# ABSTRACT

Title of Thesis: THE COMPARISON OF TOTAL AND PHASED EVACUATION STRATEGIES FOR A HIGH-RISE OFFICE BUILDING

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This research work aims to explore the difference between total and phased evacuation strategies in high-rise office buildings and provide guidance on evacuation strategies for decision-makers in determining allowable occupant load.

This work focuses on evaluating the principal factors (building height and occupant load) that may have an impact on egress time and provides a comparison of total versus phased evacuation in a hypothetical high-rise office building through a computer simulation using MassMotion. The comparison is separated into two aspects: total egress time and floor clearing time.

The current thesis determined that the difference of total egress time between these two strategies increases with increased building height. The difference of total egress time between total and phased evacuation is from 165 to 878 seconds with the heights of

building from 11 stories to 31 stories, respectively. The floor clearing time for the affected floors is similar in total evacuation strategy in different building heights. Also, in various building heights, the floor clearing time for affected floors has little difference in phased evacuation strategy. Moreover, this thesis depicted a graph of the floor clearing time in these two fire strategies with different occupant load factors. If a phased evacuation strategy is implemented, a decrease in the occupant load factor can be accommodated which results in the same floor clearing time as for a total evacuation strategy. The current thesis generated an equation to estimate the decrease in the occupant load factor between total and phased evacuation based on the same floor clearing time.

There is a limited research work available for the comparison of total and phased evacuation. This research work provides guidance for building planners and engineers in determining total and phased evacuation strategies for high-rise office buildings. For the buildings studied, an equation is provided for engineers to quantify the impact of differences in total and phased evacuations.

# THE COMPARISON OF TOTAL AND PHASED EVACUATION STRATEGIES FOR A HIGH-RISE OFFICE BUILDING

by

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# CHAPTER 1: INTRODUCTION

## 1.1 HISTORY OF THE DEVELOPMENT IN HIGH-RISE BUILDINGS

The early high-rise buildings were built from 1884 to 1939 predominantly in New York City and Chicago in the United States. This period can be separated into three stages: emergence of the skyscraper (from 1880 to 1899), the "First Great Age" (from 1900 to 1919), and inter-war period, boom and depression (from 1920 to 1939). The early skyscraper developed in the U.S. because of monetary development, the budgetary association of American organizations, and the escalated utilization of land (Condit, Carl W., 1968). The first high-rise building, William Le Baron Jenney's Home Insurance Building, was constructed in the 1880s, and was a ten-story building built in the city of Chicago using advances in the technology of construction (O'Hagan, 1977). The development of the technology of construction, which paved the way for high-rise buildings, were iron frame, wind bracing and fireproofing products, deeper foundations, available safe elevators, and new environmental advances in heating, lighting, ventilation and sanitation.

In the first stage of this period, high-rise buildings were mainly built in the United States, such as the 16-story Manhattan Building in Chicago (1888), New York World Building with a height of 106.6 meters in New York City (1890), Milwaukee City Hall with a height of 108 meters in Wisconsin (1895), and Central Tower with a height of 91 meters in California (1898). Many high-rise buildings were constructed from the late 1880s until the early 1890s in the city of Chicago, which led the way in high-rise construction. During this time, high-rise buildings were constructed combining the concerns of aesthetics and the practical use of buildings. This concern led to palazzo-styled buildings containing stores, shops, and restaurants on the first floor for commercial use, with office space usually located on the upper floors. Around the same time, high-rise buildings in narrower towers that were of an eclectic style were built in New York City. However, after 1892, Chicago prohibited the construction of buildings over 46 meters (150 feet) in height. In 1888, the term 'skyscraper' was used for the first time to refer to high-rise buildings.

In the second stage of this period, more high-rise buildings were constructed such as One Calvert Plaza (76 meters) in Baltimore (1900), Flatiron Building (86.9 meters) in New York City (1902), Ford Building (83.82 meters) in Michigan (1908), Royal Liver Building (98.2 meters) in Liverpool, England (1911), and PNC Tower (151 meters) in Ohio (1913).

High-rise buildings were constructed all over the world in the last stage of this period, such as Palacio Barolo (100 meters) in Buenos Aires, Argentina (1923), Royal Bank Tower (121 meters) in Montreal, Quebec (1928), Majorca Building (eight stories) in Melbourne, Australia (1930), Torrione INA (57.25 meters) in Italy (1932), and Aiqun Hotel (64 meters) in Guangzhou, China (1937). Between 1918 and 1939, high-rise buildings were constructed in many cities of the United States. During the 20$^{th}$ century, the number of high-rise buildings increased with the construction of buildings such as the Woolworth Building, the Metropolitan Life Insurance Tower and the Chrysler building, which expected to raise the name recognition of those companies.

From the 1930s, modern high-rise buildings came to the fore and replaced early high-rise buildings. Modern high-rise buildings are produced with structural frame of reinforced concrete and steel and utilize mechanical equipment. High-rise construction spread all over the world, including Latin America and Asia. Economics played a key role in the development of high-rise buildings in 1960s and 1970s. From 1931 to 1971, the Empire State building at a height of 380 meters, was the tallest building constructed during the Depression in the city of New York in the United States. In 1972, the Sears Tower, at 443 meters height (Council on Tall Buildings and Urban Habitat, 1997) replaced the Empire State building as the highest building in the world. Moreover, other tall buildings constructed during this period are listed in Table 1-1.

Table 1- 1: The List of Tallest Buildings for Modern High-rise Buildings Based on Council on Tall Buildings and Urban Habitat (CTBUH)

| Years Tallest | Name | Location | Height |
|---|---|---|---|
| 1931 - 1971 | Empire State Building | New York City | 381 meters |
| 1971 - 1973 | 1 World Trade Center (WTC) | New York City | 417 meters |
| 1973 - 1998 | Sears Tower | Chicago | 442 meters |
| 1998 - 2004 | Petronas Towers | Kuala Lumpur | 452 meters |
| 2004 - 2008 | Taipei 101 | Taipei | 509 meters |
| 2008 - 2010 | Shanghai World Financial Center | Shanghai | 492 meters |
| 2010 - present | Burj Khalifa | Dubai | 828 meters |

Focusing on high-rise office buildings, the first one showed up in 1931, which is the Empire State building in New York (Council on Tall Buildings and Urban Habitat, 1997). The rapid development period for high-rise office buildings occurred in the 20$^{th}$ century, during which the growth of the height of office buildings increased appreciably. Also, after World War II, there were a significant number of very tall high-rise office buildings that was constructed all over the world. The WTC in New York City was made up of typical high-rise office buildings built during this period, and its complex of buildings included landmark twin towers with the height of 427 meters and 415 meters (National Bureau of Standards [NBS], 1979).

Building high-rise real estate construction is significantly active by creating usable floor area in vertical space. On the one hand, it is advantageous to solve some problems, such as the lack of land, especially for China and India where there is a high population density. On the other hand, there are also disadvantages, such as creating more problems for evacuation and also the potential problems of the glass wall reflections.

## 1.2 LAYOUT OF HIGH-RISE OFFICE BUILDINGS

The geometry of typical floor plans is presented in Figure 1-1 for ten of the tallest office buildings in the world and seven of those ten buildings are square or have similar floor geometry (Özgen, 2009). Square configuration is common since the loads from each of the four directions are the same, and it is more stable which has led to that design becoming the preference of engineers.

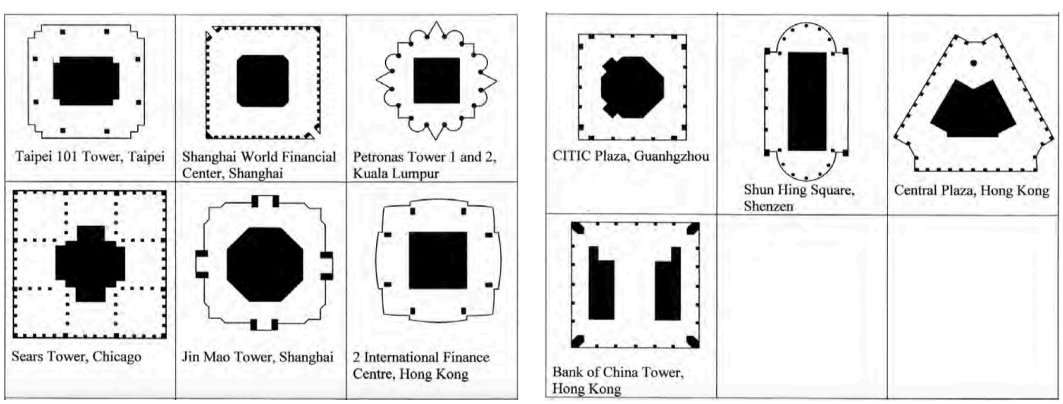



Figure 1- 1: Geometry of Typical Floor Plans of Ten Tallest Office Buildings of the World (Özgen, 2009).

## 1.3 THE DEFINITION OF HIGH-RISE OFFICE BUILDINGS

It is essential to define the various high-rise buildings before performing the egress modeling in following chapters, since this is the baseline of the height of the buildings set up in the egress models for this research. The efficient hypothetical high-rise office building developed in this thesis is based on the various definitions of high-rise buildings.

In section 3.3.37.7 of NFPA 101, *the Life Safety Code* (2018), the definition of a high-rise building is *"A building where the floor of an occupiable story is greater than 75 ft (23 m) above the lowest level of fire department vehicle access. (SAF-FUN)"*. Moreover, in Annex A in NFPA 101 (2018), the terminations of the highest occupiable floor and the level of fire department access are related to reasonable judgment from an enforcing agency.

International Building Code (IBC) has also been used as the basic guideline of the design of buildings. In Chapter 2 of the IBC (2018), the definition of a high-rise building is similar to the definition in NFPA 101 (2018), which is that *"A building with an occupied floor located more than 75 ft (22,860 mm) above the lowest level of fire department vehicle access."*

According to the database of Emporis GmbH, the Emporis Standards ESN 18727 states the definition of high-rise buildings is either in terms of height (35 meters to 100 meters) or in terms of the stories (12 stories to 40 stories) of the building. In 2005, Hall stated that the high-rise and the low-rise buildings are usually divided by seven stories such as NFPA 101 and IBC, while some standards considered more than seven stories as the boundary between the high-rise and the low-rise buildings such as EMPORIS STANDARD ESN 18727.

All in all, the high-rise buildings defined as about seven to ten stories buildings as Knoke ME stated in *Protection of Assets Manual* (2016) *"Generally, a high-rise structure is considered to be one that extends higher than the maximum reach of available fire-fighting equipment. In absolute numbers, this has been set variously between 75 feet (23 meters) and 100 feet (30 meters)"*.

Table 1-2 is a summary of various definitions of high-rise buildings. The definition of a minimum height of high-rise buildings used in this thesis is from NFPA 101, which is 22.86 meters (75 feet) from the lowest level available for fire department vehicle access to the highest level of floor occupied by occupants.

Table 1- 2: Definitions of High-rise Office Buildings.

| Source | Definition of High-Rise Buildings |
|---|---|
| NFPA 101, Life Safety Code (NFPA, 2018) | *" A building where the floor of an occupiable story is greater than 75 ft (23 m) above the lowest level of fire department vehicle access. (SAF-FUN)"* |
| International Building Code (IBC, 2018) | *"A building with an occupied floor located more than 75 ft (22,860 mm) above the lowest level of fire department vehicle access."* |
| EMPORIS STANDARD ESN 18727 | *" A high-rise building is a structure whose architectural height is between 35 and 100 meters. A structure is automatically listed as a high-rise when it has a minimum of 12 floors, whether or not the height is known. If it has fewer than 40 floors and the height is unknown, it is also classified automatically as a high-rise."* |
| Hall JR. (2005) | *"For most purposes, the cut-off point for high-rise buildings is around seven stories. Sometimes, seven stories or higher define a high-rise, and sometimes the definition is more than seven stories. Sometimes, the definition is stated in terms of linear height (feet or meters) rather than stories."* |

## 1.4 CONCERNS OF HIGH-RISE BUILDING EVACUATIONS

There are many reasons for a rapid evacuation in tall buildings, such as fire, terrorism, extreme weather, earthquake, and so on. Recent concerns of evacuation of high-rise buildings are fire and terrorism.

### 1.4.1 FIRE

Fire is a crucial reason triggering an evacuation of high-rise office buildings. Occupants may be trained through fire drills in office buildings. As a result of fire drills, occupants become generally familiar with the evacuation routes (Proulx, 2001). There were a high number of high-rise buildings that suffered fire accidents which also include many office buildings fires. From 2009 to 2013, an average of 14,500 fires occur every year in high-rise buildings in the U.S. and two percent of those were high-rise office building fires (Ahrens, 2016).

Examples of serious fires in high-rise buildings include the Cook County Administration Building, One Meridian Plaza, and the First Interstate Bank Building. In March, 2019, a high-rise office building in Bangladesh's capital had a fire, which caused 17 deaths and about 70 injures. In October 2003, the Cook County Administration Building at 69 West Washington had a fire accident that killed six occupants with several more occupants injured (Madrzykowski and Walton, 2004). In the $20^{th}$ century, the most significant fire occurred in an office building, the One Meridian Plaza in Philadelphia, Pennsylvania, which is the largest scale fire in the history of modern United States. For this 38-story office building with three enclosed stairwells, the fire started in a vacant $22^{nd}$ floor and the duration was more than 19 hours. This fire resulted in three firefighters deaths and 24 firefighters injuries in

February 1991 (Routley, Jennings, and Chubb, 1991). Another fire in Los Angeles was in May 1988, in the 62-story First Interstate Bank Building. The fire started on the fourth floor and also damaged the fifth floor. 383 firefighters took part in rescuing victims and caused an estimated $50 million dollars property loss in this fire (Los Angeles Fire Dept., 1988). Around 90% of this building installed sprinklers, but the control valve was closed waiting for installation of the rest of the fire protection system. On August 5$^{th}$, 1970, the 50-story office tower called the 1 New York Plaza located less than one mile away from the WTC towers (Lipton and Glanz, 2002) had a fire which continued for more than six hours. This fire caused two deaths and 35 injuries.

### 1.4.2 TERRORISM

Terrorism is also a principal cause for rapid evacuation in high-rise office buildings. In the United States, the worst three attacks in its history leading to evacuation occurred during attacks of the twin towers of the WTC (1993), Oklahoma Federal Building (1995), and the WTC Towers (2001).

On February 26, 1993, the WTC in New York City was a target where a bomb burst in the underground parking garage of the twin towers of the WTC. This attack damaged electricity at the beginning with an approximate pressure of 150,000 psi and caused smoke up to spread to 93 floors in both towers. Six occupants died as a result of the event and a large number of people were injured. More than 40,000 occupants in the building started to evacuate in this incident (Fahy and Proulx, 1995).

On April 19, 1995, the Alfred P. Murrah Federal Building located in Oklahoma City's downtown was attacked by a truck bomb. There were 168 people killed in this incident. This terrorist attack triggered the evacuation of 361 occupants in the building (Mallonee, Shariat, Stennies, et al,1996).

On September 11, 2001, the worst terrorist attack occurred on the WTC Twin Towers located in New York City. Around 3,000 people lost their lives and caused a total building evacuation which ranged from 10,000 to 14,000 occupants in each of these two towers (Pauls, 2002).

## 1.5 CAPACITY CONCERNS OF HIGH-RISE BUILDING EVACUATIONS

Egress time varies principally with the number of occupants, the distribution of occupants, the number and width of stairwells, building heights, travel distance to reach stairwell, the training level of occupants and the mental and physical capabilities of occupants. The number and distribution of occupants and building heights can affect travel distance, while the number and width of stairwells have an impact on the density of occupants and traveling speed. The travel distance and the speed of evacuation directly affect egress time.

For most performance-based design projects which utilize an egress model, the objective is to confirm that the Available Safe Egress Time (ASET) is greater than Required Safe Egress Time (RSET). Normally, the RSET is determined from an egress model or hand calculations, while the ASET is resolved through a fire modeling analysis. Typically, the ASET is unique to each room or space and relies upon room setup, fuel load, suppression and detection systems, and various other different components.

At the end of the 1960s, the research focused on high-rise building fire strategy to improve codes and standards for these structures (Melinek and Booth, 1975). After the terrorist attack occurred on the WTC Towers in 2001, this topic was brought to the forefront again. The effects of the efficiency of the evacuation is the main topic to be discussed in this section.

Dangerous fire events do occur in high-rise buildings. The vertical characteristics of the building are emphasized in research on the fire safety of high-rise buildings. Even the codes and standards (NFPA 101 and IBC) focus on the characteristics related to horizontal configuration of a building, the height of the building and the number of stories can also have a significant impact on the duration of evacuation. The research from Campbell shows that the mean and minimum time to clear each floor in total evacuation is related to the height of the building (Campbell, 2018). After the September 11 attacks, there were 30 recommendations from NIST (National Institute of Standards and Technology) affected the standards and codes according to WTC investigation recommendations (NIST, 2005). One accepted recommendation is to require one additional exit if the height of the building is over 128 meters.

The stairwell was the primary focus of discussions of high-rise buildings evacuation at the end of the 1960s. Stairwell width, i.e. stairwell capacity, is related to occupant load. The capacity of each exit and the location of exits on the floor plan affect the time needed for evacuation. Dwyer and Flynn did research to compare the different number of stairwells between the Empire State Building and the WTC Towers (2005). The Empire State Building had five stairwells with 0.2 million $m^2$ floor area and estimated 15,000 occupants, while WTC towers had three stairwells located in the core of floor plan serving an estimated 20,000 occupants. The number and location of stairwells was controversial.

The concerns of evacuation in high-rise office buildings includes building heights and occupant loads which will be the focus of research to be described further in following chapters.

## 1.6 TYPES OF EVACUATION STRATEGIES IN HIGH-RISE OFFICE BUILDINGS

NFPA 101 Life Safety Code (2018 edition) states in chapter 4.2.1 Occupant Protection, *"A structure shall be designed, constructed, and maintained to protect occupants who are not intimate with the initial fire development for the time needed to evacuate, relocate, or defend in place."* Like the statement above, four basic evacuation strategies are phased evacuation, total evacuation, defend-in-place, and delayed evacuation. These different evacuation strategies are chosen mainly based on the characteristics of the buildings and the occupants.

### 1.6.1 TOTAL EVACUATION STRATEGY

The definition of total evacuation in this thesis consists of the simultaneous evacuation of all occupants in the building, reaching a designated safe place outside of the building. Previous studies on the total evacuation strategy has included the use of stairwells only, the combination of stairwells and elevators, and the combination of vertical (stairwells and elevators) and horizontal (transfer floors and sky-bridges) evacuation paths (Ronchi and Nilsson, 2014). This current research focuses on a simple building layout and considers an evacuation strategy that does not include the use of elevators.

Total evacuation may be necessary for some situations such as earthquake, hurricane and some other extreme incidents for high-rise buildings. Since a large population is involved in high-rise building total evacuations, the evacuation time increases with the increase in height of the building, which may lead to a worse situation for the safety of occupants. Evacuation of a great number of occupants in the entire building causes a high level of flow density in the stairwells of high-rise buildings. Also, in high-rise buildings, occupants get fatigued because of the long travel distance, where physical performance leads to a decrease in evacuation speed (Ronchi, Reneke, & Peacock, 2016). Some occupants on higher floors may need to go across the floor in a fire.

The General Services Administration stated that *“We learned that total evacuation is neither feasible nor necessary since fires can be contained on one floor or a portion of a floor. Total evacuation may result in certain occupants going to areas where there is smoke and exposing themselves to increasing risks."* (GSA, 1971). In a total evacuation strategy, because all of the occupants on all floors attempt to enter the stairwells at the same time, queues are likely to form in the stairwells and the entrances to stairwells. Hence, because of the expected queuing to enter the stairwell in this evacuation strategy, occupants on affected floors who are in immediate danger may not be able to quickly enter stairwells and reach a place of relative safety. Thus, it is necessary to consider phased evacuation strategy during an emergency evacuation in order to optimize the use of available stairwells flows for those people most in danger (Pauls 1994).

### 1.6.2 PHASED EVACUATION STRATEGY

For phased evacuation, Ronchi and Nilsson have stated that *"This strategy is adopted in order to decrease the queuing time in the egress components and reduce people densities in the means of escape."* (2013). In a phased evacuation strategy, the occupants on the affected floors including the fire floor, as well as one or more floors above and below the floor with fire, are the only ones involved in the evacuation. As such, the reduced number of floors are selected to give the occupants on these floors the highest priority in relocating to a safe place (the stairwell) given they are threatened first. The number of adjacent floors in the definition of the affected floors varies with the needs of research i.e. two adjacent floors above and one floor below the fire floor, while Ronchi and Nilsson have stated that *"…the fire floor and floors nearby will be prioritized."* (2013). For this thesis, the term "phased evacuation" will be meant to include evacuation of three affected floors: the fire floor and one adjacent floor above and below the fire floor.

The definition of phased evacuation is not uniform. Pauls had another definition of phased evacuation in the handbook (Proulx, 2002) which is a little different than the definition above. His approach for phased evacuation is the occupants on the floors that are below the fire floor and those above the fire floor up to the top floor should evacuate to a designated safe place and then all other occupants get out of the building. In Hartmann's thesis, the affected floors are the fire floor plus two adjacent floors above and below the fire floor (Hartmann, 2005).

There are some cases in which the total evacuation is not efficient, especially in high-rise buildings. In the 1970s, the necessity of total evacuation strategy for high-rise buildings was debated, along with use of an alerting system, including fire alarm system with zoned smoke detectors and a voice evacuation alarm. In 1970, the consideration of shifting from total to phased evacuation was discussed in Confederation of Fire Protection Association (CFPA) conference, which stated, *"Basically, taller buildings and high-rise buildings should be designed with structural and technical measures and facilities aimed at safety, so that in the event of fire, only the fire story and the stories immediately above and below would need to be evacuated."* (CFPA, 1977, p. 26).

In 1971, the fire safety design of a 36-story building with an occupant load of more than 3,000 triggered the consideration of efficient evacuation strategy in high-rise buildings during a conference. In the same conference, they chose phased evacuation as their evacuation strategy. Therefore, the Seattle Federal Building became the first high-rise office building designed for the phased evacuation strategy. Petronas Towers located in Kuala Lumpur, Malaysia (Ariff, 2003), and Prudential Tower in Boston (Boston Properties, 2012) are other examples which utilized the phased evacuation strategy in its fire safety design. The performance-based design presents that the occupants in three floors with a fire, above and below floors should relocate to the three floors below these three floors.

Since the defend-in-place strategy and delayed evacuation are outside the scope of this study, this section will not introduce defend-in-place evacuation strategies.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 EVACUATION STRATEGIES

In 2012, Ronchi and Nilsson reviewed the literature on the assessment of total evacuation for tall buildings. In their report, the egress components that affect total evacuation, were introduced including stairwells, evacuation elevators, and sky-bridges (Ronchi and Nilsson, 2012).

Research work studied for stairwells include: the design of the stairwells (number of the stairwells, the width and length of stairwells, and the location) (Pauls, 2002, Pauls et al., 2007); the specific features of stairwells (the slope of the stairwells) (Graat, Midden and Bockholts, 1999); and the capacity of stairs (Pauls and Jones, 1980; Pauls, 1988). For the virtue of the merging streams in stairwells, Galea stated that *"in high-rise buildings, floors should be linked to the landing on the opposite side to the incoming stair."* (Galea et al., 2008c). The merging ratio is always about 50:50 which is independent of the location of doors for stairwells (Boyce et al., 2009). Moreover, Kratchman (2007) and Peacock (2009) performed research for counter-flow in stairwells considering the fire-fighters walk in the opposite direction of occupants in the building. Second, research work of elevator evacuation started in 1930s (Bukowski, 2009). WTC attack accelerated the debate of adding elevators in evacuation process (Kuligowski, 2011; Galea & Blake, 2004). The possibilities and availabilities of using elevators during evacuation was researched by Chien and Wen (smoke entrained into elevators causing by negative pressure in the shafts) (2011), Bukowski (special requirements for emergency power supply) (2005; 2010b), and Weismantle (the floor levels of pick-up and arrival for elevators) (2007). Third, current research analyzed the use of sky-bridges. The main contribution is from Wood (2003, 2005, 2007). Wood stated that sky-bridges should be placed in the level where the elevator zone transitions are present and also between buildings of dissimilar heights.

Moreover, some research considered the combination of egress components during evacuation (Nilsson and Jönsson, 2011; Heyes, 2009; Kinsey, 2011). In 2002, Siikonen found that if only elevators are used during total evacuation for more than 15 story office buildings, the evacuation time is less than that if stairwells are the only the means of egress used. The amount of decrease in egress time depends on the occupant load on each floor. The use of stairwells and elevators both can decrease the egress time as compared to the use of only one of those options during evacuation. In very tall high-rise buildings, using elevators as a mean of egress can reduce egress times from 2 to 3 hours to 15 to 20 minutes (Siikonen, 2002).

In 2014, Ronchi and Nilsson performed research to explore various methods to utilize for total evacuations of high-rise buildings. They compared the egress time during seven different total evacuation strategies for 50-story twin towers using different combinations of egress components including

(1) 2 stairwells

(2) 3 stairwells

(3) 2 stairwells and 24 occupant evacuation elevators

(4) 24 occupant evacuation elevators

(5) 2 stairwells, 24 occupant evacuation elevators and service elevators serving as shuttles

(6) 2 stairs and occupant evacuation elevators (mid-rise elevators serving as shuttles)

(7) 2 stairs, 24 occupant evacuation elevators, 2 transfer floors and 2 sky-bridges.

They found that methods (4) and (7) are the most efficient variations. Method (7) is highly dependent on the information provided to occupants (Ronchi and Nilsson, 2014).

For phased evacuation strategies in high-rise office buildings, Kadokura, Sekizawa, Sano, and Fujii (2015) performed research to study the flow and congestion in stairwells based on the data from a fire drill in a 25-story building in Tokyo. They found that congestion formed because of the flow merging of people from both upstairs and the floor area. They attributed the reason of congestion forming in the stairwell to the high density population in the stairwells.

The literature on the comparison of total versus phased evacuation in high-rise office buildings is limited. Proulx stated that *"Evacuation of multistory office buildings can be thought of as being of two types: uncontrolled total evacuation, and controlled selective evacuation. The former is dependent largely on the nature of evacuation sequencing or deference behavior required, and the latter on the type of control imposed and the availability of voice communication system to manage the evacuation."* (2002).

The main research to compare total and phased evacuation was accomplished in the 1970s and 1980s. Pauls performed two analyses focusing on total and phased evacuation based on the data from fire drills. In his research, fire drills were conducted in two medium-size high-rise office buildings in Ottawa, Canada. The buildings had similar occupancies and floor area. The significant differences are the floor plan and the four times effective width of stairwells compared 'Building A' to 'Building B'.[1] A total evacuation drill was performed in 'Building A' consisting of 15 stories with four exits (1709 workplaces from 2nd floor to 15th floor), while a phased evacuation drill was performed in 'Building B' a 21-story building with two exits (2404 workplaces from 2nd floor to 21st floor). The procedure of phased evacuation used in this fire drill started with evacuation from the fire floor followed by the evacuation of two floors directly adjacent to the fire floor. The occupants of the rest of the floors evacuated at the end. Floor 3 was treated as fire floor during this fire drill. In this research, Pauls did not compare total and phased evacuation directly, though Pauls did provide two graphs to depict the evacuation process tracing the observers' movements and showing the time of end of the main flow and first evacuees into exit in these two buildings (Pauls, 1980). From these two graphs, the basic difference between total and phased evacuation is evident. While the floor cleared from the bottom to the top in total evacuation, phased evacuation is cleared from the top floor to the bottom floor after the fire floor cleared first (Pauls, 1980).

There is some research work available on either the total or phased evacuation, but a comparison of total and phased evacuation is limited. One comparison for high-rise office buildings was performed by Hartmann (2005), where the difference of floor clearing time between total and phased evacuation was not identified. Hartmann conducted her research using EXIT89 (2005). Hartmann defined phased evacuation as consisting of occupants from five floors evacuating including those on the fire floor

[1] The definition of effective width of stairwell is the clear width of the stairwell excluding the boundary layer along the edges.

and two adjacent floors above and below the fire floor. She considered the top five floors to be the affected floors, which means the fire floor she chose in her thesis is the second from last floor. Hartmann set up four different building sizes (929, 2,560, 4,703, and 13,064 $m^2$) with two occupant load factors (9.3 and 25.9 $m^2$ per person) in different heights of building (11, 21, and 31 story tall buildings) to explore the comparison of total versus selected evacuation related to both the total time to clear the entire building and egress time to clear each floor. Clearing time for each floor Hartmann defined as the last occupant to pass to the next level of floor stairwell. In other words, Hartmann considered the time clearing both floor area and the landing in the same floor as the floor clearing time.

Hartmann determined that the difference in total egress time is more significant than floor clearing time. For total egress time, Hartmann identified that the difference between total and selected evacuation increases with the increase in building heights in office buildings with 2,560, 4,703, and 13,064 $m^2$, other than the 929 $m^2$ office building. In respect to the floor clearing time, the difference in the total and selected evacuation ranged from 5 to 9 seconds at the top floor to 66 seconds, 407 seconds and 698 seconds at the first floor in 11-story, 21-story, and 31-story office buildings.

## 2.2 EVACUATION MODELING

Interest in evacuation modeling developed in 1982. Evacuation modeling can be used to assess the egress time of entire buildings or parts of buildings to support life safety design. In this field, much research has been done by numerous researchers. Predtechenskii and Milinskii (1978), Fruin (1987) and Pauls (1980) provided the data that contribute to the initial development of egress modeling.

Numerous factors have an impact on the egress time of high rise buildings, such as the characteristics of occupants (i.e. size, age, and disabilities), density of occupants (i.e. occupant load), the number and width of stairwells, notification systems, and the familiarity of the egress routes. The developing process of egress models is to permit the effect of these factors to be analyzed.

There are various types of egress models available. A hydraulic-based model is one type of egress models. The evacuation of occupants is treated similarly the water flow through pipes (Gwynne and Rosenbaum, 2016). Like water flow, the movement of occupants is homogenous without interruption of individual decision-making. All occupants are the same size and moving at the same time. As for this kind of models, the density of occupants, movement speed, number of exits, width of exits, distance of exits, and floor area are keys contributing to evacuation time (Gwynne and Rosenbaum, 2016). Most of the recently developed egress models pay more attention to aspects of human behavior that affect egress time.

Gwynne and Galea (1999) reviewed the methodologies of 22 egress models, including 16 models (BGRAF, CRISP, DONEGAN'S ENTROPY MODEL, EGRESS, EXODUS, E-SCAPE, EVACNET+, EVACSIM, EXIT89, EXITT, MAGNETMODEL, PAXPORT, SIMULEX, TAKAHASHI'S MODEL, VEGAS, and WAYOUT) that existed at the time and 6 models under development. The description of methods and purpose of each model is provided by Gwynne and Galea. Kuligowski describes a further comprehensive review of evacuation models in 2003. In Kuligowski's M.S. thesis (2003), the review of models is demonstrated in aspects of purpose, availability, method, structure, and perspective of models as well as behavior and movement of occupants. Except for the models described by Gwynne and Galea, there are 12 other models listed in Kuligowski's thesis, including FPETool, Pathfinder, TIMTEX, EESCAPE, EgressPro, STEPs, Gridflow, ALLSAFE, AERI, BFIRES-2, Legion and Myriad. Kuligowski generated a table representing 26 models with their background and characteristics (see Table 2-1).

Table 2- 1: Model Features (Kuligowski, 2016).

| | Background of model | | Model characteristics | | | | | |
|---|---|---|---|---|---|---|---|---|
| Model | Developer/institution | Validation | Availability | Modeling method | Refinement of population | Refinement of structure | Refinement of behavior | Output |
| EVACNET4 | Kisko, Francis, and Nobel/Univ. of FL, U.S. | FD | Y | M-O | Ma | C | N/A | T |
| WAYOUT | Shestopal/Fire Modelling & Computing, AU | FD | Y | M | Ma | C | N/A | V |
| STEPS | Mott MacDonald, U.K. | C, FD, PE | Y | M/PB | Mi | F | D | V |
| PedGo | TraffGo, Germany | FD, PE, OM, 3P | Y | PB/B | Mi | F | S | V |
| PEDROUTE | Halcrow Fox Associates, U.K. | N | Y/N3 | PB | Ma | C | D | V |
| Simulex | Thompson/IES, U.K. | FD, PE, OM, 3P | Y | PB | Mi | Co | D | V |
| GridFlow | Purser and Bensilum/BRE, U.K. | FD, PE | Y | PB | Mi | Co | D | V |
| ASERI | Schneider/I.S.T. GmbH, Germany | FD, PE | Y | B-RA | Mi | Co | S | V |
| BldEXODUS | Galea and FSEG/University of Greenwich, U. K. | FD, PE, OM, 3P | Y | B | Mi | F | S | V |
| Legion | Legion International, Ltd., U.K. | C, FD, PE, 3P | Y | B | Mi | Co | S | V |
| FDS + Evac | VTT, NIST, Helsinki Univ of Tech | FD, PE, OM | Y | PB | Mi | Co | S | V |
| PathFinder 2009 | Thunderhead Engineering | C, FD, PE, OM | Y | PB | Mi | Co | D | V |
| SimWalk | Savannah Simulations AG | FD, PE, 3P | Y | PB | Mi | Co | S | V |
| PEDFLOW | Edinburgh Napier University, Transport Research Institute | PE | Y | B | Mi | Co | S | V |
| SpaceSensor | Sun/de Vries | FD, OM | Y | B | Mi | Co | S | V |
| EPT | Regal Decision Systems, Inc. | FD | Y, N1 | B | Mi | C, F, Co | AI | V |
| MassMotion | Arup | C, FD, PE, OM | Y, N1 | B | Mi | Co | AI, S | V |
| Myriad II | Keith Still | PE, 3P | Y, N1 | B | Mi | C, F, Co | AI | V |
| Pathfinder | Rolf Jensen and Associates, Inc. | N | N1 | M | Mi | F | N/A | V |
| ALLSAFE | InterConsult Group ASA, Norway | OM | N1 | PB | Ma | C | D | V |
| CRISP | Fraser-Mitchell/BRE, U.K. | FD | N1 | B-RA | Mi | F | S | V |
| EGRESS 2002 | Ketchell/AEA Technology, U.K. | FD | N1 | B | Mi | F | S | V |
| SGEM | Lo/University in Hong Kong | FD, OM | N1 | PB | Mi | Co | D | V |
| EXIT89 | Fahy/NFPA, U.S. | FD, OM | N2 | PB | Mi | C | D | T |
| MASSEgress | Stanford University (Civil and Env Engineering) | PE, OM | N2 | B | Mi | Co | S | V |
| EvacuatioNZ | Spearpoint/Univ of Canterbury, NZ | FD, PE, OM | N2 | B | Mi | C | S | V |

Table 2- 2: Key to Reading the Table 2-1 (Kuligowski, 2016).

**Key to reading the table:**

*Validation*:
- *C* Validation against codes
- *FD* Validation against fire drills or other people movement experiments/trials
- *PE* Validation against literature on past experiments (flow rates, etc.)
- *OM* Validation against other models
- *3P* Third-party validation
- *N* No validation work could be found on the model

*Availability to the Public*:
- *Y* The model is available to the public for free or a fee
- *N1* The company uses the model for the client on a consultancy basis
- *N2* The model has not yet been released
- *N3* The model is no longer in use
- *U* Unknown

*Modeling Method*:
- *M* Movement model
- *M-O* Movement/optimization models
- *PB* Partial behavioral model
- *B* Behavioral model
- *B-RA* Behavioral model with risk assessment capabilities
- *B-AI* Behavioral model with artificial intelligence capabilities

*Refinement of the Population*:
- *Ma* Macroscopic
- *Mi* Microscopic

*Refinement of Structure*:
- *C* Coarse network
- *F* Fine network
- *Co* Continuous

*Refinement of the Behavior*:
- *D* Deterministic
- *S* Stochastic

*Output*:
- *T* Textual output
- *V* Visual output

Three approaches including optimization, simulation and risk assessment are available for evacuation modeling (Gwynne and Galea, 1999). Optimization is the method in which, occupants tend to find an optimal route to exits without any interruption. Optimization models, such as EVACNET+ (Kisko TM, 1985; Taylor IR, 1996) incorporate homogeneous ensemble that indicates no human behavior considered (Gwynne and Galea, 1999). Another significant model type is "simulation" in which human behavior and the movement of agents are taken into account. As human behavior and decision-making vary in different models, simulation models vary accordingly. This model type includes EXIT89 which is used by Hartmann, and will be compared with MassMotion based on this research later in Section 3.1. The last model type is “risk assessment” such as WAYOUT (Shestopal VO, 1994) which incorporates hazards based on analyzing fire and emergency.

In 2005, Kuligowski and Gwynne stated that the current characteristics of evacuation models include: modeling method, scope of representation (people, structure, phases of evacuation, emergency conditions, and application area), output (textual, general, quantitative), distribution and cost of model, age of model (generation of model), and refinement of representation.

The modeling method *“describes the level of sophistication used to calculate evacuation times for buildings,”* including movement models, partial behavior models, and behavioral models (Kuligowski, 2016). Movement models calculate the movement of occupants without considering the behavioral component. Partial behavior models primarily simulate the movement of occupants while taking some behavior into consideration. Behavioral models combine the performance and movement of occupants.

There are five generations of egress models. The first generation is manual calculations applying prescriptive assumptions. The second generation is computer-based hydraulic models. From the third generation, models started to consider individuals. The third and fourth generation are ball-bearing models and rule-based models, respectively. The last generation of model is sensitive to local conditions which attempt to imitate behaviors depending on conditions experienced and data accessible.

From these reviews, egress models typically use one of the two methods (coarse and fine networks) for the representation of enclosure. Coarse network model which requires inputs of nodes and arcs to create building floor plans. The geometry of the coarse network is represented with nodes and arcs. Corridors and rooms are considered as nodes, while arcs connect all nodes. Contrast with the coarse network, the fine network seems more accurate when the structure is able to be represented by thousands of nodes (Gwynne and Galea, 1999). The difference between coarse network and fine network is that the former does not require uniform nodes and the latter produces uniform nodes (Kuligowski, 2016, p. 2158). Due to the needs of tracking individuals, the fine network is chosen from this research. Coupled with these two methods mentioned by Gwynne and Galea, there is another method presented by Kuligowski which is continuous network. Continuous network allows the structure floor plan layout in two-dimensional space and occupants are able to walk throughout the entire building (2016). Kuligowski also stated that the choice of travel route from occupants can be affected by barriers in both fine and continuous network, while coarse network "move" occupants from one portion to another (2016).

Models can represent a population individually (MassMotion) or as a homogeneous group (EXIT89). Considering individuals, decision-making contributes to the movement of each agent, while people within the homogenous group are treated as the same identities without individual recognition. As for behavioral perspectives, there are five types of behavioral systems of egress models generally, including No Behavioral Rules, Functional Analogy Behavior, Implicit Behavior, Rule-Based Behavioral System, and Artificial Intelligence Based Behavioral System (Gwynne and Galea, 1999). Implicit behavior models *"...do not declare behavioral rules, but instead assume them to be implicitly represented through the use of complicated physical methods."* (Gwynne and Galea, n.d., p. 9). Moreover, implicit behavior is

*“…represented by pre-evacuation time distributions among the occupants, unique occupant characteristics, overtaking behavior, and the introduction of smoke and its effects on the occupants.”* (Kuligowski, 2016, p. 2157).

Hartmann’s used EXIT89 to explore the difference based on its availability, but EXIT89 was a relatively crude egress model at the time, and is even more so given developments since 2005. EXIT89 is a coarse network model which does not consider the formation of queues. Given that Hartmann’s analysis was not able to show a quantitative difference in the two evacuation strategies with the EXIT 89 model, this current research seeks to revisit the comparison of phased versus total evacuation strategies with contemporary software, MassMotion. The comparison is based on estimates of the floor clearing time, because the occupants considered as safe when they are in stairwells.

## 2.3 MODEL DESCRIPTION

Computational modeling is a method to predict the evacuation duration for almost any type, size and height of building considering various elements, such as ratio of male to females, proportions in a variety of ages and the physical mobility of occupants. A brief review of some of elements is indicated in this section to present the advantages and disadvantages of MassMotion that has been chosen for this research work. Also, a review of EXIT89 is presented in Section 2.3.2 given that it was utilized in Hartmann’s research (2005).

### 2.3.1 MASSMOTION

MassMotion was developed by Oasys (Ove Arup SYStems). This software is a behavioral model taking various elements of occupant behavior into account. Based on the consideration of probability, and programming of performing movement and decision-making, agents have partial thoughts and judgments behaving like actual humans in this type of model, i.e., occupants have a consciousness to take another route with a shorter queue even though they may travel a longer distance to exit. MassMotion also takes into account social forces method to account for occupant behavior.

The density (persons/m$^2$) of agents is relatively calculated according to the accessible spacing and the other surrounding agents. The agent is able to discern the walking speed and location of other agents near them (Arup, 2015). Increasing density contributes to a decrease in walking speed following the research by Fruin (1970). Figure 2-1 and Figure 2-2 illustrate his proposed six levels of density. Level of service A, B, C, D, E, F are greater than 3.3 m$^2$/person (35 ft$^2$/person), 2.3 to 3.3 m$^2$/person (25 to 35 ft$^2$/person), 1.4 to 2.3 m$^2$/person (15 to 25 ft$^2$/person), 0.9 to 1.4 m$^2$/person (10 to 15 ft$^2$/person), 0.5 to 0.9 m$^2$/person (5 to 10 ft$^2$/person), and less than 0.5 m$^2$/person (5 ft$^2$/person), respectively.  The default speeds in MassMotion are shown in Table 2-3 based on Fruin's level of service.

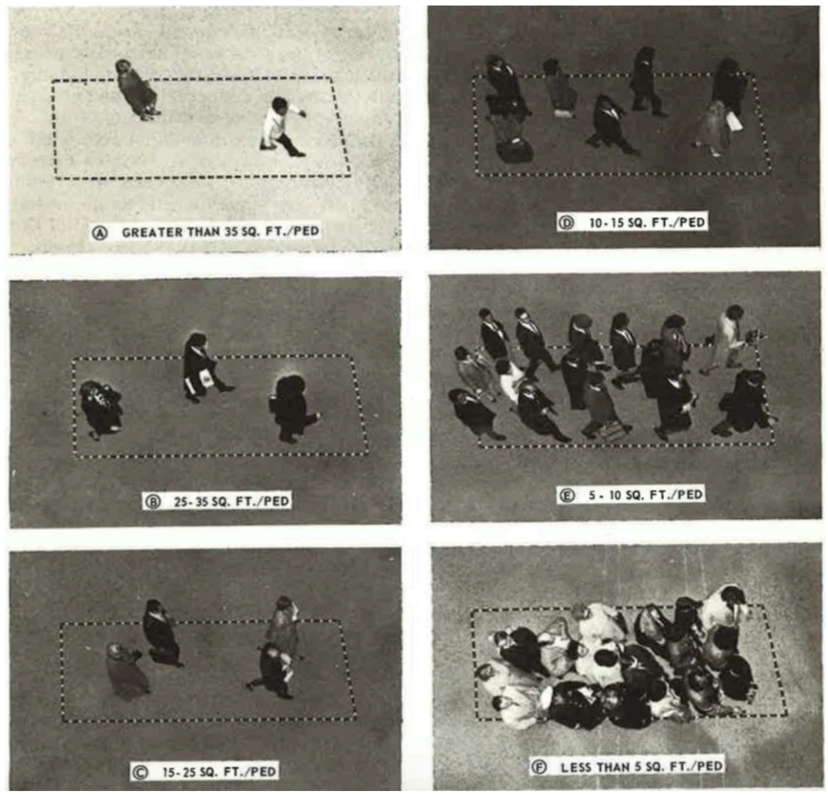



Figure 2- 1: Levels of Service for Walkways (Fruin, 1970).

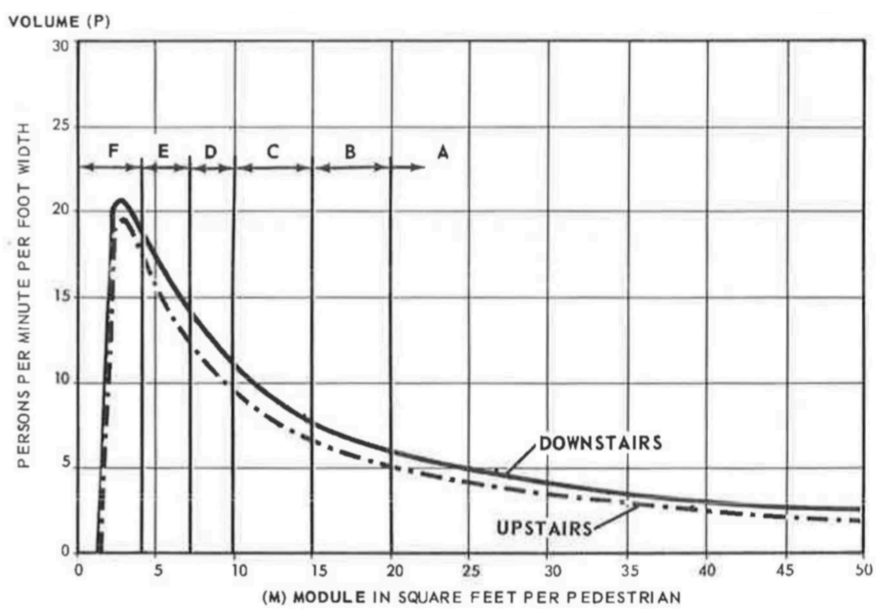



Figure 2- 2: Level-of-service Standards for Stairwells (Specific flow versus Density)

(Fruin, 1970). (1 $m^2$ = 10.8 $ft^2$)

Table 2- 3: Default speed ratio ranges.

| Level of Service | m/s | Ratio of max 1.35m/s |
|---|---|---|
| A | 1.35 | 1 |
| B | 1.321 | 0.963 |
| C | 1.270 | 0.941 |
| D | 1.219 | 0.904 |
| E | 1.143 | 0.844 |
| F | 0.762 | 0.563 |

The movement of agents is confined and the step length decreases with an increase in density. The movement force is driven by two other forces known as a neighbor force and a desire force. Developers of MassMotion describe the neighbor force as the sense of privacy distance, or personal space, that humans keep with others in physiological terms. Desire force is treated as the force impelling agents to seek exit portals. Simply, the magnitude and direction of movement force equal the vector sum of the neighbor force and desire force (Arup, 2015). The body size of agents established in MassMotion is assumed to be a circle with a radius of 0.25 meters in the default setting (Arup, 2015), while users can define their models in various body size and size distribution of agents.

MassMotion with three-dimensional (3-D) output views generates geometric components of portals, floors and stairwells, as well as 3-D elements such as agents. Agents enter and exit the building user set up, by entry portals and exit portals. Agents have an awareness of the geometry of spaces and are aware of the route to exit doors as default. Coupled with the awareness of agents the essential characteristic of agents in MassMotion is that they have awareness of the shortest egress time of various routs (Ahrens, 2018). In other words, agents are available to change their original evacuation route to another route with less time evacuating, while in a real fire event, humans would not have the same awareness of exiting with shorter evacuation time.

The walking speed in corridors is considered constant in MassMotion and it derives the walking speed for both upward and downward movement in a stairwell with a factor according to the stair incline that is listed in Table 2-4. MassMotion derives walking speed that varies in corridors and stairwells and the equation for horizontal walking speed is given in Equation 2-1 by Oasys (Arup, 2017).

$$S_{horizontal} = \frac{Speed\ on\ Stair \times cos(Stair\ Incline\ Angle)}{Stair\ Speed\ Reduction\ Factor} \quad 2\text{-}1$$

Table 2- 4: MassMotion Default Agent Attributes for Stairs (Arup, 2017).

| Stair Incline (degrees) | Upward Stair Factor (%) | Downward Stair Factor (%) |
|---|---|---|
| > 27 | 42.5 | 57.4 |
| 27 - 32 | 42.5 - 37.8 (interpolate) | 57.4 - 49.8 (interpolate) |
| < 32 | 37.8 | 49.8 |

In 2017, Ove Arup & Partners, Ltd. set up several verification tests including corridor walking speeds, stair walking speeds, exit flow rates, pre-evacuation time, movement around corners, assignment of parameters, counter-flow, crowd exit usage, exit allocation, stair congestion, movement disabilities, affiliation, dynamic availability of exits, stair merging and stair flows (Arup, 2017). The test results conformed to International Maritime Organization (IMO) and National Institute of Standards and Technology (NIST) guidance.

Door way flow rates for door widths ranging from 0.8m to 1.5m were tested by Oasys and the relationship shows a linear dependence between the increase of door width and flow rate (Arup, 2017). Moreover, this research tested pre-evacuation time in terms of different types of distribution: uniform distributions, triangular distribution, and normal distribution. For all three of the distribution types, the pre-evacuation time increased with the growth of agent numbers (Arup, 2017).

Other defaults in MassMotion used in this research are listed in Table 2-5 (Arup, 2015).

Table 2- 5: Default Agent Attributes (Arup, 2015) (Reproduced).

| Parameter | Default Data | Basis of Default Values |
|---|---|---|
| Preferred Horizontal Terrain Walking Speed Distribution (m/s) | Minimum = 0.65 Maximum = 2.05 (Mean = 1.35 Standard Deviation = 0.25) | The default preferred horizontal terrain walking speed distribution range (0.65m/s to 2.05m/s – uniformly distributed) is based on Fruin's (1971, 1987) observations of commuter speed profile for a range of ages and genders. |
| Maximum Acceleration ($m/s^2$) | 3.0 | The default maximum acceleration, turning rate and shuffle factor is based on qualitative model observations and sensitivity analysis by Oasys. |
| Maximum Turn Rate (degrees/s) | 45.0 | |
| Shuffle Factor (% of Preferred Horizontal Terrain Walking Speed Below Which Agents can Shuffle in Any Direction) | 0.1 | |
| Direction Bias | Direction: Keep Right Strength: Strong | The default direction bias is calibrated to yield crowd characteristics (in terms of flow and motion) that are consistent with Fruin's Levels of Service A to F (1971, 1987).<br><br>The 'Keep Right' value was selected based on an observed preference (in a number of countries) to favour moving to the right when resolving movement conflict. |
| Horizontal Distance Cost (factor)<br><br>Vertical Distance Cost (factor)<br><br>Queue Cost (factor)<br><br>Processing Cost (factor) | Minimum = 0.75 Maximum = 1.25<br><br>Minimum = 0.75 Maximum = 1.25<br><br>Minimum = 0.75 Maximum = 1.25<br><br>Minimum = 0.75 Maximum = 1.25 | The underlying network route costs, that the agents respond to, are based on the costs for journey segments in the Transport for London, Business Case Development Manual (2003).<br><br>The default variability ranges are intended to produce stochastic variation within a population where route options have very similar costs, without significantly altering the mean distribution of route choices. |

### 2.3.2 EXIT89

Since the advance phase preparation of this research work is to verify the feasibility of MassMotion comparing with EXIT89, here it is essential to describe EXIT89. EXIT89 (Fahy, 1999b, p. 819) is a partial behavior model based on data from the research work of Predtechenskii and Milinskii (1978) that demonstrates the relationship between density and speed of occupants for different types of building components. This model is a coarse network model. There are ten inputs available for users that include units of values, body sizes, movement types, route, smoke data, contra flow, output parameters, number of stairwells, stairwell travel directions, and delay time. One of the user-manipulated options is the evacuation route of individuals that is either the shortest one chosen automatically or the route defined by the user. However, when the exit is not accessible due to certain reasons, such as smoke blockage, individuals evacuate in other ways rather than the original route. The output includes tables showing the movement of individuals, the evacuation time, the number of stuck occupants and the clearing time of each floor. (Fahy, 1999)

Human behavior modeled in EXIT89 is implicit. There are three body sizes available: 0.0906 $m^2$, 0.1130 $m^2$ and 0.1458 $m^2$ representing American, Soviet, and Austrian populations, respectively (Fahy, 1999). Body sizes contribute to occupant density. The equation of the occupant density is given in Equation 2-2.

$$D = \frac{N \times f}{w \times L} \qquad 2\text{-}2$$

Where N is the number of occupants; f is the area of horizontal projection of a person; w and L are the width and length of the flow. As mentioned earlier, the speed of occupants is related to occupant density given by Predtechenskii and Milinskii (1978) who also indicate that the speed may be adjusted for emergency evacuation.

# CHAPTER 3: EVALUATION METHODOLOGY

In this chapter, the research methodology is introduced. This research is separated into two phases: The comparison with Hartmann's thesis (2005), and the comparison of total versus phased evacuation for high-rise office buildings using MassMotion. The goal of the former is to determine if MassMotion is a reasonable egress model to explore the comparison between total and phased evacuation strategies. The second phase uses MassMotion to compare the impact of building heights and occupant loads on these two evacuation strategies in high-rise office buildings.

## 3.1 COMPARISON OF RESULTS WITH HARTMANN'S THESIS

As mentioned in Chapter 2.1, Hartmann performed the research to compare the difference between total evacuation and phased evacuation for high-rise office buildings using EXIT89. However, Hartmann did not identify a quantitative difference between these two evacuation strategies. Thus, this section introduces the comparison of current thesis results using MassMotion and Hartmann's results using EXIT89 in order to determine if MassMotion can get different results as compared to EXIT89 and verify that it is worth continuing the comparison of total and phased evacuation strategies using MassMotion.

EXIT89 (Hartmann, 2005) was used to compare the total evacuation and phased evacuation in high-rise office buildings. The results of the comparison depict *"The relative time difference is not as significant as had been originally anticipated and is relatively stable as building height varies."* (Hartmann, 2005). The phased evacuation that was described in the above-mentioned thesis includes selected occupants in five floors that include one fire floor and two adjacent floors above and below the fire floor evacuating during phased evacuation fire strategy. As mentioned in Section 2.1, she considered the top five floors as the affected floors, which means the fire floor she chose in her thesis is the second from last floor. It is worth mentioning that, Hartmann selected the heights of 11-story, 21-story, and 31-story buildings in order to have occupants traveling in stairwells of 10 stories, 20 stories, and 30 stories to reach first floor equivalently. In other words, occupants on the second floor to the top floor evacuate. For more information about EXIT89 refer to section 2.3.2.

The methodology of the first phase of this research includes setting up the models in MassMotion with the same inputs as Hartmann's thesis (see Section 3.1.1), and comparing the results of total evacuation time and floor clearing time from EXIT89 and MassMotion (see Section 3.1.3) using the definition of floor clearing time utilized by Hartmann.

The current research attempts to compare the results between MassMotion and EXIT89, where MassMotion is used for the same purpose as EXIT89 used in Hartmann (2005), which is the comparison of total and phased evacuation using the same model inputs introduced in Section 3.1.1. The results of hypothetical buildings in these two software packages are compared and discussed in this chapter, which is divided into two parts. Section 3.1.1, Section 3.1.2 and Section 3.1.3 describe model inputs, comparison of the model results from this research and Hartmann's thesis, and the analysis of the results respectively.

### 3.1.1 MODEL DESCRIPTION

In order to compare the results of this thesis with Hartmann's thesis, the simulation set up in MassMotion has the same inputs as with Hartmann's EXIT89 simulation. The user options in EXIT89 utilized by Hartmann are shown in Figure 3-1.

| |
|---|
| UNITS (1-METRIC,2-STD) =2 |
| SIZE (1-AUST,2-SOVIET,3-US) =1 |
| SPEED (1-EMER,2-NORMAL) =1 |
| PATH (1-SHORTEST,2-DIRECTED)=1 |
| SMOKE (1-CFAST,2-USER/NONE) =2 |
| CONTRA (1-IF CONTRA FLOWS) =0 |
| OUTPUT (1-FULL,2-BRIEF) =1 |
| NUM OF STAIRWAYS (00-10) =02 or 04 |
| STAIR TRAVEL (1-DOWN, 2-UP) =1 |
| RANDOM DELAY (1-Y,2-N) =2, PROB = 50, |
| MIN TIME (SEC) = 1, MAX TIME (SEC) = 5. |

Figure 3- 1: The Ten User Options Chosen For The Hypothetical Buildings (Hartmann, 2005).

For these ten user options in Figure 3-1, Hartmann chose English units. The body size used in her thesis is Austrian (0.1458 $m^2$). She considered the speed based on a fire (emergency) condition and chose the shortest route for the evacuation. She did not consider smoke blockage of the egress route in her simulations. No contra flow was chosen. The number of stairwells in her thesis ranged from two or four for different buildings, though only the cases with two exits were used in this comparison. Also, no time delay was considered.

Model inputs are separated into four significant parts, including occupant load factor, building size, building height, and building layout. The first essential input is occupant load factor. This was considered as 9.3 $m^2$ per person which is based on "gross floor area". It was defined as *"the floor area within the inside perimeter of the outside walls of the building under consideration with no deductions for hallways, stairs, closets, thickness of interior walls, columns, or other features."* in NFPA 101 (Life Safety Code) (NFPA, 2003a). Because 9.3 $m^2$ per person value is the minimum occupant load factor required in the code (NFPA 101, 2003), this research work only focuses on the comparison with her thesis using the 9.3 $m^2$ per person occupant load factor.

The second input is the building size. The floor area is considered to be 930 $m^2$. Thus, the corresponding floor dimension would be 30.5 meters by 30.5 meters. Because Hartmann identified that the total evacuation time increases with the increased building heights in 2,560, 4,703, and 13,064 $m^2$ office buildings, the comparison with her thesis will only consider 930 $m^2$ floor area.

As a third input, the height between two floors is 3.7 meters. As a result, the corresponding heights of the 11-story, 21-story, and 31-story buildings are 40.2 meters, 76.8 meters, and 113.4 meters, respectively.

Other than occupant load factor, building size, and building height, another important input is building layout (see Figure 3-2). NFPA 101 (Life Safety Code) (NFPA, 2003a) stated that two exits are required with up to 499 occupants per floor. To meet the requirement of maximum occupant load per floor, there were two exits designed in the floor plan for all three heights of buildings based on the number of occupants per floor. Moreover, 138 persons chosen by Hartmann's thesis will be set up in MassMotion. In addition to that, the total cumulative occupant load assigned to each stairwell is less than 2,000 persons. For these inputs, as stated in NFPA 101 (Life Safety Code), a new stairwell width was chosen to be 1.12 meters in 11-story and 21-story buildings from Hartmann, while 1.42 meters was selected in 31-story building as the total cumulative occupant load assigned to each stairwell was greater than 2,000 persons (NFPA101, 2003a). The two stairwells were designed in the outer edges of the floor plan with the steps of tread 7 inches deep by 11 inches high. Doors leading into stairwells and as exits to the outside are 0.914 meters wide. Landings in the stairwells are located in the middle between two floors that is 1.829 meters high away from the lower floor. Each floor has a core layout that allows elevators and restrooms to be designed in the core of the floor plan with an open office plan area surrounding the core. Table 3-1 explains the inputs of models that were used in this thesis for the comparison between MassMotion and EXIT89.

Table 3-1: Inputs of Models Used in This Comparison.

| floors | 11 stories | 21 stories | 31stories |
|---|---|---|---|
| occupant load factor | 9.3 $m^2$/person | 9.3 $m^2$/person | 9.3 $m^2$/person |
| floor area ($m^2$) | 930 | 930 | 930 |
| number of occupants (total evacuation) | 1,380 | 2,760 | 4,140 |
| number of occupants (phased evacuation) | 690 | 690 | 690 |
| number of exits | 2 exits | 2 exits | 2 exits |
| exits width (meters) | 1.12 | 1.12 | 1.42 |

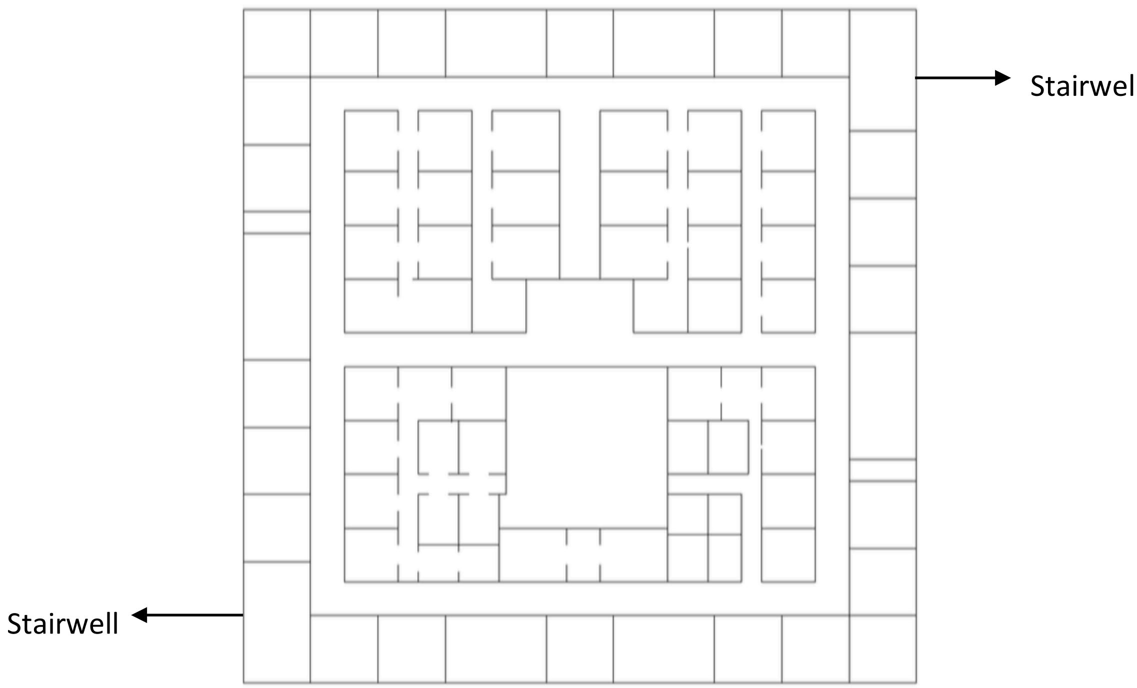



Figure 3- 2: 930 $m^2$ Building Floor Layout (not to scale) (Hartmann, 2005).

In addition to the user inputs chosen from EXIT89 and the inputs Hartmann utilized in her thesis, there are some defaults and more details introduced below which can impact the egress time, based on the difference between EXIT89 and MassMotion. By default, path traversal does not affect the speed of occupants. The speed of occupants will decrease in order to follow the occupant which is immediately in front. Occupants walk at an assigned speed when there is nothing around them. However, the acceleration or deceleration of speed (3 $m/s^2$) will be utilized to adjust the original speed from other occupants or barriers around them. Default speeds in MassMotion are listed in Table 2-3 (Chapter 2.3.1). Moreover, the default body size is 0.5 meters (diameter). All other defaults in MassMotion are as mentioned in Table 2-5 (Chapter 2.3.1).

### 3.1.2 MODEL RESULTS

Based on the description of models in the previous section, the simulation results of Hartmann's research and this research are given in Appendix A to Appendix C. The results are divided into the total egress time and the floor clearing time (the time for the last occupant to pass to the next stairwell).

### 3.1.3 RESULTS ANALYSIS

With the same inputs as Hartmann's models described in Chapter 3.1.1, this research obtained different results. One essential difference is that the difference in the values between total evacuation and phased evacuation increases with the height of the building in MassMotion, while in Hartmann's research the dependence on building height is not present (see Figure 3-3).

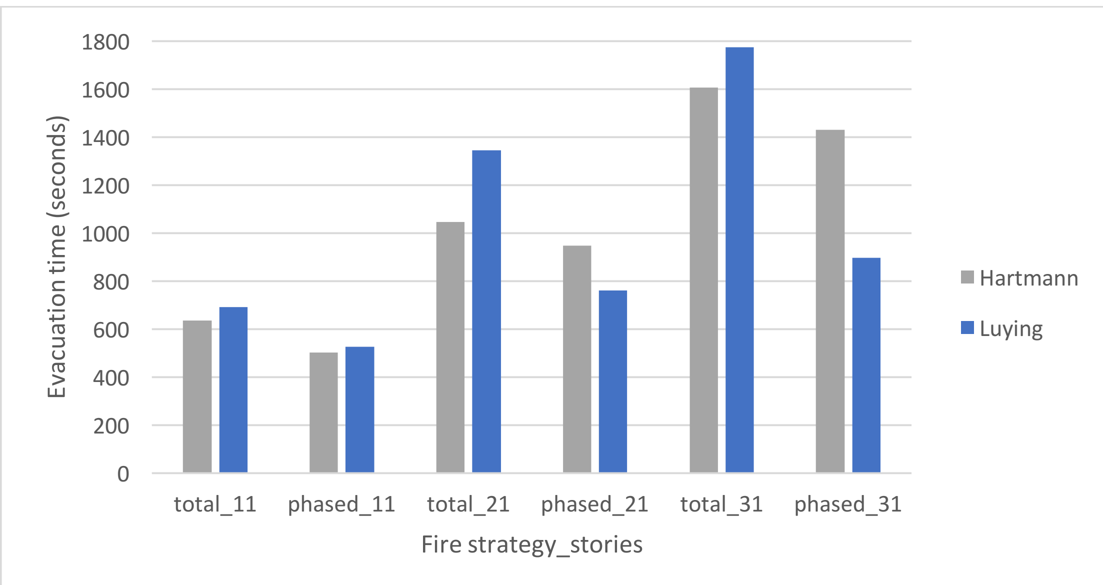



Figure 3- 3: Total Evacuation Time for Total and Phased Evacuation Strategies in 11-story, 21-story and 31-story High-rise Office Building with 930 $m^2$ Floor Area from Hartmann and Luying.

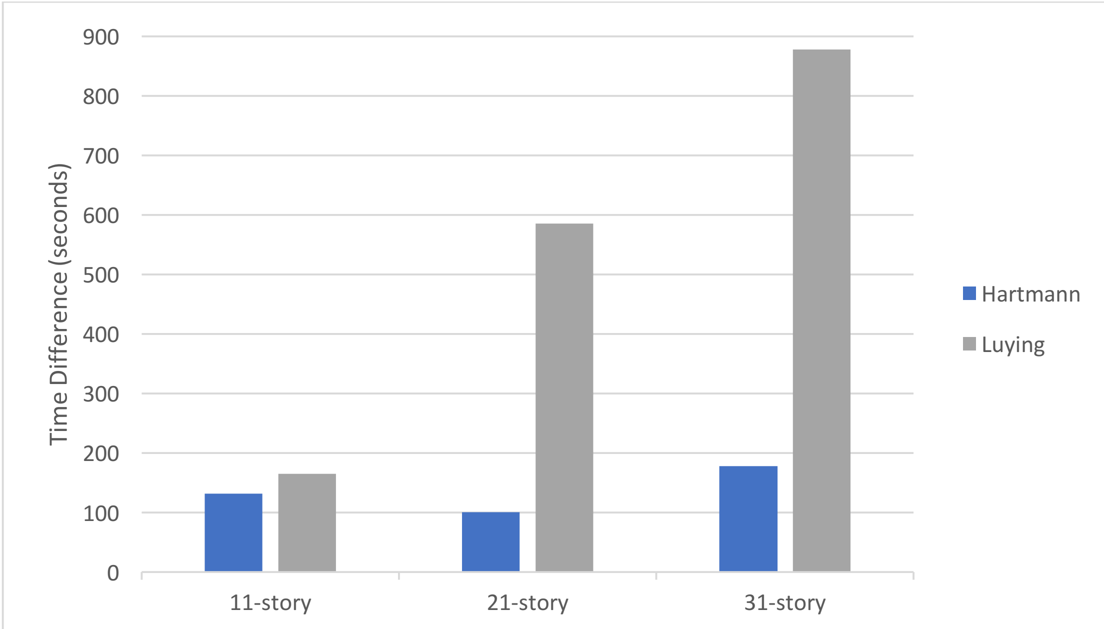



Figure 3- 4: Time Difference: Total – Phased Evacuation for 11-story, 21-story and 31-story Office Building with 930 $m^2$ Floor Area from Hartmann and Luying.

The differences of the time to clear a floor for the total evacuation versus phased evacuation strategies determined by Hartmann are 132 seconds, 100 seconds, 178 seconds in 11-story, 21-story and 31-story office buildings, respectively. In comparison, these differences are 165 seconds, 585 seconds and 878 seconds accordingly was observed from using MassMotion. The results from MassMotion are more reasonable as the difference of occupant numbers between total evacuation and phased evacuation increases with the increasing height of a building. This is expected because the number of occupants increases with the number of stories which should lead to an increase in total evacuation time. On the other hand, the phased evacuation time also increases with the height of the building but not as rapidly as the egress time during total evacuation. Thus, the difference of phase evacuation and total evacuation should increase with the height of the building.

Coupled with the discussion of the comparison between total and phased evacuation in total evacuation time, the essential part of this comparison is also to discover the difference of the evacuation time clearing each floor. This is described in the Figure 3-6, 3-8 and 3-10 for 11, 21 and 31 stories buildings.

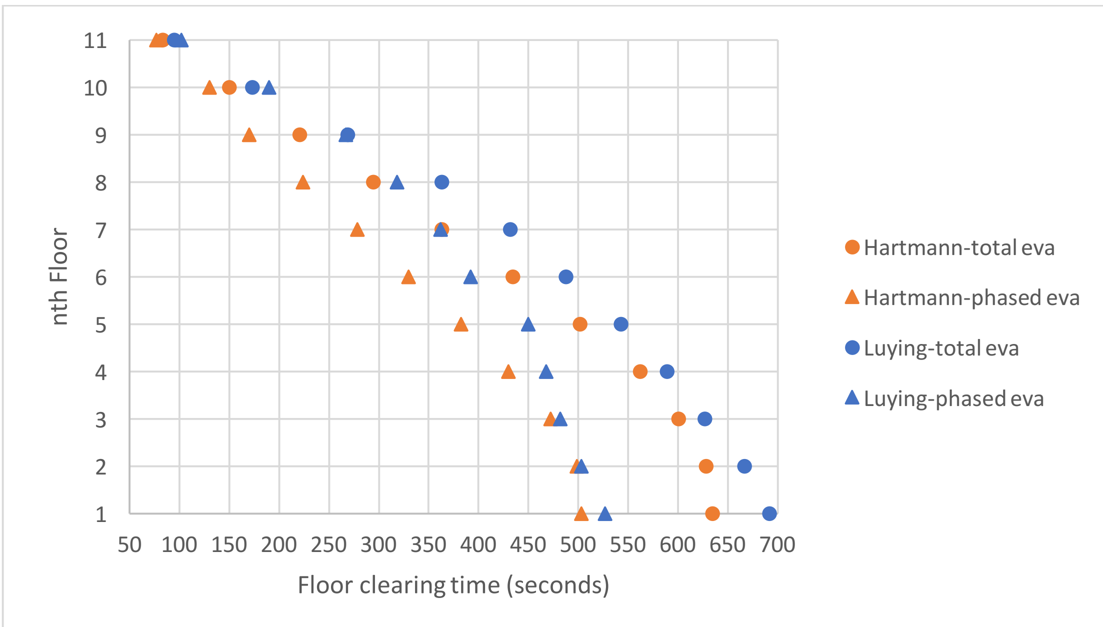



Figure 3- 5: Floor Clearing Time of a 930 $m^2$ 11-story Office Building from Hartmann and Luying.

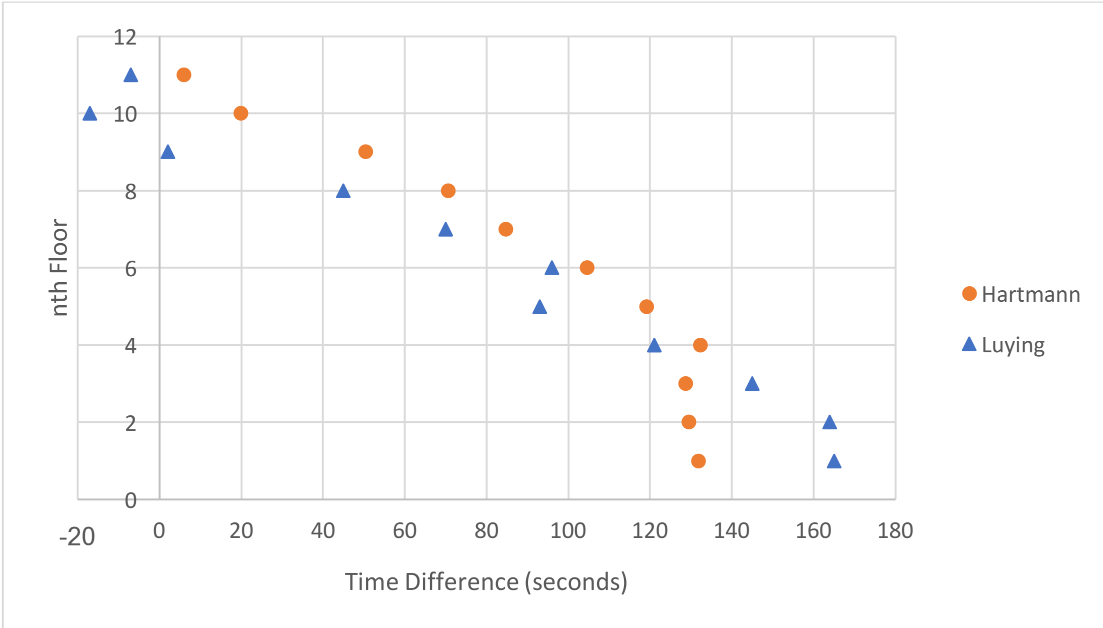



Figure 3- 6: Floor Clearing Time Difference Between Total and Phased Evacuation for a 11-story Office Building from Hartmann and Luying.

The results of the difference in time to clear each floor for total and phased evacuation are similar in both the research by Hartmann and current thesis for the 11-story building (see Figure 3-6), but it is not the case for 21 and 31 story buildings (see Figure 3-8 and Figure 3-10). For 21 and 31 story buildings, the difference in floor clearing time determined by Hartmann does not change much with the floor level but it changes rapidly in this current research. Thus, in the current analysis it is evident that the difference in floor clearing time increases from top floor to the bottom floor. For a total evacuation strategy, occupants continuously evacuate into stairwells which is a major reason the clearing time increases for each floor. The accumulated process is the principal cause of an increased difference in the floor clearing time.

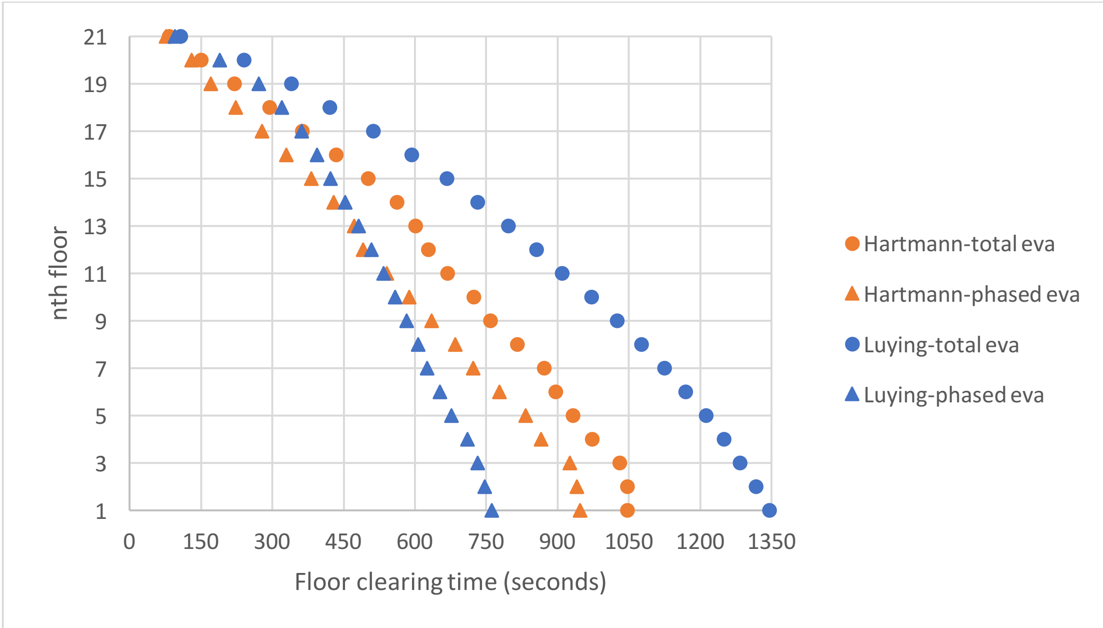



Figure 3- 7: Floor Clearing Time of a 930 $m^2$ 21-story Office Building from Hartmann and Luying.

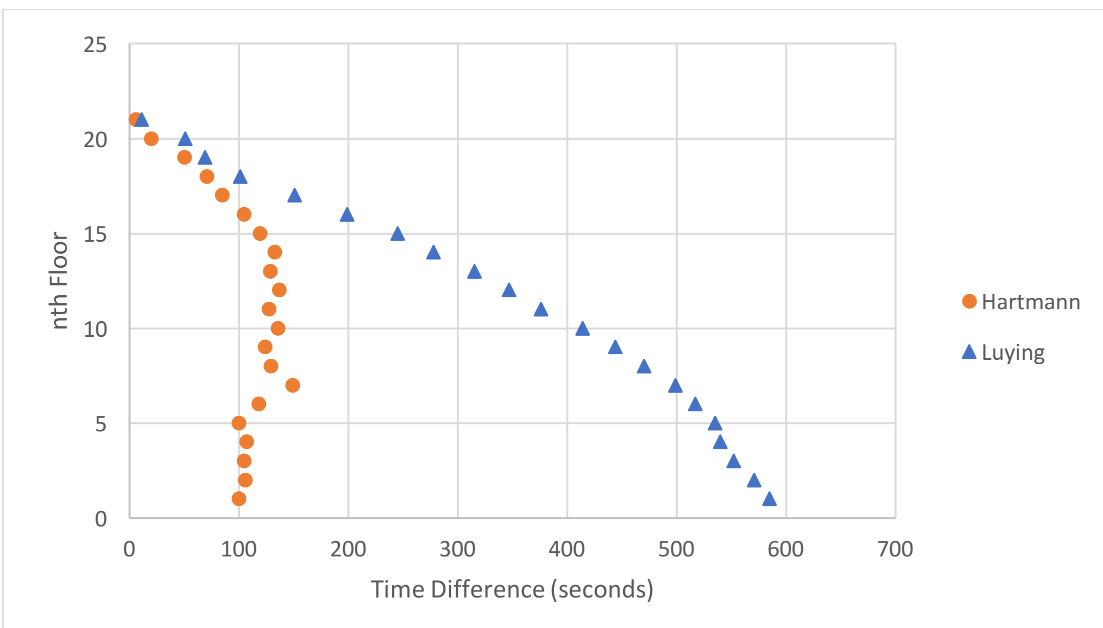



Figure 3- 8: Floor Clearing Time Difference Between Total and Phased Evacuation for 21-story Office Building from Hartmann and Luying.

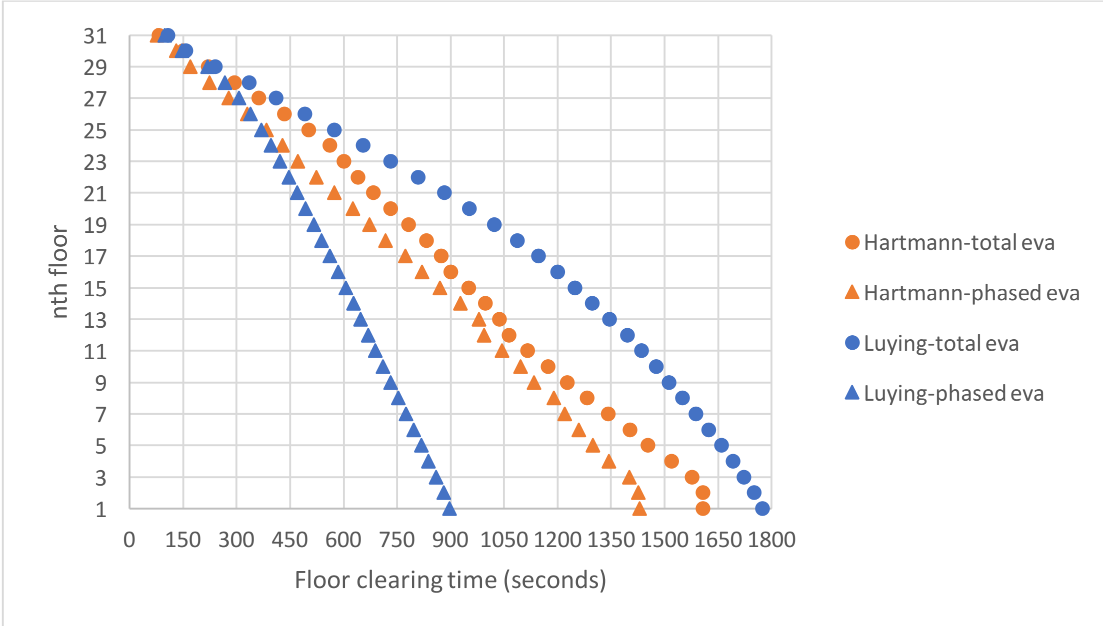



Figure 3- 9: Floor Clearing Time of a 930 m$^2$ 31-story Office Building from Hartmann and Luying.

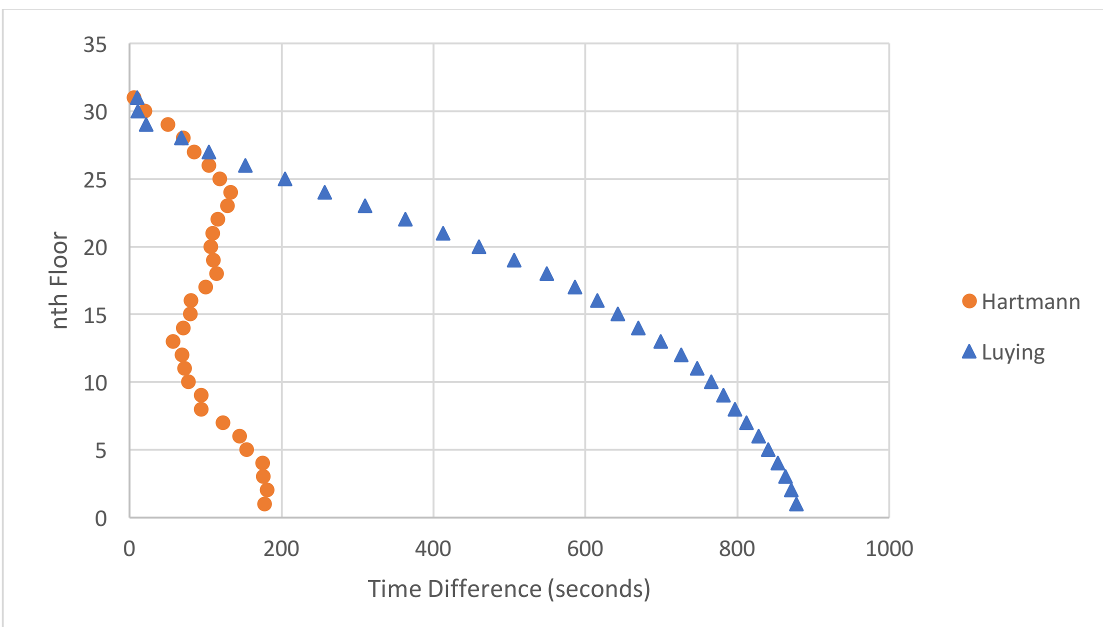



Figure 3- 10: Floor Clearing Time Difference Between Total and Phased Evacuation for 31-story Office Building from Hartmann and Luying.

The difference in MassMotion becomes even more apparent in the comparison of total and phased evacuation in the 31-story and 21-story buildings versus the 11-story building (see Table 3-5, Table 3-6, and Table 3-7). These results support the observation that after agents finish moving to the floors below the top five floors, the walking speed becomes constant in a phased evacuation (see orange line in Figure 3-7 and Figure 3-9) as the slope is constant. Hartmann's thesis does not show this different pattern as mentioned before.

In summary, results from MassMotion more clearly demonstrate the difference of clearing time from the top to the bottom floor is increases as the height of the building increases, which EXIT89 does not show. The main reason why the different results generated from the same inputs in these two egress models relates to the basic differences between the two models. EXIT89 uses a coarse network and MassMotion use a continuous network for the representation of enclosure as mention in Chapter 2.3. EXIT89 is a crude egress model which cannot simulate queues forming.

The results indicate that it is worth performing the second phase of this research to utilize MassMotion for a detailed comparison of total versus phased evacuation strategies in high-rise office buildings, as described in the following parts of this thesis.

## 3.2 INTRODUCTION OF METHODOLOGY

Technically, this research work attempted to explore any difference between total and phased evacuation in high-rise office buildings through egress modeling, MassMotion. Moreover, this research tends to analyze the difference between these two fire strategies to provide limited guidance for building owner and reference of life safety design for engineers.

The prior preparation for this research work demonstrated the obvious difference between these two evacuation strategies based on the models in MassMotion. Thus, this will evaluate the magnitude of the difference between total and phased evacuation in various building design conditions by conducting simulations with MassMotion of three building heights, one building size and occupant loads ranging from 70 to 150 persons per floor.

In this phase of the research, there are some important differences with the research by Hartmann. Here, the phased evacuation plan will consist of three floor levels as opposed to the five by Hartmann. Thus, difference is based on the tendency for engineers to design contemporary high-rise office buildings based on this evacuation strategy considering only three floors. During phased evacuation, since the occupants on affected floors will be in danger first, occupants on the other floors will evacuate after the occupants on affected floors evacuate into stairwells. In other words, the floor clearing time of occupants on the affected floors will not be affected by the evacuation from occupants on the other floors. Thus, the simulation of evacuation for the phased evacuation strategy considers movement of occupants only on the affected floors. Another principal difference is that the metric "floor clearing time" is defined as the time for all occupants to leave the office space of the floor and enter the stairwell. This is a more relevant measure of the achievement of evacuation rather than departure from a landing in a stairwell which was used by Hartmann.

The first comparison conducted by this research is to assess the influence of building heights in total and phased evacuation strategies. The second comparison relates to the influence of occupant load on the floor clearing times using phased versus total evacuation. Pre-evacuation delays are not considered in this second phase of the research, as the goal is to explore the difference between total and phased evacuation.

# CHAPTER 4: EVACUATION MODEL

## 4.1 INTRODUCTION OF EVACUATION MODEL

MassMotion is an egress model that is able to predict the egress time and track the location and movement of occupants in high-rise office buildings with a large population as mentioned in the introduction of MassMotion in Chapter 2.3.1.

This chapter aims to describe the parameters including occupant load, building size, building layout, and building height used in the simulations conducted using MassMotion. These parameters are described in Section 4.2 through 4.6. The Figures 4-1 and 4-2 illustrate the view of the egress model with multiple stories, and the geometry included in the model.

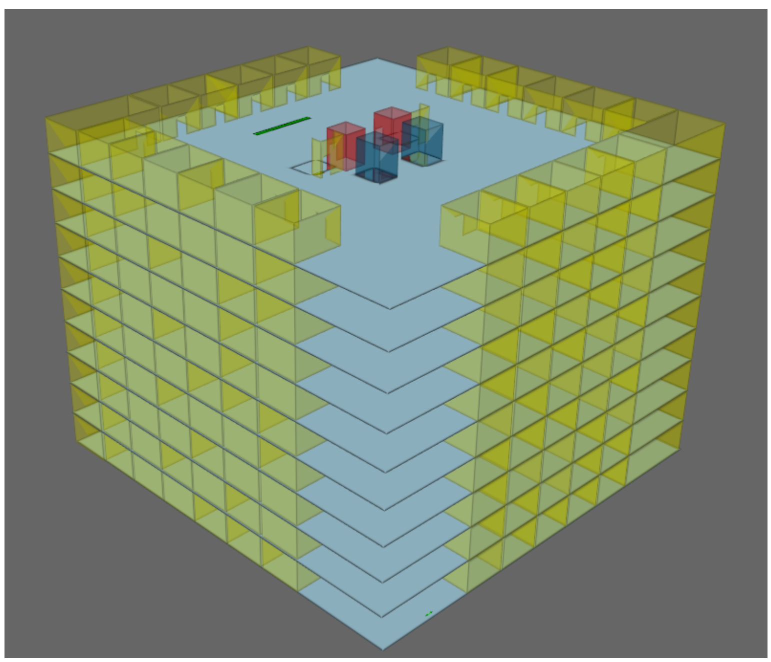


Figure 4- 1: View of Egress Model with Multiple Stories.

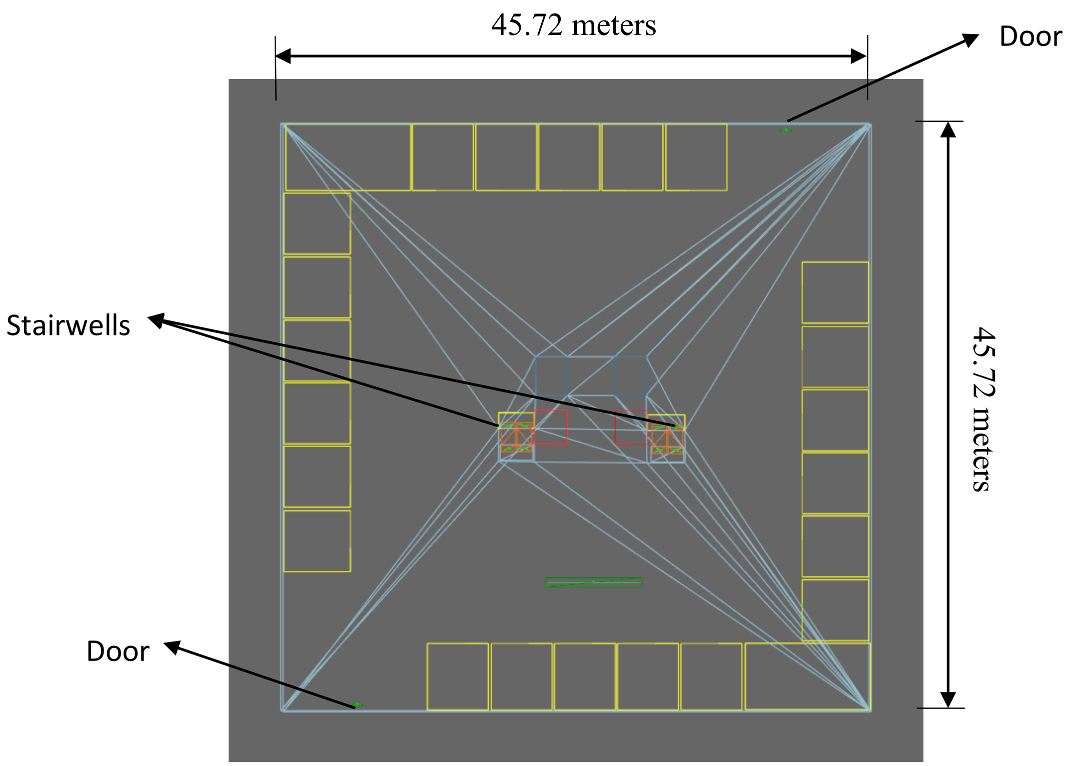



Figure 4- 2: Geometry of Egress Model Typical Floor.

## 4.2 OCCUPANT LOAD

The first input is occupant density, represented by the occupant load for each floor. NFPA 101 (2018) defines occupant load in Section 3.3.170.2, as *"The total number of persons that might occupy a building or portion thereof at any one time."* In Table 7.3.1.2 (Life Safety Code, 2018), the occupant load factor is 13.95 $m^2$ per person for business use. This research considers this number as the minimum occupant load factor. To discuss the impact of occupant load for total and phased evacuation, different occupant load factors are chosen in order to depict a much more accurate graph of the comparison. The current thesis includes a range of 70 to 150 occupants per floor.

## 4.3 OCCUPANT CHARACTERISTICS

First, the general setting of agents in MassMotion includes profile, radius, speed, and movement of agents. Profile and movement of agents in MassMotion utilizing in current thesis are set as ‘Fruin Commuter’. The size of agents is treated as a circle with ‘constant’ radius of 0.25 meters. The minimum, maximum, mean, and standard deviation speed of agents are 0.65, 2.05, 1.35, and 0.25 m/sec.

Moreover, agents are considered to be single set up in current simulations. All agents are aware of the route evacuating to exits. As for the route choice, the horizontal, vertical, queue, and processing route cost weights are set as ‘uniform’ with a minimum of 0.75 and maximum of 1.25. In the aspect of agent behavior, the direction bias is right strong. In MassMotion, there is no setting for age and gender of agents. Also, considering the distribution, agents are randomly located on the floor before evacuating. Other defaults in MassMotion are stated in Chapter 2.3.1.

## 4.4 BUILDING SIZE

The third significant parameter is building size. This research focuses on the influence of occupant load and the building height. Here the scope of this research work is limited by single building size. Thus, only one building size is chosen for all models in this research work. According to the minimum occupant load factor (13.95 $m^2$ per person) mentioned before, the dimension of the floor area is considered to be 45.72 m x 45.72 m. Thus total 2,090 $m^2$ floor area was considered for this hypothetical building. Accordingly, there is 150 persons on each floor based on the minimum occupant load factor.

## 4.5 BUILDING LAYOUT

The layout of the floor plan of each floor mainly includes the number of means of egress and exits, door width, stair width and travel distance and distribution of stairwells. Being the maximum occupant load on each floor is 150 persons, NFPA 101 requires a minimum of two stairwells (Section 7.4.1.1, NFPA 101, 2018). In IBC (2018), Table 1006.3.2 also requires minimum number of exits or access to exits from story is two for occupant load not more than 500 persons per floor. Thus, two stairwells are included in the building design for this research.

Doors are located on the edge of the floor plan (see Figure 4-2) and the door width is set as 0.914 meters as per NFPA 101 7.2.1.2.3.2, which states that *"Door openings in means of egress shall be not less than 32 in. (810 mm) in clear width."* As all models in this research do not exceed the limit of 2000 persons evacuating per stairwell, two 1.118 meters clear width stairwells are designed in all models. (NFPA 101 Table 7.2.2.2.1.2(B)).

In the stairwells, the landing is taken as 1.12 meters in the direction of travel as per NFPA 101 7.2.2.3.2.4, which says that *"Landings shall not be required to exceed 48 in. (1220 mm) in the direction of travel, provided that the stair has a straight run."* Also, the landings are positioned in the middle of two floors as well as at each floor level. The intermediate landings are 1.829 meters from each floor.

Each floor is designed following a core plan with elevators, stairwells, and restrooms in the core area of the floor plan. The hypothetical office building in this research is designed as an open-plan office layout. Stairwells are located in the core of each floor with step size of 0.18 meters deep by 0.28 meters high. The size of restrooms and elevators are selected to be 9 $m^2$ and 8.12 $m^2$ respectively, according to the typical industrial requirements.

## 4.6 BUILDING HEIGHT

Three building heights of 10-story, 20-story and 30-story are arbitrarily selected, other than to select heights that quality them for consideration as a high-rise building, as defined in Chapter 1. The distance between two floors is considered to be 3.66 meters. Therefore, the building heights for 10-story building 20-story building and 30-story building are 36.6 meters, 73.2 meters and 109.8 meters respectively.

Table 4-1 includes a list of the parameters of the buildings used in these simulations for the purpose of exploring the impact of building heights on the total and phased evacuation, while Table 4-2 includes a list of occupant loads used to assess the influence of occupant loads on the results.

Table 4- 1: Parameters of Buildings and Input of Occupant Load for the Impact of Building Heights on the Total and Phased Evacuation

| Floors | 10 stories | 20 stories | 30 stories |
|---|---|---|---|
| Building height (meters) | 36.6 | 73.2 | 109.8 |
| Floor area ($m^2$) | 2090 | 2090 | 2090 |
| Number of exits | 2 exits | 2 exits | 2 exits |
| exits width (meters) | 1.12 | 1.12 | 1.42 |
| Occupant load - total evacuation (persons/floor) | 70, 80, 90, 100, 115, 125, 140, 150 | | 70, 80, 90, 100, 115, 125 |
| Occupant load - phased evacuation (persons/floor) | 70, 80, 90, 95, 100, 110, 125, 135, 150 | | |

Table 4- 2: Parameters of Buildings and Input of Occupant Load for the Impact of Occupant Loads on the Difference Between Total and Phased Evacuation

| Floors | 10 stories |
|---|---|
| Building height (meters) | 36.6 |
| Floor area ($m^2$) | 2090 |
| Number of exits | 2 exits |
| exits width (meters) | 1.12 |
| Occupant load - total and phased evacuation (persons/floor) | 70, 80, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 150 |

Here, it is worth clarifying why the specific occupant loads included in Table 4-1 were chosen. Because the first comparison (see Table 4-1) in the second phase of this research includes the impact of building heights on floor clearing time for the two evacuation strategies separately, rather than comparing the difference of floor clearing time between total and phased evacuation. The occupant loads are arbitrarily chosen from 70 to 150 occupants in the analyses of 20-story and 30-story buildings for both total and phased evacuation. In other words, the occupant loads chosen in 20-story and 30-story buildings for total and phased evacuation can be different. For the 30-story building, the range of occupant loads is from 70 to 125 occupants per floor. In order to utilize the same width of stairwells, 125 occupants per floor is the largest occupant load selected for the 30-story building.

# CHAPTER 5: MODEL RESULTS

## 5.1 OVERALL RESULTS

The prior work in Chapter 3.1 of this research discusses the difference between the floor clearing time for total evacuation and phased evacuation processes. The results in this chapter focus on the floor clearing time on the top three floors, where the difference between total and phased evacuation strategies is the smallest case comparing to any other three floors randomly picked in the same building. Thus, it is the most conservative case to estimate the decrease of occupant load factor between total and phased evacuation based on the floor clearing time on the top three floors.

## 5.2 MODEL OUTPUT

The outputs of MassMotion are separated into two parts, details and overall information. The details incorporate the number of agents exiting the building in a unit time (one minute) along with the number of total agents in the building. Also, the details of agents "removed with errors" are mentioned in the output, including an identification of which agents were removed and the reason for their removal. The overall information includes the number of agents created in the simulations (how many agents that users set) and successfully evacuated, simulation time, total evacuation time, the date completed, and the version of MassMotion.

Based on the rendering video generated along with each simulation, several details including the location and egress time of each agent can be observed. Since this research is focused on the floor clearing time that is not available on the output window, the data for floor clearing time were collected from a review of the rendering videos.

## 5.3 EGRESS TIME

The results in this chapter are focused on the floor clearing time for the top three floors (time for the last occupant to enter the stairwell). When the last occupant steps for that floor into the stairwell on that same floor, this floor is considered to be cleared. The evacuation time is defined as the time period from the start of the evacuation to the time when the floor is cleared.

## 5.4 FLOOR CLEARING TIME FOR EACH BUILDING

The floor clearing time of the top three floors is given in Table 5-1 to Table 5-6. Table 5-1 and Table 5-2 include the results for total and phased evacuation processes in the 10-story building respectively. In Table 5-3 and Table 5-4, the results of the floor clearing time for the 20-story building are presented for total and phased evacuation processes, while Table 5-5 and Table 5-6 are for the 30-story building.

Table 5- 1: Floor Clearing Time (seconds) of Total Evacuation for the 10-story Office Building.

| | Floor Level | | |
|---|---|---|---|
| Occupant Load | 10 | 9 | 8 |
| 70 persons/floor | 85 | 104 | 133 |
| 80 persons/floor | 82 | 111 | 158 |
| 90 persons/floor | 87 | 124 | 178 |
| 95 persons/floor | 86 | 122 | 196 |
| 100 persons/floor | 85 | 131 | 206 |
| 105 persons/floor | 92 | 135 | 212 |
| 110 persons/floor | 92 | 140 | 214 |
| 115 persons/floor | 103 | 149 | 224 |
| 120 persons/floor | 91 | 165 | 244 |
| 125 persons/floor | 96 | 153 | 260 |
| 130 persons/floor | 93 | 165 | 282 |
| 135 persons/floor | 96 | 186 | 310 |
| 140 persons/floor | 102 | 186 | 326 |
| 150 persons/floor | 107 | 198 | 370 |

Table 5- 2: Floor Clearing Time (seconds) of Phased Evacuation for the 10-story Office Building.

| | Floor Level | | |
|---|---|---|---|
| Occupant Load | 10 | 9 | 8 |
| 70 persons/floor | 80 | 99 | 134 |
| 80 persons/floor | 85 | 108 | 145 |
| 90 persons/floor | 102 | 112 | 158 |
| 95 persons/floor | 91 | 129 | 165 |
| 100 persons/floor | 97 | 133 | 176 |
| 105 persons/floor | 93 | 146 | 184 |
| 110 persons/floor | 97 | 147 | 191 |
| 115 persons/floor | 95 | 155 | 201 |
| 120 persons/floor | 98 | 158 | 204 |
| 125 persons/floor | 99 | 163 | 209 |
| 130 persons/floor | 91 | 156 | 219 |
| 135 persons/floor | 101 | 171 | 226 |
| 140 persons/floor | 97 | 171 | 230 |
| 150 persons/floor | 109 | 184 | 243 |

Table 5- 3: Floor Clearing Time (seconds) of Total Evacuation for the 20-story Office Building.

| | Floor Level | | |
|---|---|---|---|
| Occupant Load | 20 | 19 | 18 |
| 70 persons/floor | 85 | 104 | 140 |
| 80 persons/floor | 86 | 105 | 153 |
| 90 persons/floor | 92 | 118 | 175 |
| 100 persons/floor | 92 | 130 | 204 |
| 110 persons/floor | 95 | 152 | 220 |
| 115 persons/floor | 93 | 150 | 228 |
| 125 persons/floor | 95 | 138 | 266 |
| 140 persons/floor | 102 | 193 | 328 |
| 150 persons/floor | 106 | 220 | 375 |

Table 5- 4: Floor Clearing Time (seconds) of Phased Evacuation for the 20-story Office Building.

| | Floor Level | | |
|---|---|---|---|
| Occupant Load | 20 | 19 | 18 |
| 70 persons/floor | 82 | 95 | 131 |
| 80 persons/floor | 95 | 101 | 141 |
| 90 persons/floor | 88 | 126 | 157 |
| 95 persons/floor | 97 | 114 | 165 |
| 100 persons/floor | 89 | 125 | 174 |
| 110 persons/floor | 98 | 142 | 191 |
| 125 persons/floor | 101 | 159 | 210 |
| 135 persons/floor | 96 | 170 | 227 |
| 150 persons/floor | 108 | 189 | 241 |

Table 5- 5: Floor Clearing Time (seconds) of Total Evacuation for the 30-story Office Building.

| | Floor Level | | |
|---|---|---|---|
| Occupant Load | 30 | 29 | 28 |
| 70 persons/floor | 84 | 104 | 136 |
| 80 persons/floor | 90 | 120 | 152 |
| 90 persons/floor | 89 | 109 | 170 |
| 100 persons/floor | 90 | 117 | 196 |
| 110 persons/floor | 90 | 121 | 202 |
| 115 persons/floor | 99 | 137 | 223 |
| 125 persons/floor | 98 | 148 | 258 |

Table 5- 6: Floor Clearing Time (seconds) of Phased Evacuation for the 30-story Office Building.

| | Floor Level | | |
|---|---|---|---|
| Occupant Load | 30 | 29 | 28 |
| 70 persons/floor | 90 | 97 | 138 |
| 80 persons/floor | 95 | 103 | 142 |
| 90 persons/floor | 97 | 120 | 160 |
| 95 persons/floor | 95 | 115 | 166 |
| 100 persons/floor | 99 | 122 | 168 |
| 110 persons/floor | 98 | 135 | 183 |
| 125 persons/floor | 97 | 156 | 209 |
| 135 persons/floor | 100 | 176 | 227 |
| 150 persons/floor | 107 | 194 | 247 |

As an example to illustrate the results obtained, one selected graph is provided in Figure 5-1. Graphs for all simulations are presented in Appendix D and E. Analysis of the results will be presented in Chapter 6.

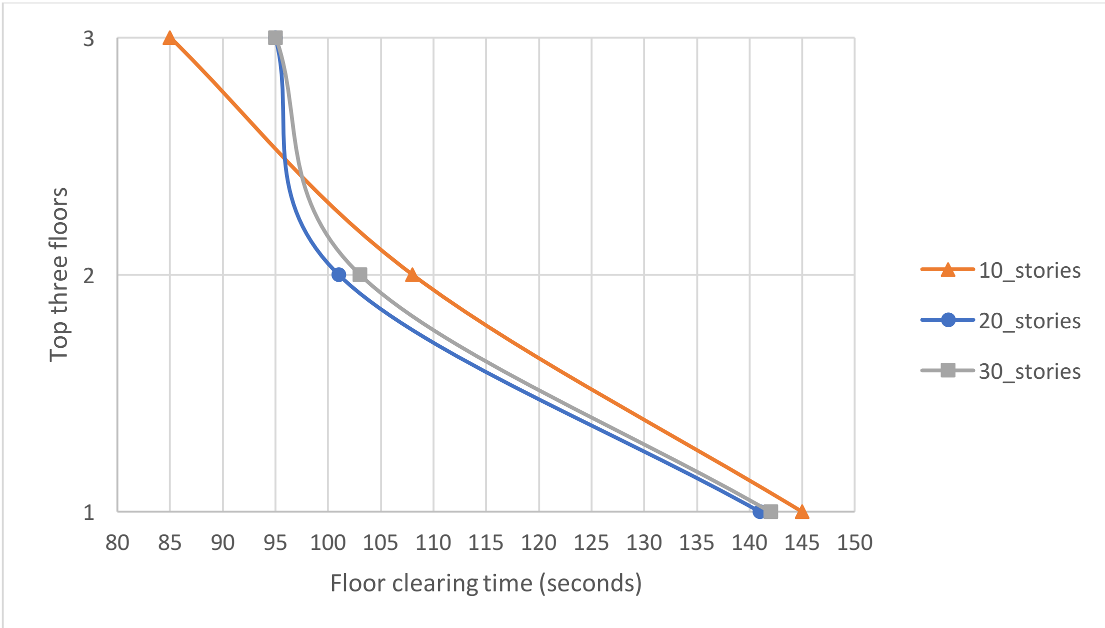



Figure 5- 1: Floor Clearing Time in Top Three Floors in 10-story, 20-story and 30-story Office Buildings with 2,092.5 $m^2$ Floor Area for 80 persons/floor Occupant Load in Total Evacuation.

# CHAPTER 6: ANALYSIS OF RESULTS

## 6.1 OVERALL ANALYSIS

Before analyzing the results, it as a reminder the goal of this research is to explore any difference between the performance of total and phased evacuation fire strategies in high-rise office buildings. Furthermore, it is also an essential aspect of this thesis to determine the impact of various building heights and occupant loads on these two fire strategies. The metric used for the comparison of the strategies is the floor clearing time for affected floors.

In Section 6.3, this thesis compares the effect of various occupant loads between total and phased evacuation in a hypothetical 10-story high-rise office building. The analysis includes a 20-story and a 30-story building with the same floor plan to assess whether the trends identified are dependent on the heights of the building.

## 6.2 ANALYSIS OF RESULTS OF FLOOR CLEARING TIME FOR DIFFERENT BUILDING HEIGHTS

Instead of comparing the different occupant load in all 10-story, 20-story and 30-story buildings first, it is worthwhile comparing the floor clearing time for different heights of buildings for both total and phased evacuation. If the floor clearing time for 10-story, 20-story and 30-story buildings is similar, the results analysis in Section 6.3 can be used to be a reference regardless of building heights.

### 6.2.1 TOTAL EVACUATION

The floor clearing time during total evacuation of the top three floors for different occupant loads (70 persons/floor, 80 persons/floor, 90 persons/floor, 100 persons/floor, 115 persons/floor, 125 persons/floor, 140 persons/floor, and 150 persons/floor) between 10-story, 20-story, and 30-story buildings are similar. The results for three occupant loads that cover the range of occupant loads analyzed (70 persons/floor, 90 persons/floor, and 125 persons/floor) are presented in Figure 6-1. The results for the all of the other occupant loads included in the analysis are presented in Appendix D.

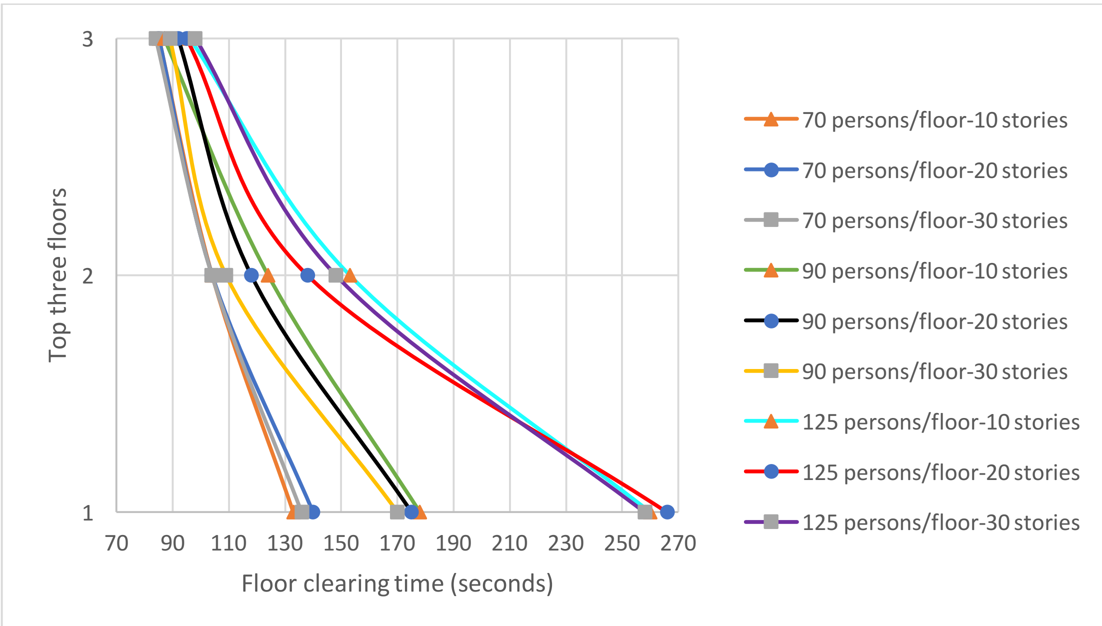



Figure 6- 1: Floor Clearing Time in Top Three Floors in 10-story, 20-story, and 30-story Office Buildings with 2,092.5 $m^2$ Floor Area for 70 persons/floor, 90 persons/floor, and 125 persons/floor Occupant Load in Total Evacuation.

The difference in floor clearing time between the top floors of the buildings those are 30$^{th}$ floor, 20$^{th}$ floor and 10$^{th}$ floor is from 0 second to 10 seconds for above mentioned occupant loads, while the difference between 29$^{th}$ floor, 19$^{th}$ floor and 9$^{th}$ floor of 30-story, 20-story and 10-story building respectively is from 0 second to 19 seconds (see Figure 6-1 and Appendix D). Moreover, it can be seen in Figure 6-2 that the absolute difference value between 10-story and 20-story buildings in 8th floor and 18th floor for floor clearing time is from two seconds to seven seconds. The difference of floor clearing time between the 10-story and 30-story buildings in 8th floor and 28th floor is from one to 12 seconds (see Figure 6-2 and 6-3). Thus, all differences for this comparison are lesser than 12 seconds that is negligible comparing to total egress time in the top three floors (which is the worst case). Focus is on the floor clearing time in the bottom of the affected floors, being the greatest egress time.

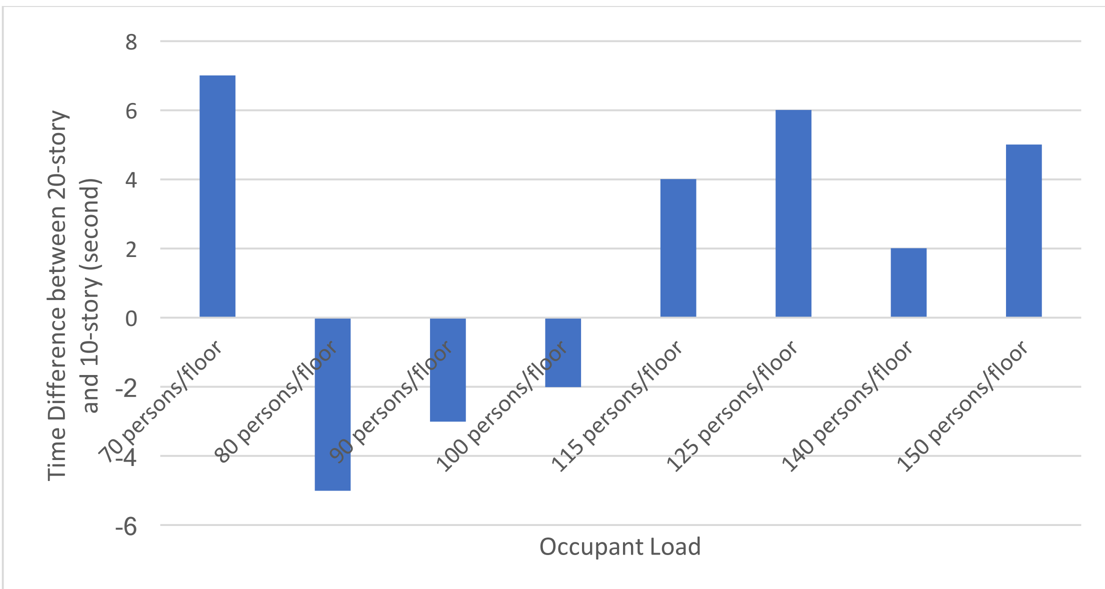



Figure 6- 2: Time Difference Between 20-story and 10-story Office Buildings with 2,092.5 $m^2$ Floor Area in the Bottom Floor of the Top Three Floors for Total Evacuation.

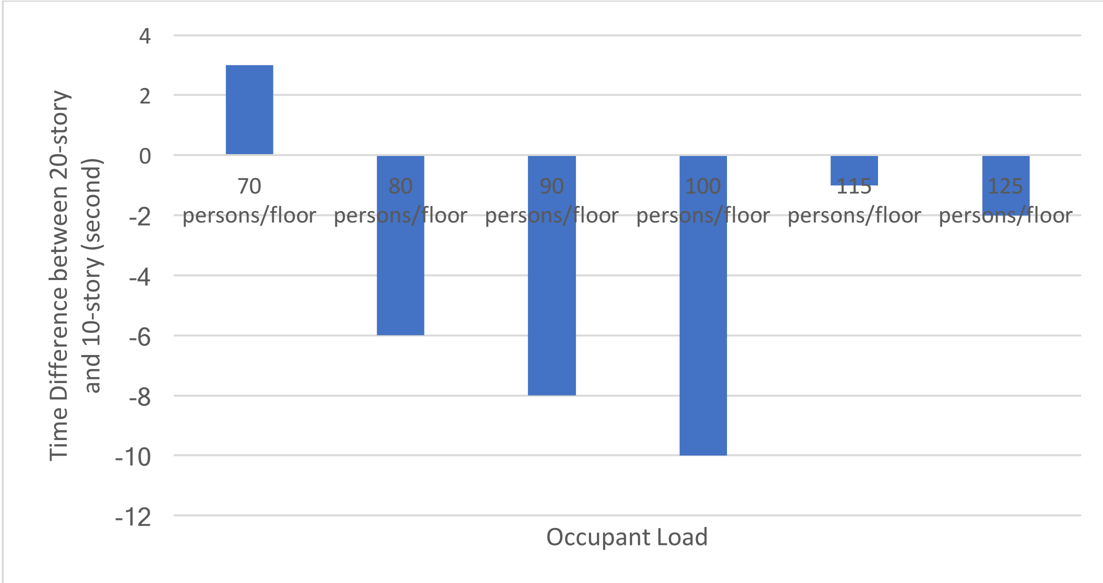



Figure 6- 3: Time Difference Between 30-story and 10-story Office Buildings with 2,092.5 $m^2$ Floor Area in the Bottom Floor of the Top Three Floors for Total Evacuation.

### 6.2.2 PHASED EVACUATION

The floor clearing time during total evacuation of the top three floors in different occupant loads (70 persons/floor, 80 persons/floor, 90 persons/floor, 95 persons/floor, 100 persons/floor, 110 persons/floor, 125 persons/floor, 135 persons/floor, and 150 persons/floor) between 10-story, 20-story and 30-story buildings are similar that is the same as total evacuation. Figure 6-4 depicts the evacuation time in the top three floors for three occupant loads those are 70 persons/floor, 110 persons/floor, and 150 persons/floor. Comparison for the rest of the occupant load can be observed in Appendix E.

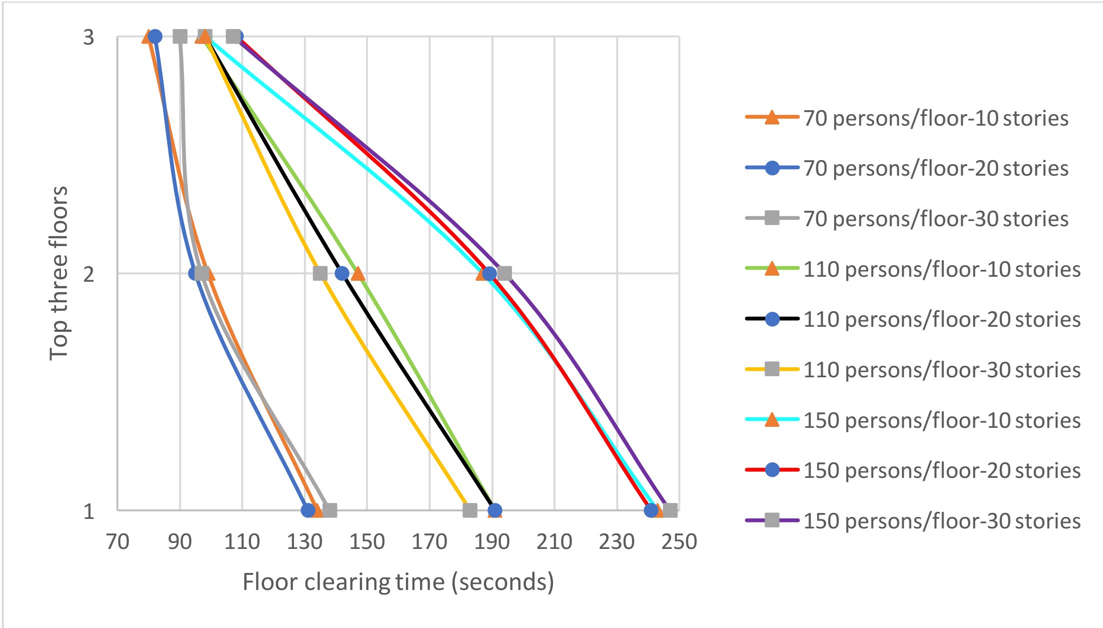



Figure 6- 4: Floor Clearing Time in Top Three Floors for 10-story and 20-story Office Buildings for 70, 110, and 150 persons/floor Occupant Load in Phased Evacuation.

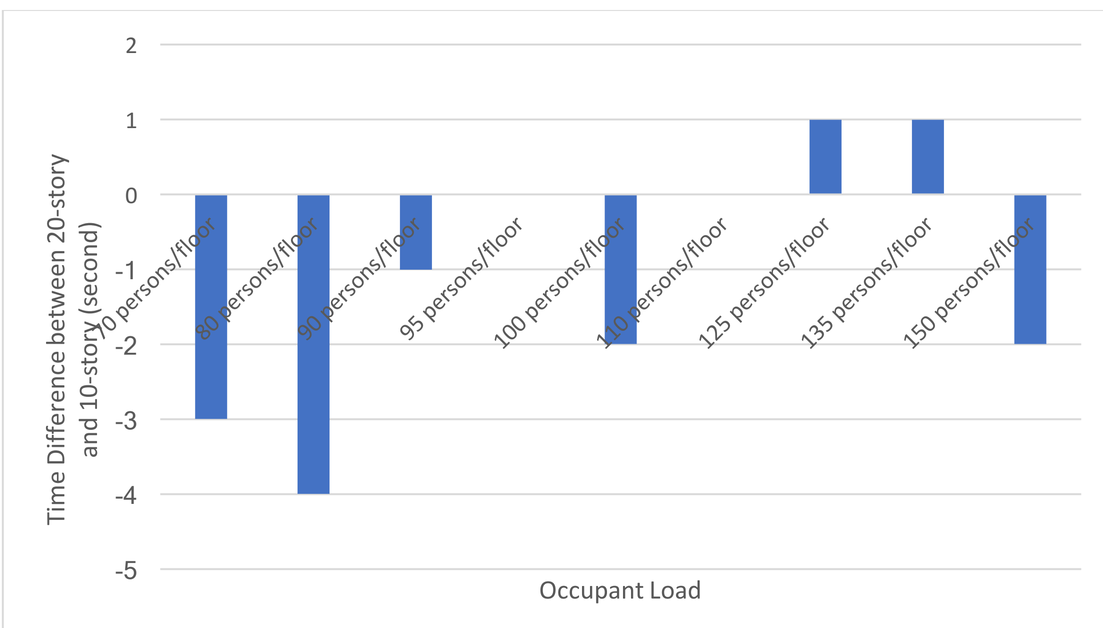



Figure 6- 5: Time Difference Between 20-story and 10-story in the Bottom Floor of the Top Three Floors for Phased Evacuation.

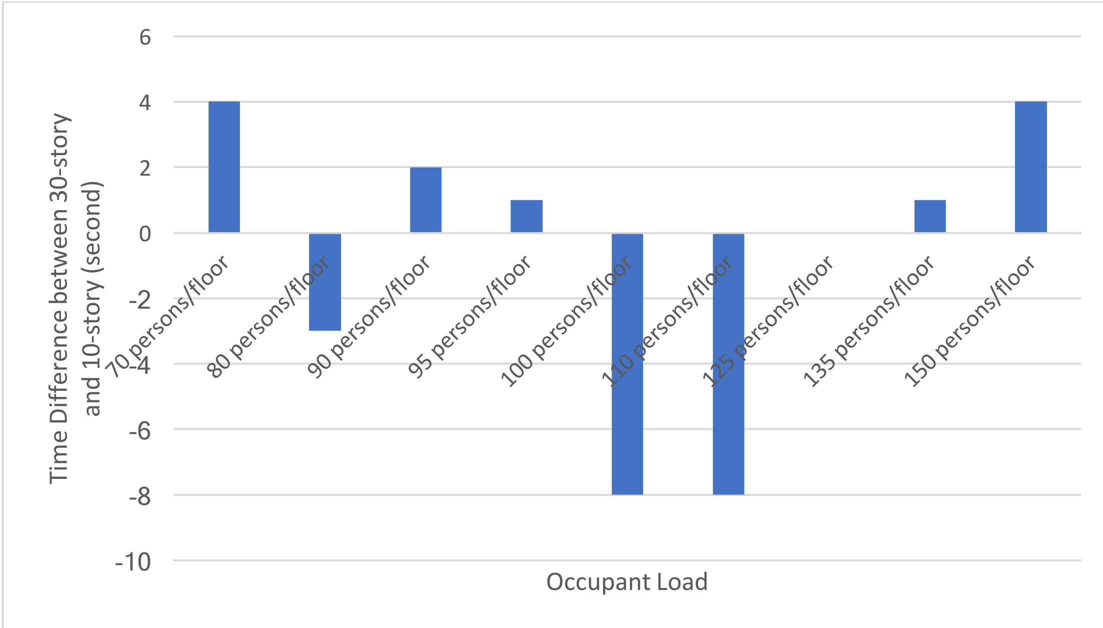



Figure 6- 6: Time Difference Between 30-story and 10-story in the Bottom Floor of the Top Three Floors for Phased Evacuation.

For phased evacuation, the absolute difference between 10-story, 20-story and 30-story buildings for floor clearing time is no more than eight seconds, which is negligible comparing to total egress time in the top three floors (see Figure 6-5 and 6-6).

In summary, since heights of the building rarely affect the floor clearing time in the top three floors, this thesis will focus in the comparison of total versus phased evacuation in 10-story building in the following section (Chapter 6.3). For a particular evacuation strategy, the floor clearing time of the top three floors is independent of building heights for a high-rise office building, which is expected. For phased evacuation, only occupants on the top three floors evacuate, with no interference from occupants on other floors. Thus, it is obvious that the time of evacuation in each floor is independent of the building heights. For total evacuation, the top three floors are the first three floors to clear. In other words, the higher the floor level is, the more priority occupants have to evacuate into stairwells. Thus, the number of floors below the top three floors would not be expected to affect the floor clearing time for the top three floors.

## 6.3 ANALYSIS OF RESULTS OF FLOOR CLEARING TIMES IN DIFFERENT OCCUPANT LOAD IN 10-STORY OFFICE BUILDING

This section compares the floor clearing time for total and phased evacuation strategies with different occupant load factors. Being the floor clearing time in the bottom most floor of the top three floors is the longest egress time, Figure 6-7 depicts the floor clearing time on the eighth floor (the bottom floor of the top three floors) with 14 different occupant loads (70 persons/floor, 80 persons/floor, 90 persons/floor, 95 persons/floor, 100 persons/floor, 105 persons/floor, 110 persons/floor, 115 persons/floor, 120 persons/floor, 125 persons/floor, 130 persons/floor, 135 persons/floor, 140 persons/floor, and 150 persons/floor). Figure 6-7 using occupant load depicts egress time in the bottom floor of the top three floors in total and phased evacuation in 10-story office building with 2,092.5 $m^2$ floor area. In order to provide the graph independent of the floor area, the Figure 6-8 is using occupant load factor transferred from occupant loads in Figure 6-7.

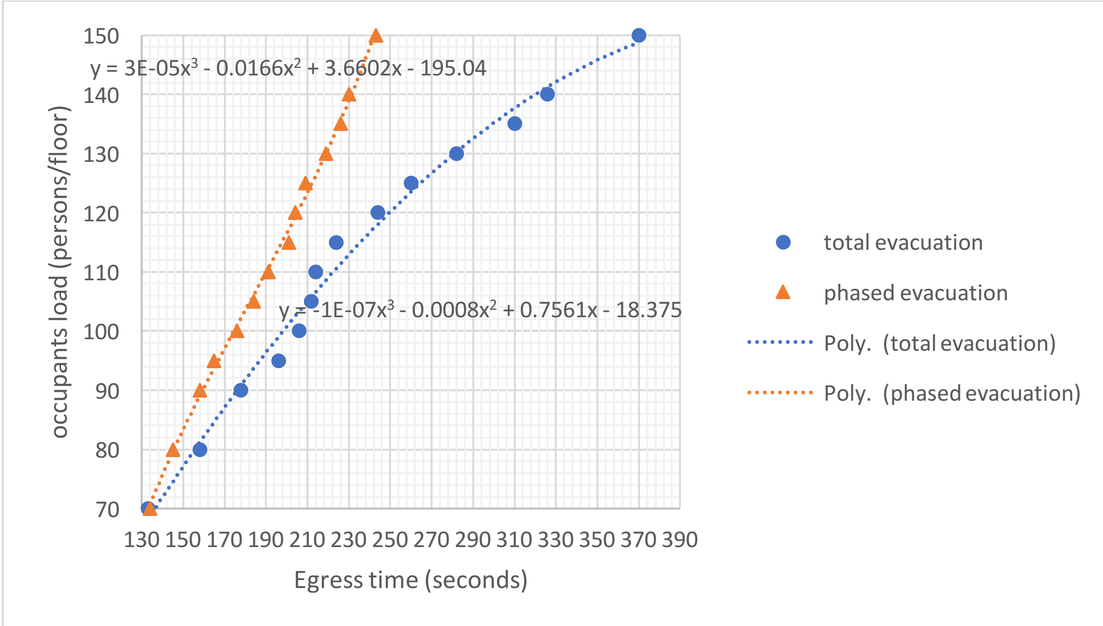



Figure 6- 7: Egress Time in the Bottom Floor of the Top Three Floors in Total and Phased Evacuation in 10-story Office Building with 2,092.5 $m^2$ Floor Area (Occupant Load).

The graph in Figure 6-7 is based on the 10-story hypothetical office building described in Chapter 4 and 5. Based on the same occupant load factor, the difference of the floor clearing time between total and phased evacuation persistently increases and the difference varies from 1 seconds to 127 seconds with variation in the occupant load factors from 30 $m^2$ per person to 14 $m^2$ per person (accordingly, occupant load increase from 70 occupants per floor to 150 occupants per floor in the building).

For both total and phased evacuation fire strategies, the floor clearing time is similar for the three building heights included in the analysis, and does not change with the building heights. Moreover, the results presented in Figure 6-7 indicated that the same floor clearing time is achieved with a greater occupant load using a phased evacuation strategy as compared to that with a total evacuation strategy.

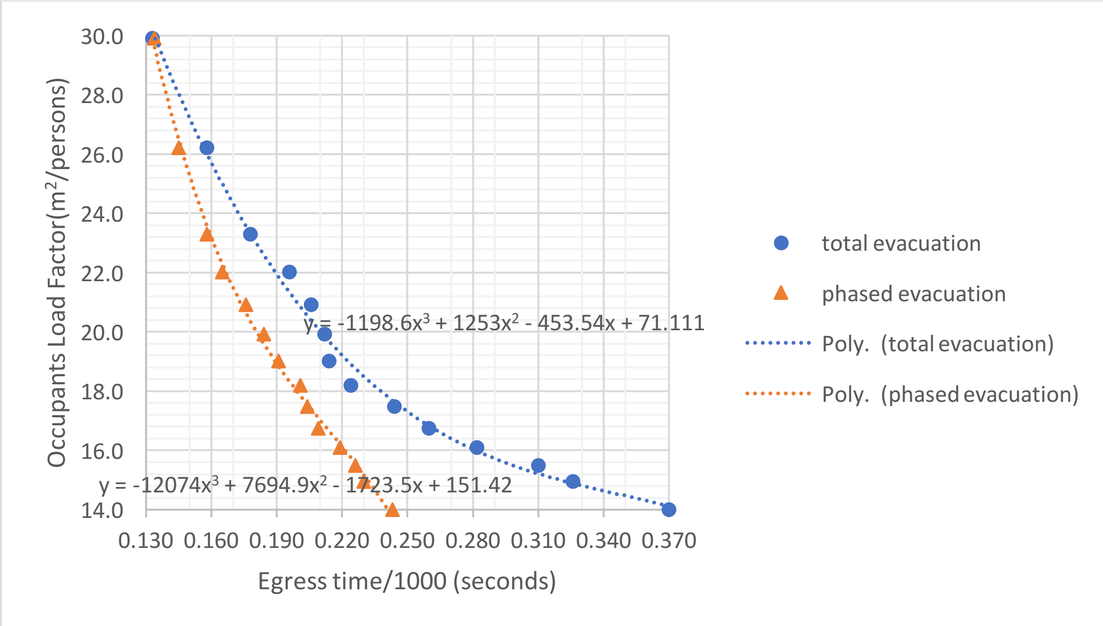



Figure 6- 8: Egress Time in the Bottom Floor of the Top Three Floors in Total and Phased Evacuation in 10-story Office Building with 2,092.5 $m^2$ Floor Area (Occupant Load Factor).

In order to provide a more common graph, Figure 6-8 is represented as using the occupant load factor, converted from Figure 6-7. Moreover, to provide a more accurate equation, the x-axis is presented in terms of ‰ second in Figure 6-8. In other words, the actual egress time is equal to the time in x-axis multiply 1000. Figure 6-8 indicates that the available occupant load factor can be chosen in these two fire strategies under the same floor clearing time of the top three floors in high-rise office buildings. If a phased evacuation strategy is implemented, an increase in the occupant load can be accommodated which results in the same floor clearing time as for a total evacuation strategy. This equation is equal to the equation of total evacuation minus the equation of phased evacuation (see Figure 6-8).

$$y = 10875.4x^3 - 6441.9x^2 + 1269.96x - 80.31 \quad \text{6-1}$$

$$(0.134 \leq x \leq 0.243)$$

In the equation,

y: decrease of occupant load factor ($m^2$/person);

x: ‰ time of floor clearing time (‰ seconds).

This equation is limited to the floor clearing time for phased evacuation strategy less than 243 seconds which is the time for an occupant load of 14 $m^2$/person (the minimum occupant load in NFPA101 (2018) mentioned in Chapter 4.2). Equation 6-1 can be used only for top three floors in comparison of total versus phased evacuation for high-rise office buildings. On the other hand, this equation is independent of building heights for high-rise office buildings.

So far, the nationally recognized codes and standards do not provide a limitation of the time to evacuate to a designated safe place for high-rise office buildings. This equation can allow engineers to have an awareness of the difference of total and phased evacuation strategies in terms of floor clearing time, and to determine the difference in the occupant load factor between total and phased evacuation strategies based on the same floor clearing time. From this equation, if considering 230 seconds floor clearing time, 'x' is equal to 0.23 and 'y' obtained from Equation 6-1 is 3.3 $m^2$/person. It means that the occupant load factor in phased evacuation strategy can be maximum 3.3 $m^2$/person less than the occupant load factor in total evacuation strategy considering 230 seconds floor clearing time.

# CHAPTER 7: CONCLUSION

## 7.1 CONCLUSION

As mentioned before, the current thesis attempts to support design engineers determining the fire evacuation strategy in high-rise office buildings. The values generated by the simulations in MassMotion are provided by this thesis to assist decision-makers to have a clear sense of the difference between total and phased evacuation for high-rise office buildings. This thesis also can assist building owners and standards organizations in determining the allowable occupant load in high-rise office buildings with any height while comparing total and phased evacuation strategies. For high-rise buildings, the evacuation time may be long if queues form either in or to enter in the stairwell. The likelihood of queue formation is related to occupant load. Thus, the relationship of floor clearing time between total and phased evacuation is generated regardless of buildings size but depends on occupant load. Specifically, this research work focuses on the effect that the evacuation strategy has on the allowable occupant load in each floor of a high-rise office building. The research also explores if the building height has an impact on the floor clearing time of the affected floors (the top three floors) during total and phased evacuation. The comparison of the results obtained by Hartmann using EXIT89 (one of the earlier evacuation models developed) with a contemporary model, MassMotion, regarding the total egress time for total and phased evacuation strategies for the top five floors.

In summary, this research has identified that the difference of egress time clearing the entire office building for total versus phased evacuation increases with increased building heights. The difference of total egress time between total and phased evacuation ranges from 165 to 878 seconds with the heights of building from 11 stories to 31 stories, respectively. Moreover, the time of evacuating the affected floors (the top three floors) is not affected by the building heights in both total and phased evacuation fire strategies, as such the results are applicable to a wide range of building heights. Based on this identification, the current thesis provides information for decision-makers to determine a reasonable occupant load when applying total or phased evacuation fire strategies. In particular, the occupant load factor can be decreased if a phased evacuation strategy is used as compared to a total evacuation strategy without impacting the floor clearing time according to the equation: $y = 10875.4x^3 - 6441.9x^2 + 1269.96x - 80.31$. For example, if engineers consider the occupant load factor as 21 $m^2$ per person in a total evacuation fire strategy, a reduced occupant load factor (i.e. increase in the number of occupants) of approximately 17 $m^2$ per person with a phased evacuation fire strategy will result in the same floor clearing time.

## 7.2 LIMITATIONS AND FUTURE WORK

This research work did not account for some elements that may affect egress time, such as the effects of smoke and human behavior, e.g. egress delay and response under stress. Fatigue is one essential element of human behavior and it is reasonable to take fatigue into consideration for high-rise office building, because the travel distance may be very large, thereby causing an additional extension in the egress time (Averill et al., 2005, Galea et al., 2008a; Spearpoint & MacLennan, 2012). In addition, another limitation is that the MassMotion has the body area in circular shape, since Ahrens stated the circular body area may affect the egress time (2018).

Even though this research work attempted to explore any identical difference of total versus phased evacuation in high-rise office building, the limits of the aspects lies in how occupant load and building heights affect the egress time during these two fire strategies. Moreover, this research did not get a chance to explore the difference in the floor clearing time with the two evacuation strategies with data from fire drills.

Based on the current thesis, some additional research is recommended, as listed below:

- Consider human behavior, especially fatigue into the same models to discuss its effects to egress time.
- Explore the effects of smoke during total and phased evacuation using the same model inputs.
- Assess the impact of stairwell width, location of stairwells and number of stairwells on evacuation strategies.
- Assess the impact of body area and shape (elliptical vs. circular).

# Appendix A

The Evacuation Time of All Compared Models.

| Stories & Evacuation Strategy | Total Number of Occupants | Number of Occupants per Floor | Time (seconds) from Hartmann | Time (seconds) from Luying |
|---|---|---|---|---|
| 11-story Total | 1380 | 138 | 635 | 692 |
| 11-story Select | 690 | 138 | 503 | 527 |
| 21-story Total | 2760 | 138 | 1047 | 1346 |
| 21-story Select | 690 | 138 | 947 | 761 |
| 31-story Total | 4140 | 138 | 1607 | 1775 |
| 31-story Select | 690 | 138 | 1430 | 897 |

# Appendix B

Time for the Last Occupant to Pass to the Next Stairwell In 11-story, 21-story, and 31-story Buildings from Hartmann's Research.

| floors | total_11 | phased_11 | total_21 | phased_21 | total_31 | phased_31 |
|---|---|---|---|---|---|---|
| 31 | - | - | - | - | 83.08 | 77.11 |
| 30 | - | - | - | - | 150.36 | 130.43 |
| 29 | - | - | - | - | 220.56 | 170.06 |
| 28 | - | - | - | - | 294.46 | 223.8 |
| 27 | - | - | - | - | 363.1 | 278.45 |
| 26 | - | - | - | - | 434.56 | 329.95 |
| 25 | - | - | - | - | 501.69 | 382.95 |
| 24 | - | - | - | - | 562.28 | 429.34 |
| 23 | - | - | - | - | 600.85 | 472.21 |
| 22 | - | - | - | - | 640.71 | 524.58 |
| 21 | - | - | 83.08 | 77.11 | 682.84 | 573.76 |
| 20 | - | - | 150.36 | 130.43 | 732.4 | 625.47 |
| 19 | - | - | 220.56 | 170.06 | 781.96 | 671.98 |
| 18 | - | - | 294.46 | 223.8 | 831.51 | 716.91 |
| 17 | - | - | 363.1 | 278.45 | 872.95 | 772.58 |
| 16 | - | - | 434.57 | 329.95 | 900.64 | 820.06 |
| 15 | - | - | 501.69 | 382.59 | 950.2 | 870.68 |
| 14 | - | - | 562.27 | 429.34 | 997.34 | 926.71 |
| 13 | - | - | 600.85 | 472.21 | 1037.38 | 980.17 |
| 12 | - | - | 628.62 | 491.64 | 1063.39 | 994.6 |
| 11 | 83.08 | 77.11 | 668.28 | 540.6 | 1116.51 | 1044.43 |
| 10 | 150.36 | 130.43 | 723.58 | 588.11 | 1173.72 | 1096.02 |
| 9 | 220.56 | 170.06 | 758.44 | 634.74 | 1227.88 | 1133.28 |
| 8 | 294.46 | 223.8 | 814.84 | 685.46 | 1282.73 | 1188.6 |
| 7 | 363.1 | 278.45 | 871.35 | 722.26 | 1342.15 | 1219.52 |
| 6 | 434.57 | 329.95 | 895.98 | 777.68 | 1403.04 | 1258.68 |
| 5 | 501.69 | 382.59 | 932.97 | 833.05 | 1453.29 | 1298.84 |
| 4 | 562.28 | 429.95 | 972.35 | 865.23 | 1518.91 | 1344.1 |
| 3 | 600.85 | 472.21 | 1030.39 | 926.03 | 1577.52 | 1401.3 |
| 2 | 628 | 498.54 | 1046.71 | 940.79 | 1607.31 | 1426.07 |
| 1 | 634.87 | 503.02 | 1046.71 | 946.96 | 1607.31 | 1429.53 |

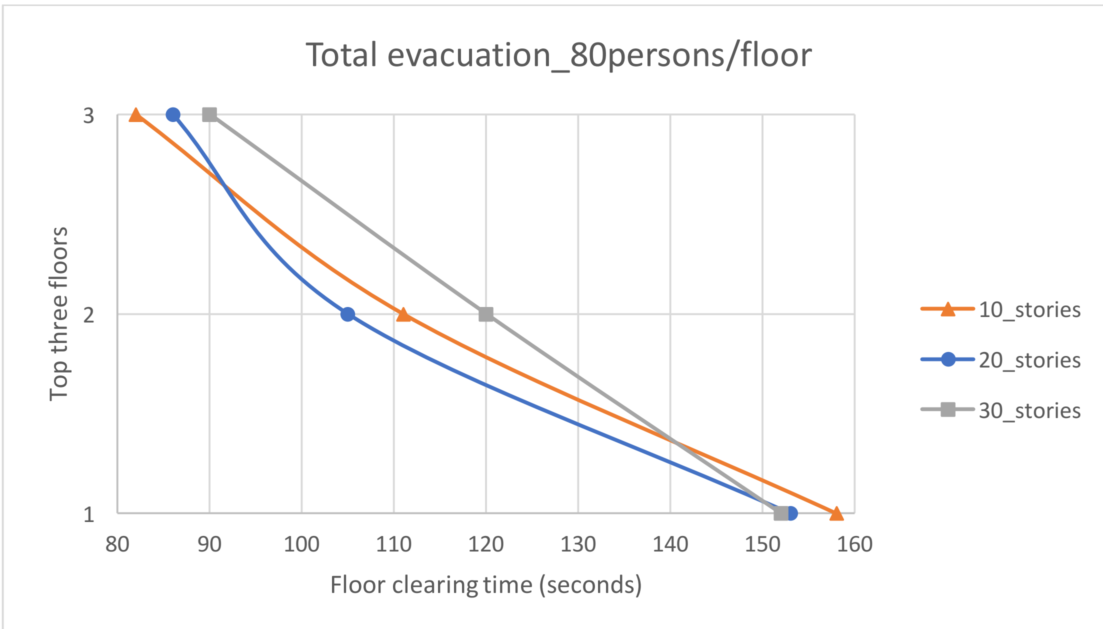
# Appendix C

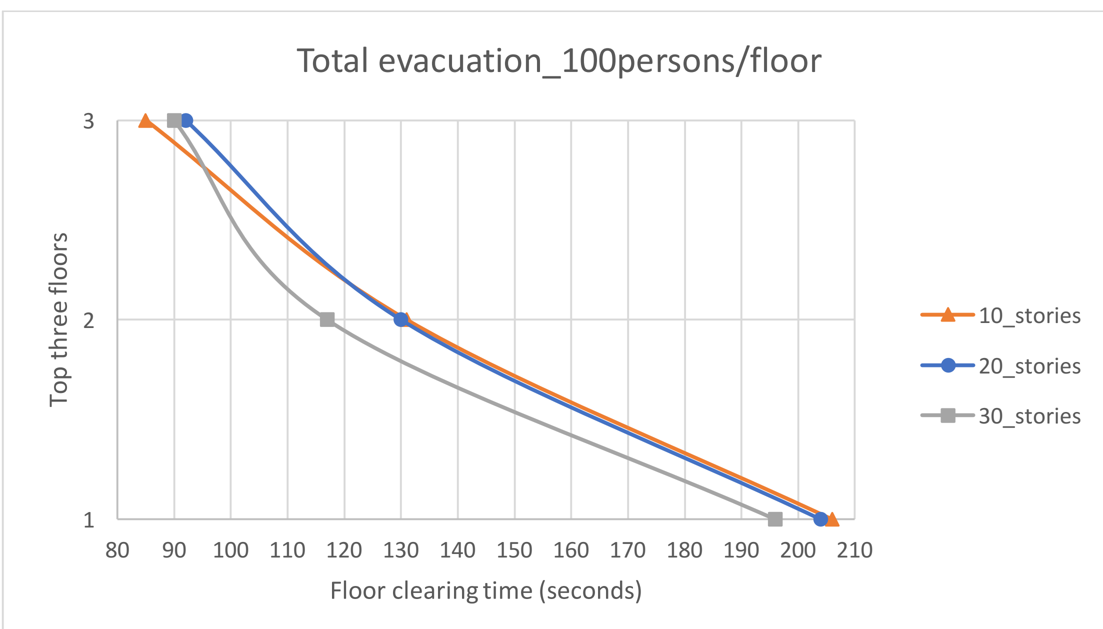
Time for the Last Occupant to Pass to the Next Stairwell In 11-story, 21-story, and 31-story Buildings from Current Research.

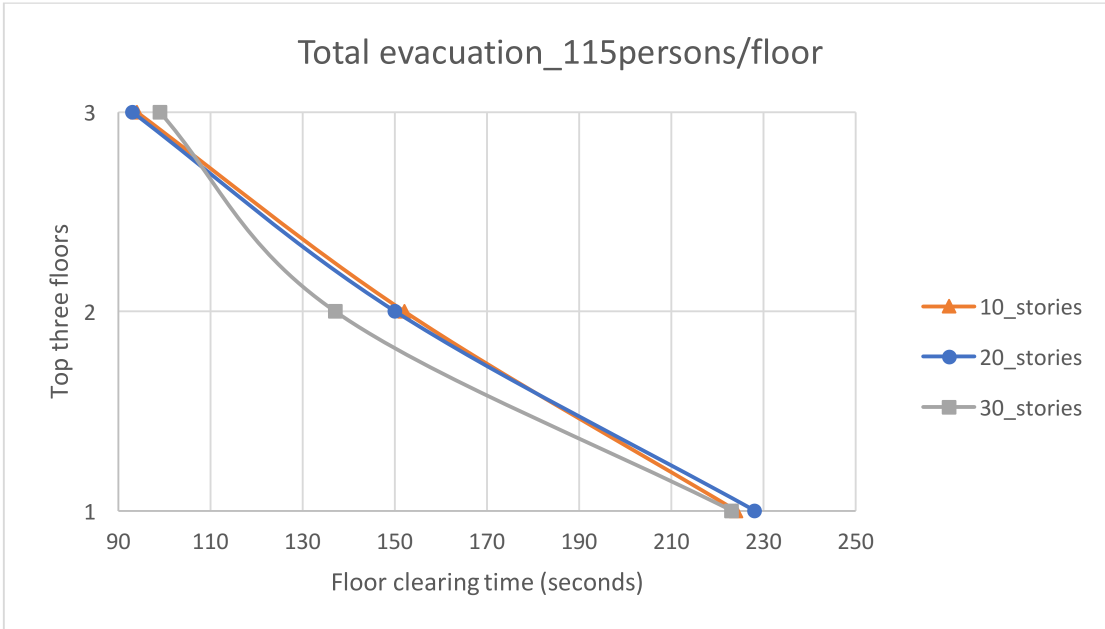
| floors | total_11 | phased_11 | total_21 | phased_21 | total_31 | phased_31 |
|---|---|---|---|---|---|---|
| 31 | - | - | - | - | 108 | 98 |
| 30 | - | - | - | - | 157 | 146 |
| 29 | - | - | - | - | 240 | 218 |
| 28 | - | - | - | - | 336 | 268 |
| 27 | - | - | - | - | 410 | 306 |
| 26 | - | - | - | - | 491 | 339 |
| 25 | - | - | - | - | 574 | 369 |
| 24 | - | - | - | - | 654 | 397 |
| 23 | - | - | - | - | 731 | 421 |
| 22 | - | - | - | - | 809 | 446 |
| 21 | - | - | 107 | 96 | 883 | 470 |
| 20 | - | - | 241 | 190 | 953 | 493 |
| 19 | - | - | 340 | 271 | 1022 | 516 |
| 18 | - | - | 421 | 320 | 1087 | 538 |
| 17 | - | - | 513 | 362 | 1147 | 561 |
| 16 | - | - | 593 | 394 | 1200 | 584 |
| 15 | - | - | 668 | 423 | 1249 | 606 |
| 14 | - | - | 732 | 454 | 1298 | 628 |
| 13 | - | - | 797 | 482 | 1346 | 647 |
| 12 | - | - | 856 | 509 | 1395 | 669 |
| 11 | 95 | 102 | 910 | 534 | 1436 | 689 |
| 10 | 173 | 190 | 972 | 558 | 1476 | 710 |
| 9 | 269 | 267 | 1026 | 582 | 1513 | 731 |
| 8 | 363 | 318 | 1077 | 607 | 1550 | 753 |
| 7 | 432 | 362 | 1125 | 626 | 1587 | 775 |
| 6 | 488 | 392 | 1169 | 652 | 1624 | 796 |
| 5 | 543 | 450 | 1212 | 677 | 1659 | 818 |
| 4 | 589 | 468 | 1250 | 710 | 1691 | 838 |
| 3 | 627 | 482 | 1284 | 732 | 1722 | 859 |
| 2 | 667 | 503 | 1318 | 747 | 1751 | 880 |
| 1 | 692 | 527 | 1346 | 761 | 1775 | 897 |

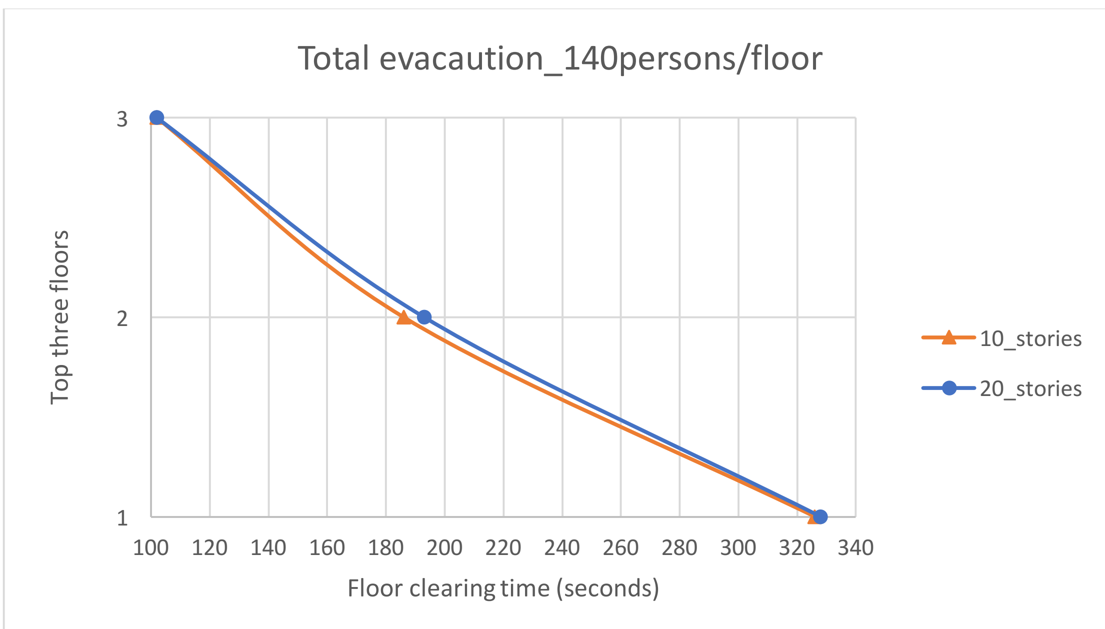
# Appendix D

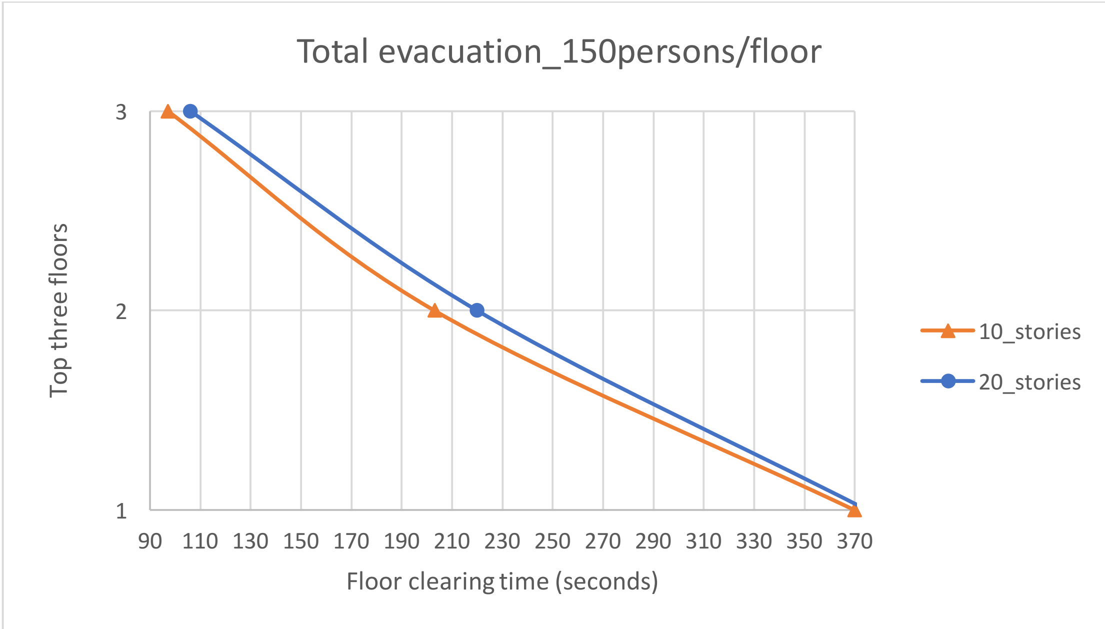
Floor Clearing Time in Top Three Floors for 10-story, 20-story and 30-story Office Buildings with 2,092.5 $m^2$ for 80, 100, 115, 140, and 150 persons/floor Occupant Load in Total Evacuation.




Total evacuation_115persons/floor
Top three floors
Floor clearing time (seconds)
3
2
1
90
110
130
150
170
190
210
230
250
10_stories
20_stories
30_stories

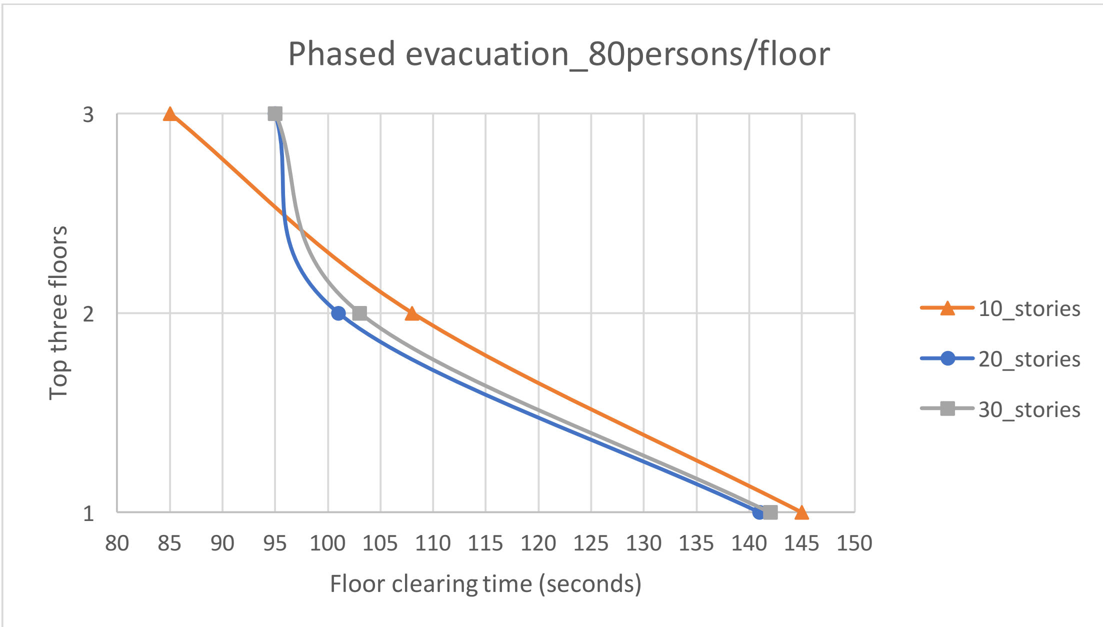

Total evacaution_140persons/floor
Top three floors
Floor clearing time (seconds)
3
2
1
100
120
140
160
180
200
220
240
260
280
300
320
340
10_stories
20_stories

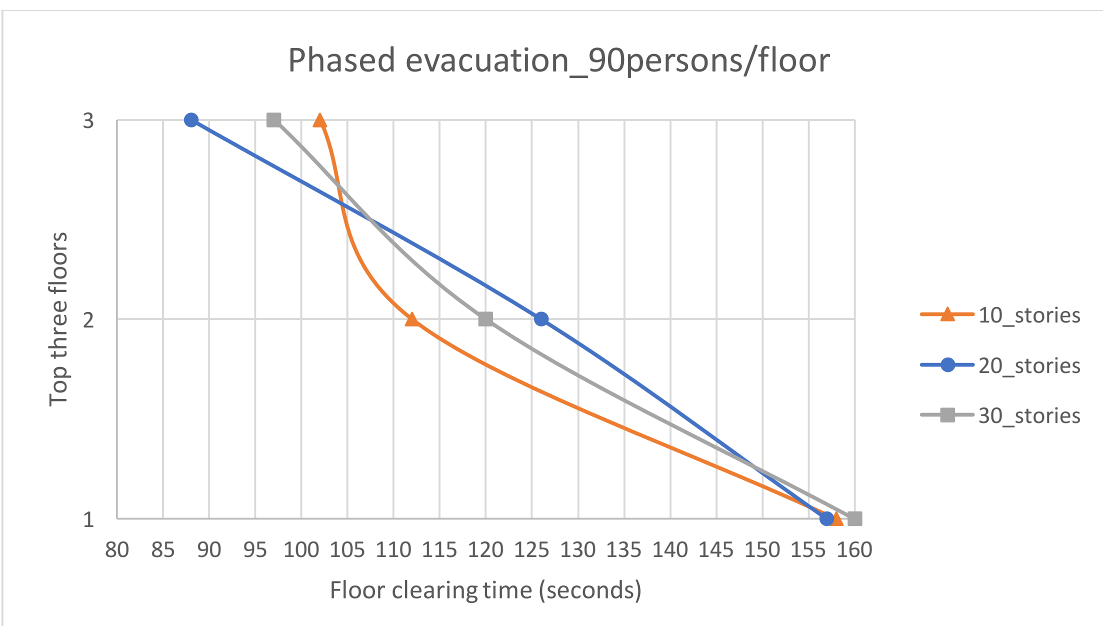


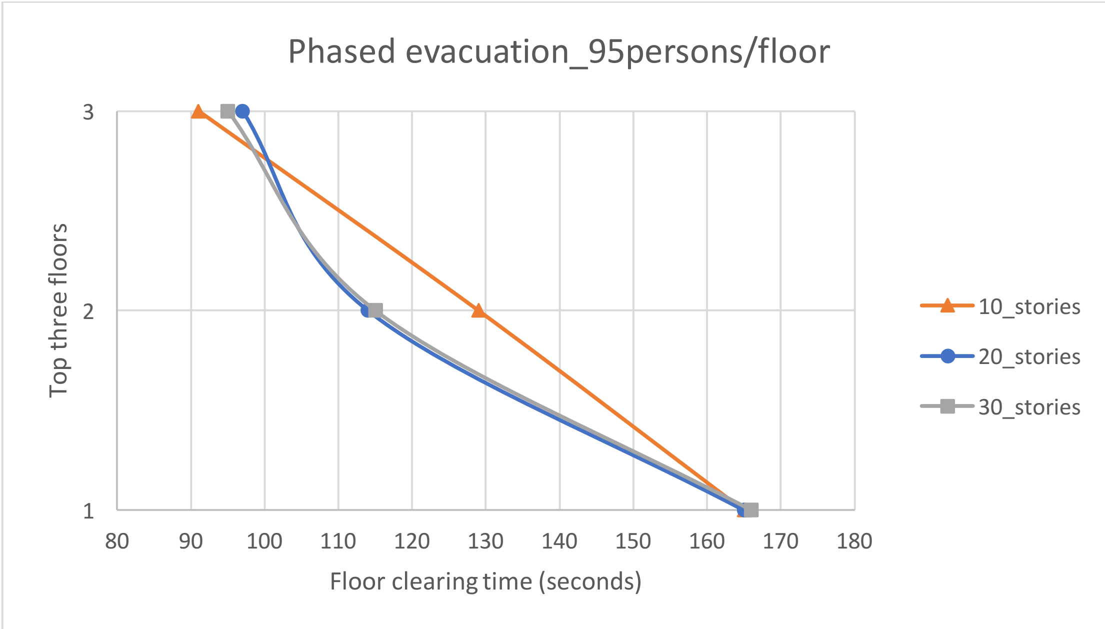
Total evacuation_150persons/floor
Top three floors
3
2
1
90
110
130
150
170
190
210
230
250
270
290
310
330
350
370
Floor clearing time (seconds)
10_stories
20_stories

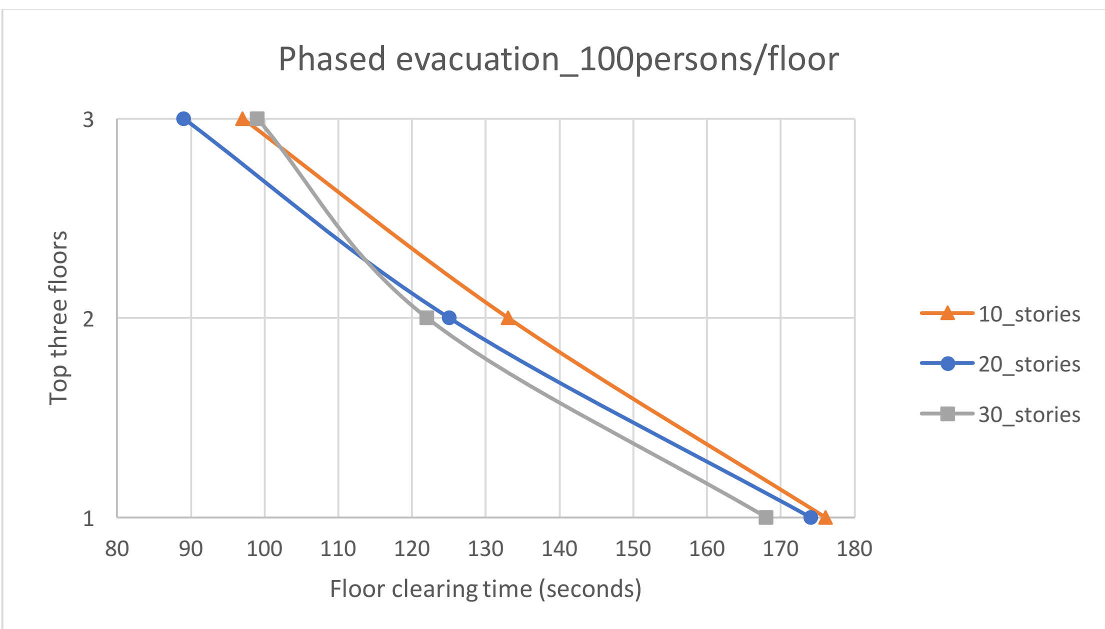
# Appendix E

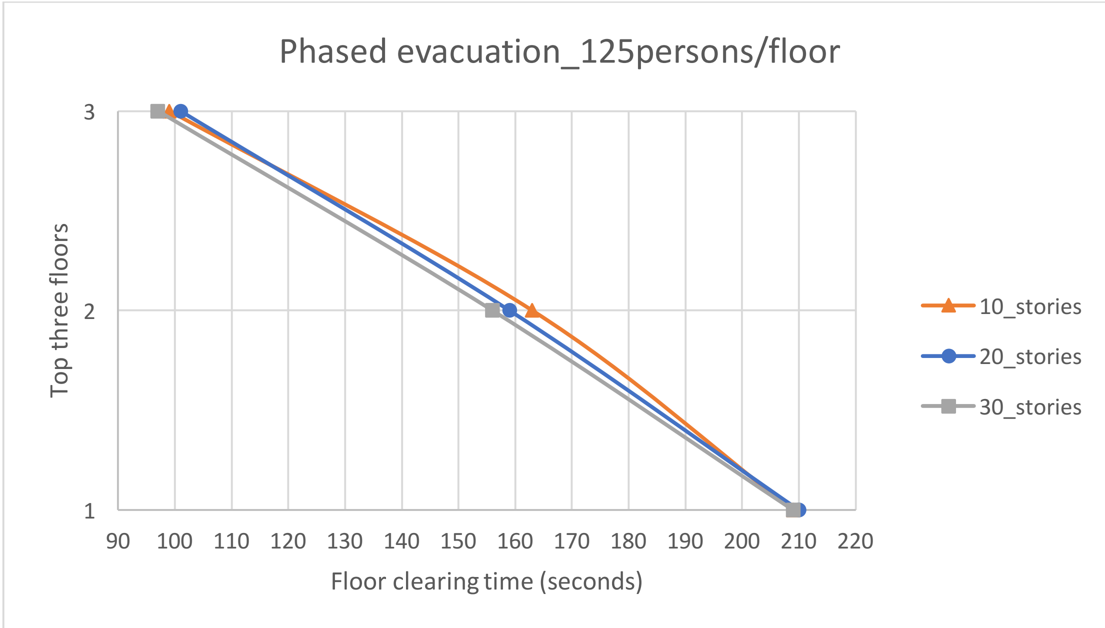
Floor Clearing Time in Top Three Floors for 10-story, 20-story and 30-story Office Buildings with 2,092.5 $m^2$ for 80, 90, 95, 100, 125, and 135 persons/floor Occupant Load in Phased Evacuation.

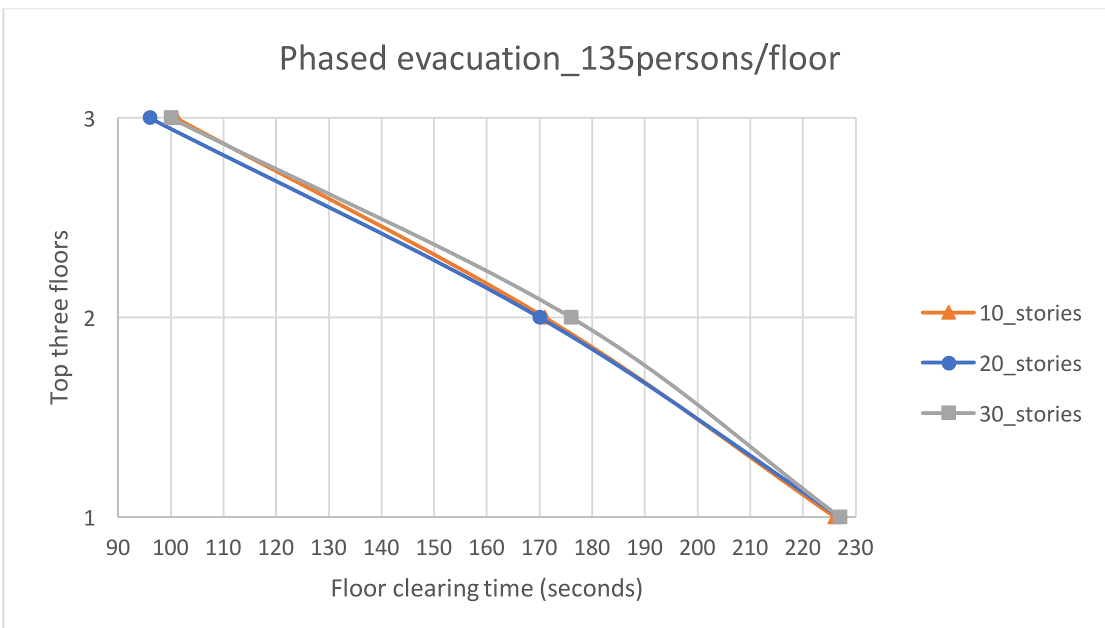



Phased evacuation_95persons/floor
Top three floors
3
2
1
80
90
100
110
120
130
140
150
160
170
180
Floor clearing time (seconds)
10_stories
20_stories
30_stories


Phased evacuation_100persons/floor
Top three floors
3
2
1
80
90
100
110
120
130
140
150
160
170
180
Floor clearing time (seconds)
10_stories
20_stories
30_stories


Phased evacuation_125persons/floor
Top three floors
3
2
1
90
100
110
120
130
140
150
160
170
180
190
200
210
220
Floor clearing time (seconds)
10_stories
20_stories
30_stories


Phased evacuation_135persons/floor
Top three floors
3
2
1
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
Floor clearing time (seconds)
10_stories
20_stories
30_stories

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