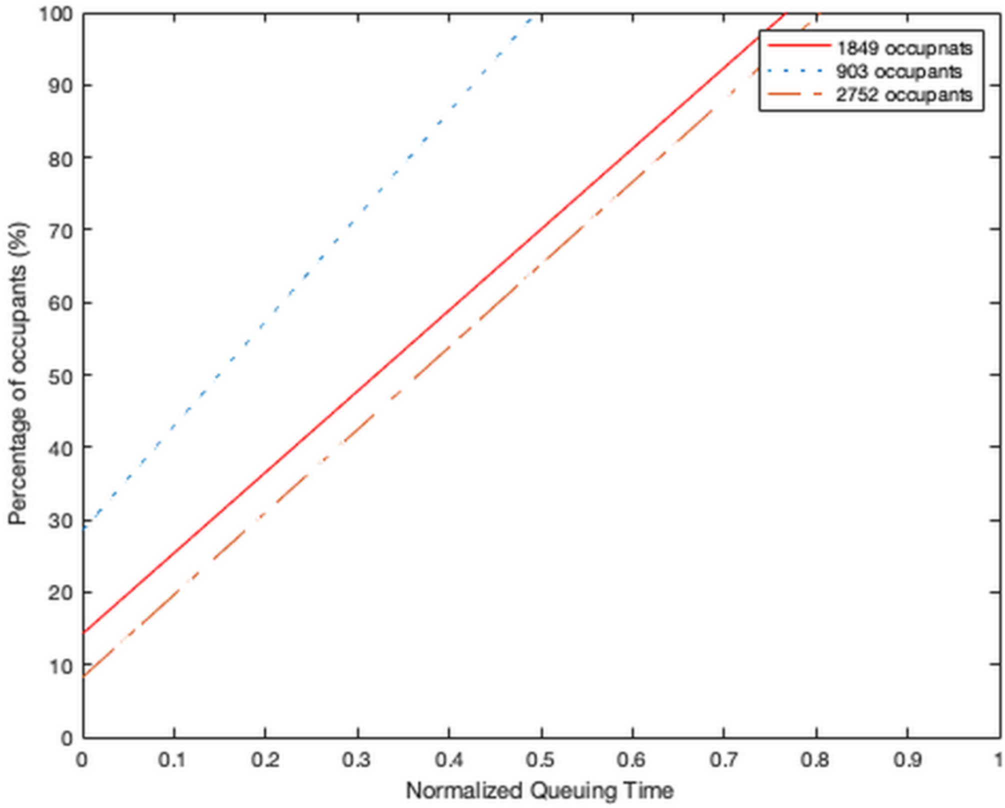


Figure 4.22. Relative queuing times of occupants for different occupant load.

4.4.2. Pre-evacuation time

Due to the fact that different occupants respond differently the notification of evacuation and the pre-evacuation behaviors of the occupants differ from each other, some occupants are expected to respond more quickly to alarm than others. As mentioned previously, the distribution of pre-evacuation time among occupants follows a log-normal distribution. A curve with a different distribution, but with the same minimum and maximum values and double the mean and standard deviation, is used to investigate the impact of this variable on the egress performance.

For residential buildings where occupants are considered unfamiliar with the building such as a hotel, pre-evacuation time can be as high as 600 seconds (New Zealand, 2014). In the first case, three scenarios were created where in the first the pre-evacuation times and distribution are as described for the benchmark model, in the second the building has been divided into three portions using the non-occupied floors 12 and 29 where all the occupants on the top portion are given the maximum pre-evacuation time of 600 seconds, those on the middle portion are given the benchmark pre-evacuation time with a minimum of 11 seconds and a maximum of 181 seconds following a log-normal distribution, and all those on the bottom portion are given no pre-evacuation time of 0 seconds. This can be said to represent a worst-case or quasi-worst-case scenario to produce maximum queuing on the stairs. From the results the total evacuation times are 1640 seconds, 1621 seconds and 1641 seconds respectively. This suggest that the pre-evacuation time has a minimal impact on the total evacuation time in high-rise buildings. Also, it would suggest that the normalcy bias occupants in high-rise buildings tend to exhibit has more impact on the evacuation time than the distribution curve, albeit not very significant. The normalized Cumulative Waiting Time graph of the three is shown in Figure 4.23.

For buildings lower than 23 meters, the Figure 4.24 indicates the straightening a more significance of pre-evacuation time not on total evacuation time but on the total number of people exited with time. Also, a low-rise building with no pre-evacuation time resembles a high-rise building with a log-normal distribution of the pre-evacuation times of the occupants as the two curves in Figure 4.24 suggest when compared with Figure 4.23.

Lastly, the change of pre-evacuation time from the benchmark to no pre-evacuation produces a change in evacuation time not only by the pre-evacuation time itself. With a minimum pre-evacuation time of 11 seconds, the change in the total evacuation time is from 1618 seconds to 1640 seconds, a 22 second increase in time.

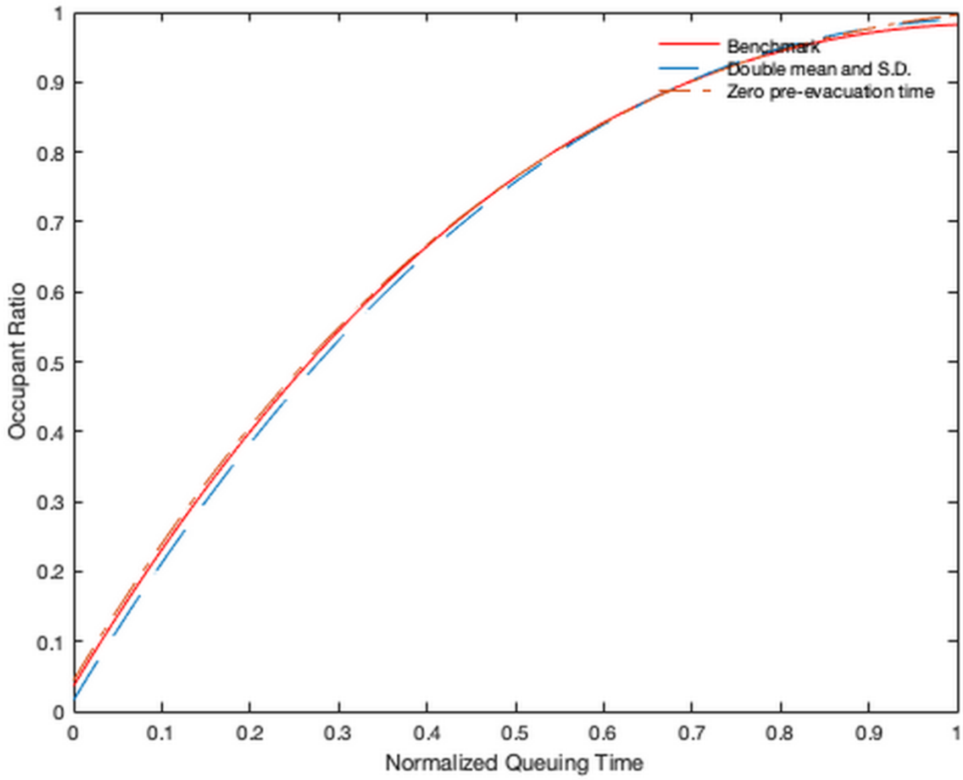


Figure 4.23. Relative queuing times of three high-rise pre-evacuation scenarios.

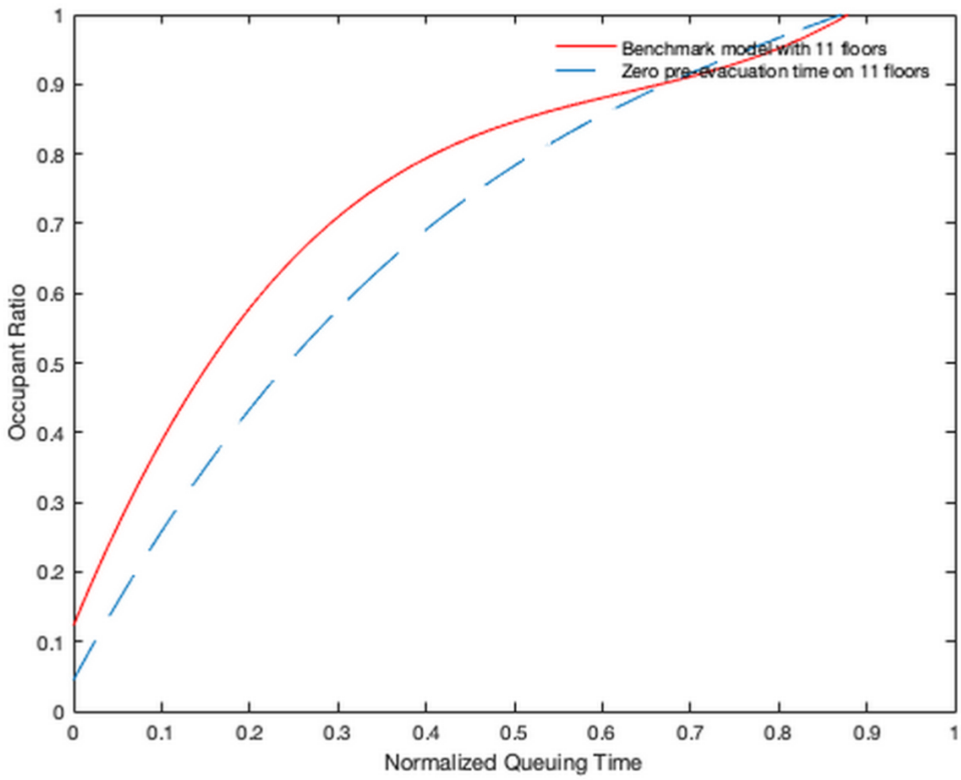


Figure 4.24. Relative queuing times for 11 floors benchmark and no pre-evacuation time.

4.4.3. Fatigue and Walking Speed

Although the impact of fatigue is hard to discern, the impact of a change in walking speed can easily be investigated by decreasing the occupant speeds. The speed of occupants in the benchmark model are distribute between 1.2 – 1.5 m/s. A fatigue of the evacuees with respect to physical attribute of speed will result in a decrease in the average speed of the evacuees. As a result, an evacuation where the speed of the occupants has been reduced to 1.0 – 1.2 m/s is simulated for comparison. The total evacuation time increased from 1725 seconds to 1717 seconds. While this does not categorically represent the impact of fatigue, it does show that however, that the speed of occupants travelling down the stairs in a queue does not impact the total evacuation time. However, as Figure 4.25 indicates, it can lead to some occupants evacuating faster than others. Therefore, with the same flow rate but different travel speed, occupants evacuated at a certain time during the evacuation may be different while the total evacuation time stays the same. For example, the evacuation time of those starting on the 10th floor is 1809 seconds and 1844 seconds for the respective cases.

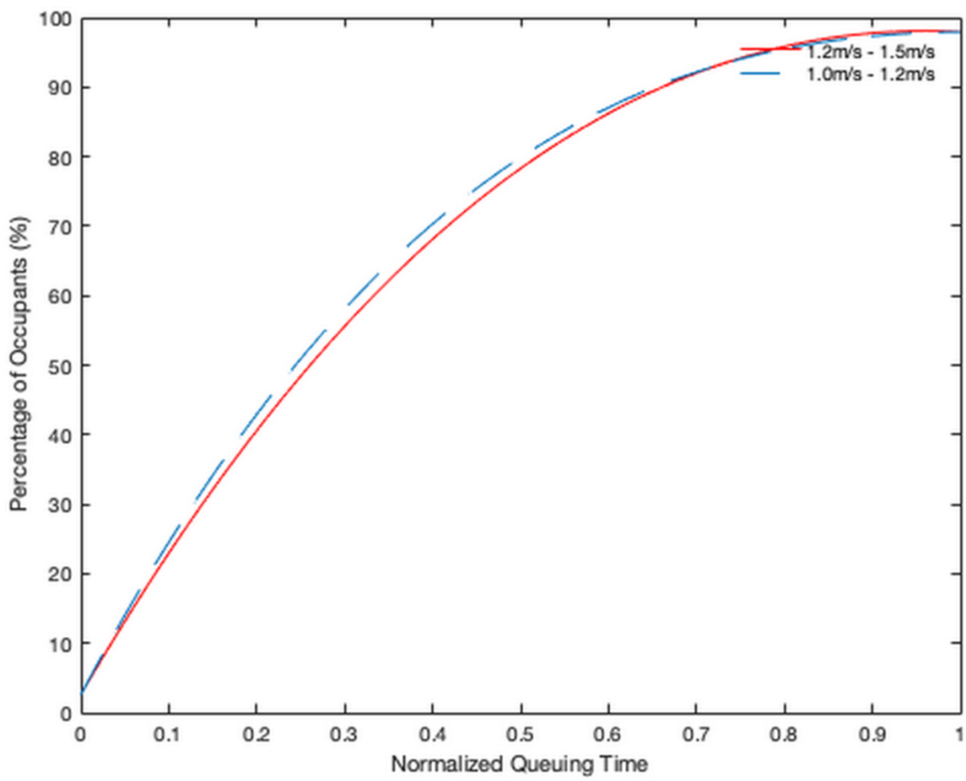


Figure 4.25. Range of waiting times for high-speed and low-speed evacuation.

4.4.4. Patience

Another evacuee attribute investigated is the patience level of the occupants. As Figure 4.26 shows, the effect of the compliance level of evacuees on evacuation time of high-rise residential buildings is minimal. With similar exit usage, OPS values of 0.229 for simulation 1 and 0.157 for the simulation 2 arising due to difference in location of occupants in the different simulations, the two lines in the graph look similar. Figure 4.27 on the other hand shows that a similarity of behavior but a change in the range of queuing time.

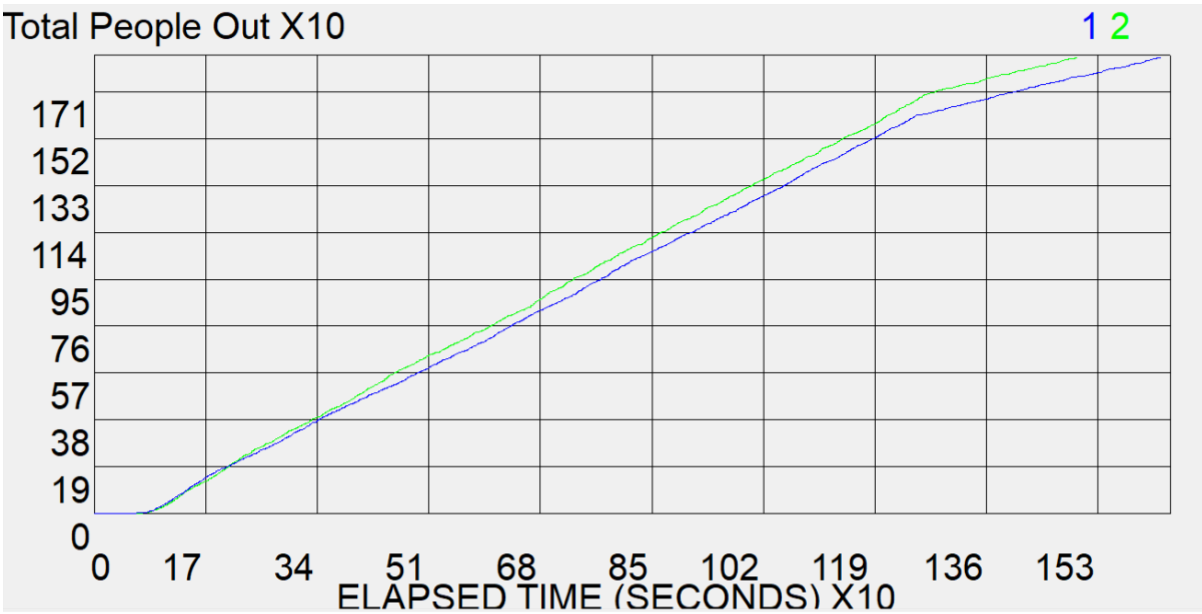


Figure 4.26. Total Evacuation Time: 1. Zero patience for all evacuees 2. Benchmark patience levels.

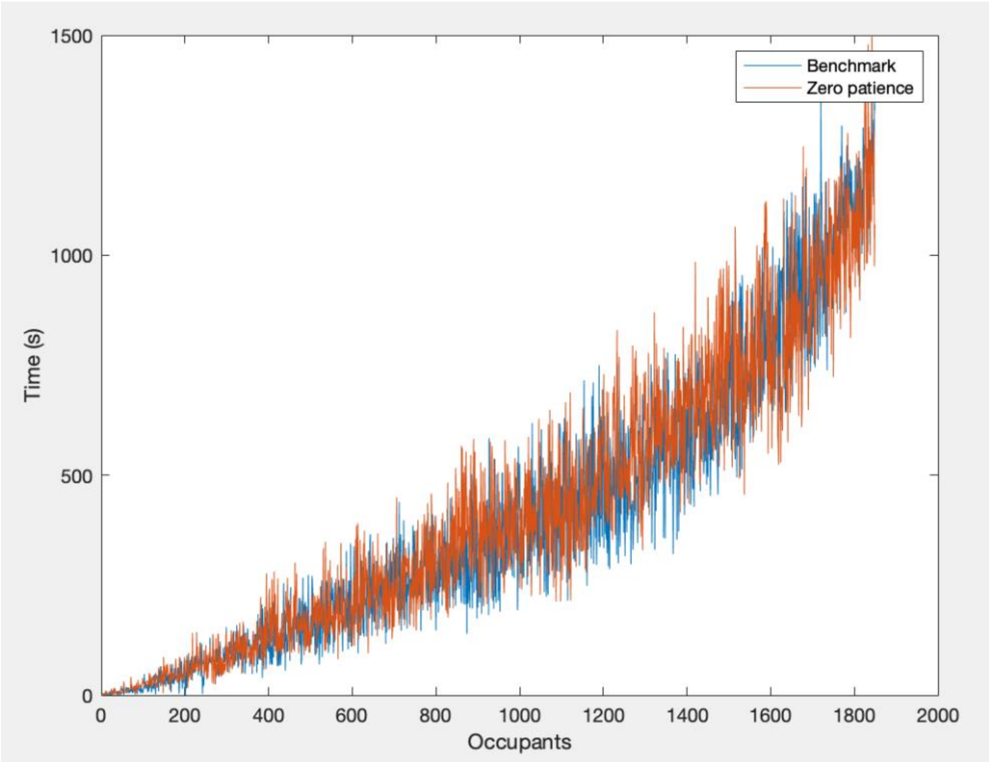


Figure 4.27. Cumulative Waiting Time for patient and non-patient evacuees.

4.4.5. FED Effects

From the fire simulation performed in PyroSim, the change of visibility with time was computed for the whole floor. The fire starting from one of the apartments leads to a breach in tenability in less than four minutes. According to the tenability limits of C/VM2, the all occupants on or above the floor of the fire outbreak should leave before this time after which the occupants are completely incapacitated. Assuming that the doors are opened, it takes less than four minutes for the smoke to spread to both stairwells on the floor. And within this period, the visibility falls below the threshold even on the nearest stairwell and corridors.

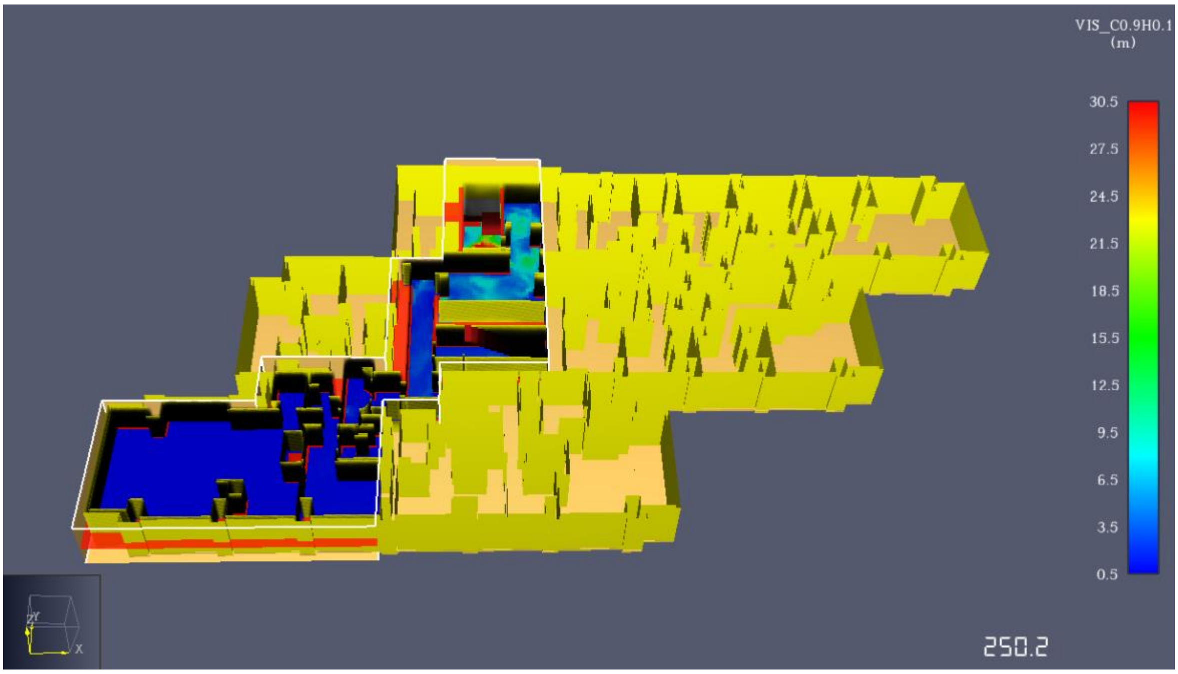


Figure 4.28. Visibility distance after four minutes.

In order to investigate the effect of other toxic gases, assumptions have been made regarding CO, CO_2, HCN and temperature. A scenario in which the fire occurred on the 29th floor and has spread to both stairwells was assumed. A linear growth with a gradient of 0.1 was assumed for temperature, HCN, CO, CO_2 and smoke, and -0.05 for Oxygen depletion. This simplification is not intended to provide a description of the likely fire scenario but rather to show how the impediment caused by fire on the occupants affects the evacuation process. FIN, FICO, FIH, FLD and FIC have been considered and Purser model for hyperventilation effect (VCO_2) has been utilized. Figure 4.29 and Figure 4.30 represents the Exit time and CWT graphs respectively.

In this scenario, 591 casualties (32%) is estimated to have occurred. Figure 4.29 and Figure 4.30 give the Exit time graph and queuing graph respectively of this scenario. Figure 4.29 shows an exit time of zero for occupants that have collapsed and are incapacitated, and it can be observed that all of them are above floor 25. Interestingly, no occupant from floor 31 survives and occupants closest to the fire floor are the most affected.

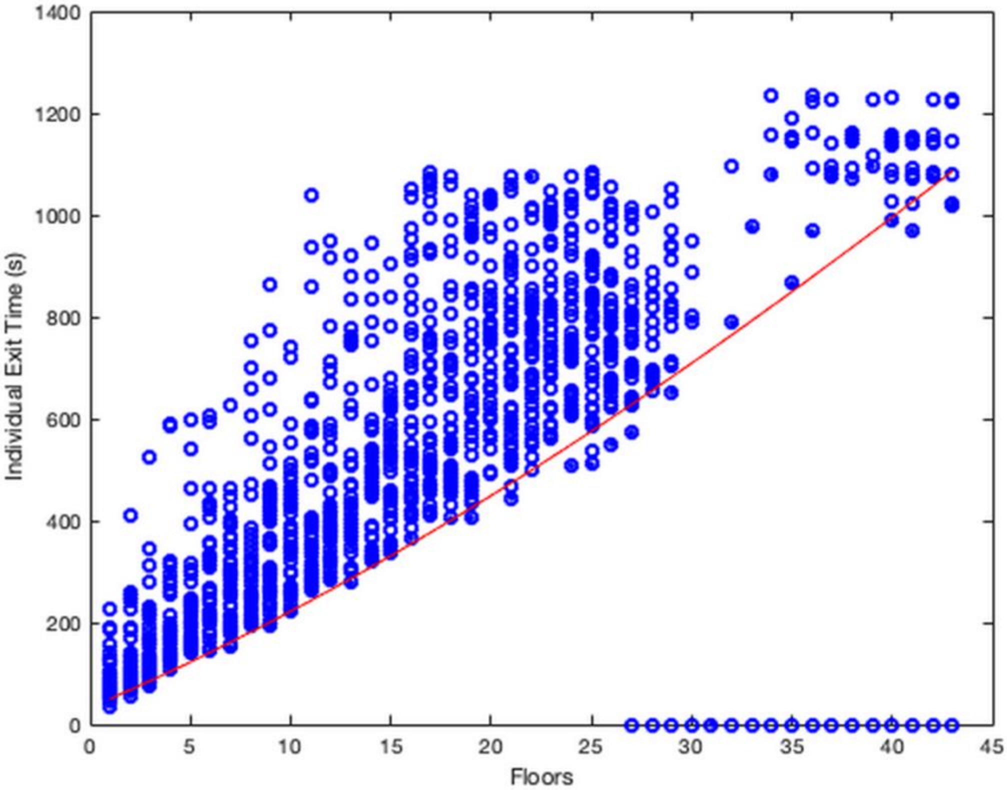


Figure 4.29. Exit Time of evacuees in a fire affected scenario.

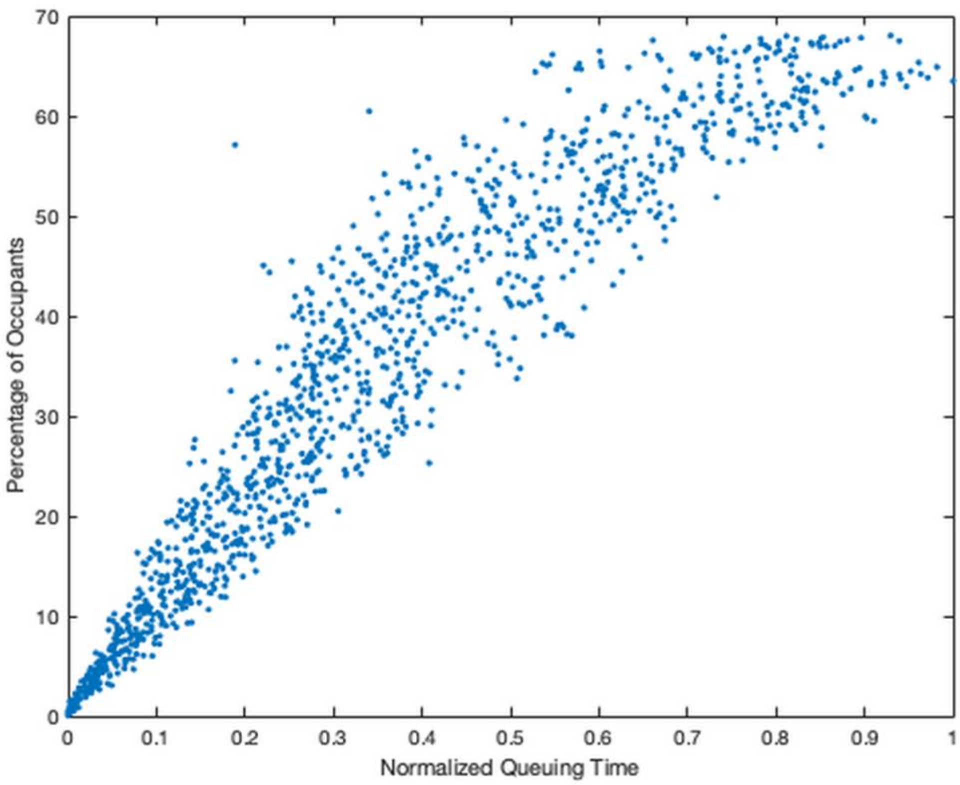


Figure 4.30. Cumulative Waiting Time of evacuees in a fire affected scenario.

4.5. Fire Safety Analysis

Fire detection time can be determined from a deterministic fire modelling of an automatic detection and alarm system. This is useful in evaluating both ASET and RSET. In C/VM2, the notification time for standard evacuation strategies is taken as 30 seconds. From the parametric studies, it can be deduced that the impact of the pre-evacuation time on the total evacuation can be evaluated as time lost if no pre-evacuation time is modelled. This implies that for high-rise simultaneous building evacuation, the queueing density on the stairs indicate that the escape time is more sensitive to the congestion time than to the occupants' speed, pre-evacuation time or transition time.

The risk formulation would also suggest that a fire with the same probability of occurrence but with different ASET will give rise to a higher level of risk if at the time at which RSET is reached, more occupants have evacuated. For high-rise buildings, the assessment of RSET will depend on attributes such as occupant load while the assessment of RSET will depend on attributes such as fire load and location of fire occurrence. From the studies carried out in the previous section, one can conclude that the effect of fire on evacuees in an important issue to take into consideration when carrying out fire safety analysis or design. Also, the queuing effect in high-rise building is a significant contributing factor to the egress performance total evacuation time.

Lastly, when carrying out fire suppression by the fire brigade, more focus should be on occupants on higher floors and fires on lower floors as these pose the most threat to the number of occupants' lives that can be saved. The materials used in construction should also be taken into consideration as a fast spread of fire should demand quicker and more efficient design of egress systems.

5. CONCLUSIONS AND RECOMMENDATIONS

The primary objective of life safety FSE design is to minimize the probability of death or injury of the building occupants. In this thesis, the subjects necessary for the assessment of the fire safety of occupants in high-rise residential buildings have been outlined. It has been shown that several variables contribute to the changes in the egress performance of high-rise buildings and the deviations of these variables have been used to describe this effect. For the fire scenario, a plausible-upper bound was set from code specifications and high-rise building data. The following conclusions were drawn from the study of the evacuation of occupants in a high-rise residential building under fire:

- An increase in the height of a building leads to a nonlinear increase in total evacuation time. In designing a building twice as high a particular building, for example, the stair increase recommendations should not be on the assumption that for two buildings of similar characteristics but with twice the number of floors, it will take twice as long to complete evacuation. Rather, delay due to congestion is a very important factor to take into account.
- Evacuation in high-rise buildings of varying heights exhibit similar characteristic with regard to the relative egress performance. On the other hand, the life safety from fire expected to occur on the top third of high-rise buildings should be evaluated with a different risk than one expected to breakout within about the bottom two-thirds of the building.
- The effect of occupant load density on the total evacuation time is linear.
- The range of queuing time spent between occupants remaining in a building increases with time.
- The impact of the occupants' average speed of evacuees is more so on amount of the occupants exited or remaining at a particular time during the evacuation than on the total evacuation time.
- The pre-evacuation time effect is minimal in high-rise buildings as compared to low-rise buildings. However, this change is not just the substitute of the pre-evacuation time.
- High-rise building evacuation is more sensitive to the queuing time than the pre-evacuation time.

- The floor rate of doors is more important in low-rise than in high-rise building evacuation.
- About half of the evacuation time is a result of the movement restriction or congestion on the stairs.

As a result, it is suggested that building designers should pay attention to the sensitivity of the above-mentioned egress parameters.

Also, the fire model and its impact on the occupants has shown that the threat of fire on the occupants' ability to escape is most severe on the occupants closest to the fire source and those exposed to the fire effluents for the most amount of time. This issue should be taken into consideration in the design of alarm systems.

Moreover, a framework for risk characterization has been outlined. In assessing the time required for the fire brigade to intervene, this can be very useful. Since the egress time and performance respond differently to buildings with height greater than the high-rise definition threshold, they should be assessed differently than those with height below. Greater number of occupants can be saved if fire is suppression starts from below. Also, in designing passive systems for fire protection, the use of combustible materials especially in a zone that will trap or have maximum toxic effects on the occupants should be avoided.

Finally, it is important to expand the study on the toxic effects of fire on the egress variables as data on the psychological effects of fire effluents on human behavior catches up with the advanced algorithmic models of environmental effects on evacuees. A more detailed model of fire will provide more precise information on the impact of evacuees' physical attribute deterioration on the egress performance of high-rise residential buildings.

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APPENDIX A

MATLAB CODE FOR PLOTTING EXIT TIME AND QUEUING TIME GRAPHS

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Evacuation.m                                                           %
% This code is written to analyse the egress performance of evacuees     %
% from the results generated in buildingEXODUS                           %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc                                % Clear up the command Window
clear                              % Remove all variables in the Workspace
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%-------------------------------Input Data-------------------------------%
m = 43;                            % number of people per floor
n = 43;                            % number of occupied floors
%------------------------------------------------------------------------%

%------------------------Read Egress Results Data------------------------%
Egress = fullfile('Egress_results.txt');
Egress2 = fullfile('Egress_results_28_floors.txt');
Egress3 = fullfile('Egress_results_19_floors.txt');
%------------------------------------------------------------------------%

%------------------------Sort Egress Results Data------------------------%
T = readtable(Egress);             % Egress Results Table
Pos = table2array(T(:,1));         % Number of Individuals Column Vector
CWT = table2array(T(:,11));        % Cumulative Wait Time Column Vector
SS = sortrows(T,5);                % Egress result table ascending with floor
S = [SS(388:430,:); SS(818:860,:); SS(1291:1333,:); SS(1635:1849,:);...
    SS(1:387,:); SS(431:817,:); SS(861:1290,:); SS(1334:1634,:)];
PET = table2array(S(:,13));         % Individual Elapsed Time per floor
E = reshape(PET ,[m,n]);           % Individual Building Exit Matrix
%------------------------------------------------------------------------%

%-----Form the matrix of the exit time difference bar for each floor-----%
x = zeros(m,n);
y = zeros(m,n);
for i = 1:n
    for j = 1:m
        x(i,j) = i;
        y(i,j) = E(j,i);
    end
end
%------------------------------------------------------------------------%
```

Figure A.1. Code for sorting simulation data into matrix.

```
%------------------------Graph the difference bars-----------------------%
figure('Name','Exit Time Difference Bars','NumberTitle','off')
plot(x,y,"bo")
hold on
f = (1:n);
pfirst = E(1,:);        % first person to evacuate on each floor
plast = E(m,:);         % flast person to evacuate on each floor
fittop = fit(f',plast','poly2','Normalize','on','Robust','on');
fitbot = fit(f',pfirst','poly2','Normalize','on','Robust','on');
plot(fittop,f,plast)
plot(fitbot,f,pfirst)
hold on
xlabel('Floors');
ylabel('Individual Exit Time (s)');
legend('off')
hold on
%-----------------------------------------------------------------------%

%---------------------Graph the Cumulative Wait Times--------------------%
figure('Name','Cumulative Wait Time','NumberTitle','off')
plot(Pos,CWT, 'b.')
hold on
xlabel('Individual Occupants');
ylabel('Queuing Time (s)');
legend('Benchmark model', 'One floor equivalent')
%-----------------------------------------------------------------------%
```

Figure A.2. Code for plotting graphs.