THE IMPACT OF ELEVATOR USAGE AND ZONING ON HIGH-RISE BUILDING EVACUATION

Miqdad Iqbal Kilpady

Fire Safety Engineering
Lund University
Sweden

Report 5591, Lund 2019

Master Thesis in Fire Safety Engineering

HOST UNIVERSITY: Lund University

FACULTY: Faculty of Engineering

DEPARTMENT: Department of Fire Safety Engineering

Academic Year 2018-2019

THE IMPACT OF ELEVATOR USAGE AND ZONING ON HIGH-RISE BUILDING EVACUATION

Miqdad Iqbal Kilpady

Promoter:

Enrico Ronchi, Lund University

Master thesis submitted in the Erasmus Mundus Study Programme

International Master of Science in Fire Safety Engineering

The Impact of Elevator Usage and Zoning on High-Rise Building Evacuation

Miqdad Iqbal Kilpady

Report 5591

ISRN: LUTVDG/TVBB—5591--SE

Number of pages: 71

Illustrations: 24

Keywords

Elevator, waiting time, elevator zoning, total evacuation time

Abstract

For decades, the use of elevators has been prohibited during emergencies but with the ever-increasing heights of the buildings, safe and timely vertical evacuation by the conventional means of stairs seems more and more of a challenge. With the recent push for a better understanding of the pros and cons of use of elevators for evacuation by various concerned parties, it is imperative that there is a better understanding of the performance, advantages and risks involved with this evacuation strategy. This thesis aims to shed some light on the impact of the number of available elevators, number of occupants using the elevators and the maximum waiting time for elevators on the overall performance and application of the elevators for evacuation in high-rise buildings.

This thesis was undertaken to analyze the impact of elevator usage variables and zoning on the use of Occupant Evacuation Elevators in high-rise buildings. The study was conducted on a hypothetical high-rise building comprising of 37 floors with a total of 25 elevators considered as the base scenario. Based on the number of available elevators, number of elevator users and the maximum waiting time for the use of the elevators; seven scenarios were short-listed and study of each scenario was carried out in the Pathfinder evacuation model using the hydraulic model (SFPE method by Gwynne & Rosenbaum) to simulate agent movement.

The simulations were performed by making assumptions regarding possible behaviors of the occupants during emergencies to enable quantitative representation of the chosen scenarios. Results refer to the analysis of total evacuation times. The quickest evacuation times were obtained when a higher number of occupants were willing to use to elevators without re-routing to using stairs for evacuation. The study also suggests that the effectiveness of the use of elevators for evacuation significantly decreases when there is an uneven distribution of the elevator zoning.

Fire Safety Engineering

Lund University

P.O. Box 118

SE-221 00 Lund

Sweden

DISCLAIMER

This thesis is submitted in partial fulfilment of the requirements for the degree of *The International Master of Science in Fire Safety Engineering (IMFSE)*. This thesis has never been submitted for any degree or examination to any other University/programme. The author(s) declare(s) that this thesis is original work except where stated. This declaration constitutes an assertion that full and accurate references and citations have been included for all material, directly included and indirectly contributing to the thesis. The author(s) gives (give) permission to make this master thesis available for consultation and to copy parts of this master thesis for personal use. In the case of any other use, the limitations of the copyright have to be respected, in particular with regard to the obligation to state expressly the source when quoting results from this master thesis. The thesis supervisor must be informed when data or results are used.

20190430

Read and approved

Miqdad Iqbal Kilpady

ಸಾರಾಂಶ

ದಶಕಗಳ ಕಾಲ, ಎಲಿವೇಟರ್ಗಳ ಬಳಕೆಯು ತುರ್ತುಸ್ಥಿತಿಗಳಲ್ಲಿ ನಿಷೇಧಿಸಲ್ಪಟ್ಟಿದೆ ಆದರೆ ಕಟ್ಟಡಗಳ ನಿರಂತರವಾಗಿ ಹೆಚ್ಚುತ್ತಿರುವ ಎತ್ತರಗಳೊಂದಿಗೆ, ಸುರಕ್ಷಿತ ಮತ್ತು ಸಕಾಲಿಕ ಲಂಬವಾದ ಸ್ಥಳಾಂತರಿಸುವಿಕೆಯು ಸಾಂಪ್ರದಾಯಿಕ ಮೆಟ್ಟಿಲುಗಳ ಮೂಲಕ ಹೆಚ್ಚು ಸವಾಲಿನಂತೆ ತೋರುತ್ತದೆ. ವಿವಿಧ ಸಂಬಂಧಪಟ್ಟ ಪಕ್ಷಗಳಿಂದ ಸ್ಥಳಾಂತರಿಸುವಿಕೆಗೆ ಎಲಿವೇಟರ್ಗಳ ಬಳಕೆಯ ಉತ್ತಮ ಸಾಧನೆಗಾಗಿ ಇತ್ತೀಚಿನ ತಳ್ಳುವಿಕೆಯೊಂದಿಗೆ, ಈ ಸ್ಥಳಾಂತರಿಸುವಿಕೆಯ ಕಾರ್ಯನೀತಿಯೊಂದಿಗೆ ಒಳಗೊಳ್ಳುವ ಕಾರ್ಯಕ್ಷಮತೆ, ಅನುಕೂಲಗಳು ಮತ್ತು ಅಪಾಯಗಳ ಬಗ್ಗೆ ಉತ್ತಮ ತಿಳುವಳಿಕೆ ಇದೆ ಎಂದು ಕಡ್ಡಾಯವಾಗಿದೆ. ಈ ಪ್ರಬಂಧವು ಲಭ್ಯವಿರುವ ಲಿಫ್ಟ್ಗಳ ಸಂಖ್ಯೆಯ ಪ್ರಭಾವದ ಮೇಲೆ ಬೆಳಕು ಚೆಲ್ಲುವ ಗುರಿಯನ್ನು ಹೊಂದಿದೆ, ಎಲಿವೇಟರ್ಗಳನ್ನು ಬಳಸುವ ನಿವಾಸಿಗಳ ಸಂಖ್ಯೆ ಮತ್ತು ಎತ್ತರದ ಕಟ್ಟಡಗಳಲ್ಲಿ ಸ್ಥಳಾಂತರಿಸುವಿಕೆಗೆ ಒಟ್ಟಾರೆ ಕಾರ್ಯಕ್ಷಮತೆ ಮತ್ತು ಲಿಫ್ಟ್ಗಳ ಅಳವಡಿಕೆಗೆ ಎಲಿವೇಟರ್ಗಳಿಗೆ ಗರಿಷ್ಠ ಕಾಯುವ ಸಮಯ.

ಈ ಪ್ರಮೇಯವನ್ನು ಎಲಿವೇಟರ್ ಬಳಕೆಯ ಅಸ್ಥಿರಗಳ ಪ್ರಭಾವವನ್ನು ವಿಶ್ಲೇಷಿಸಲು ಮತ್ತು ಎತ್ತರದ ಕಟ್ಟಡಗಳಲ್ಲಿ ಒಕ್ಯೂಪೆಂಟ್ ಇವ್ಯಾಕ್ಯುವೇಶನ್ ಎಲಿವೇಟರ್ಗಳ ಬಳಕೆಗೆ ಜೋನ್ ಮಾಡಲಾಗುತ್ತಿತ್ತು. ಬೇಸ್ ಸನ್ನಿವೇಶದಲ್ಲಿ ಪರಿಗಣಿಸಲಾದ 25 ಎಲಿವೇಟರ್ಗಳೊಂದಿಗೆ 37 ಮಹಡಿಗಳನ್ನು ಒಳಗೊಂಡಿರುವ ಕಾಲ್ಪನಿಕ ಎತ್ತರದ ಕಟ್ಟಡದ ಮೇಲೆ ಈ ಅಧ್ಯಯನವನ್ನು ನಡೆಸಲಾಯಿತು. ಲಭ್ಯವಿರುವ ಲಿಫ್ಟ್ಗಳ ಸಂಖ್ಯೆ, ಎಲಿವೇಟರ್ ಬಳಕೆದಾರರ ಸಂಖ್ಯೆ ಮತ್ತು ಲಿಫ್ಟ್ಗಳ ಬಳಕೆಗಾಗಿ ಗರಿಷ್ಠ ಕಾಯುವ ಸಮಯವನ್ನು ಆಧರಿಸಿ; ಏಳು ಸನ್ನಿವೇಶಗಳು ಅಲ್ಪ-ಪಟ್ಟಿಮಾಡಲ್ಪಟ್ಟವು ಮತ್ತು ಏಜೆಂಟ್ ಚಲನೆಯನ್ನು ಅನುಕರಿಸಲು ಹೈಡ್ರಾಲಿಕ್ ಮಾದರಿಯನ್ನು (ಗ್ವಿನೆ ಮತ್ತು ರಾಸೆನ್ಬ್ಯಾಮ್ರಿಂದ SFPE ವಿಧಾನ) ಬಳಸಿಕೊಂಡು ಪಾತ್ ಫೈಂಡರ್ ಸ್ಥಳಾಂತರಿಸುವ ಮಾದರಿಯಲ್ಲಿ ಪ್ರತಿ ಸನ್ನಿವೇಶದ ಅಧ್ಯಯನವನ್ನು ನಡೆಸಲಾಯಿತು.

ಆಯ್ದ ಸನ್ನಿವೇಶಗಳ ಪರಿಮಾಣಾತ್ಮಕ ಪ್ರತಿನಿಧಿತ್ವವನ್ನು ಸಕ್ರಿಯಗೊಳಿಸಲು ತುರ್ತುಸ್ಥಿತಿಗಳಲ್ಲಿ ನಿವಾಸಿಗಳ ಸಂಭವನೀಯ ನಡವಳಿಕೆಗಳ ಬಗ್ಗೆ ಊಹೆಗಳನ್ನು ಮಾಡುವ ಮೂಲಕ ಸಿಮ್ಯುಲೇಶನ್ಗಳನ್ನು ನಡೆಸಲಾಯಿತು. ಫಲಿತಾಂಶಗಳು ಒಟ್ಟು ಸ್ಥಳಾಂತರಿಸುವ ಸಮಯದ ವಿಶ್ಲೇಷಣೆಯನ್ನು ಉಲ್ಲೇಖಿಸುತ್ತವೆ. ಹೆಚ್ಚಿನ ಸಂಖ್ಯೆಯ ನಿವಾಸಿಗಳು ಸ್ಥಳಾಂತರಿಸುವಿಕೆಗೆ ಮೆಟ್ಟಿಲುಗಳನ್ನು ಬಳಸುವುದನ್ನು ಮರು-ರೌಟಿಂಗ್ ಮಾಡದೆಯೇ ಲಿಫ್ಟ್ಗಳಿಗೆ ಬಳಸಲು ಸಿದ್ಧರಿದಾಗ ತ್ವರಿತ ಸ್ಥಳಾಂತರದ ಸಮಯವನ್ನು ಪಡೆಯಲಾಯಿತು. ಎಲಿವೇಟರ್ ಝೋನಿಂಗ್ನ ಅಸಮ ವಿತರಣೆಯಾದಾಗ ಸ್ಥಳಾಂತರಿಸುವಿಕೆಗೆ ಎಲಿವೇಟರ್ಗಳ ಬಳಕೆಯ ಪರಿಣಾಮಕಾರಿತ್ವವು ಗಮನಾರ್ಹವಾಗಿ ಕಡಿಮೆಯಾಗುತ್ತದೆ ಎಂದು ಅಧ್ಯಯನವು ಸೂಚಿಸುತ್ತದೆ.

Acknowledgments

This completion of this thesis would not be possible without the help, encouragement and support of so many people in my life, to whom I owe my gratitude and thanks.

First and foremost, to my promoter Enrico Ronchi. Thank you. He sowed the first seeds of interest in my mind regarding Human Evacuation. Without his constant support, guidance, encouragement and faith in me, this thesis would not be complete.

To my friends in IMFSE, each and every one who supported and encouraged me in their own way, throughout the course of my Masters. This cohort of 2017-2019 has been a family away from home. A special thanks to Ines Cilenti, Silvia Parra Diettes, Bogdan-Grigore Brãnișteanu Albulescu and Balša Jovanović, without their aid, I would not have completed the simulations on time.

To my family. My parents Mohammed Iqbal Kilpady and Safia Begum, who supported me unconditionally in my decision to pursue this Masters. To my brothers and sister, Maher, Miqdam and Manal who supported me and forgave my extended periods of absence during this last semester.

To the all the IMFSE staff, who have made this course an experience of a lifetime, you have my utmost gratitude and thanks.

Table of contents

List of abbreviations 7

List of figures 8

List of tables 9

1. Introduction 10

2. Aim & Objectives 16

    2.1. Aim 16

    2.2. Scope 16

    2.3. Limitations & Delimitations 16

3. Earlier Works on Occupant Evacuation Elevators 19

    3.1. Advantages of the use of OEEs 19

    3.2 Public Perception of Elevator Evacuation 20

    3.3 Elevator Zoning 22

4. Evacuation Strategies 23

    4.1 Egress Methods 24

5. Methodology 26

    5.1 Convergence of evacuation model results 27

6. Definition of the Scenarios 28

    6.1 Summary Description of Scenarios 29

    6.2 Egress Route Distribution 31

7. Calibration of modelling inputs 33

    7.1 Geometric Layout 33

    7.2 Agent Characteristics 38

    7.3 Modelling Pre-Evacuation Delays 38

    7.4 Elevator modelling 39

8. Results 41

9. Discussion 44

    9.1 Future research 46

10. Conclusions 47

11. References 48

12. Appendices 54

List of abbreviations

ADA	Americans with Disability Act
ADL	Activities of Daily Living
CDC	Centers for Disease Control and Prevention
GSA	General Services Administration
IBC	International Building Code
ICC	International Code Council
ISO	International Organization for Standardization
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
OEE	Occupant Evacuation Elevator
SFPE	Society of Fire Protection Engineers
TET	Total Evacuation Time
VR	Virtual Reality
WTC	World Trade Center

List of figures

Figure 1: Warning sign to prevent occupants from using elevators during emergencies 14
Figure 2: Graphical representation of the correlations by Heyes, Jönsson et al. and the average of the two for percentage of elevator usage per floor...32
Figure 3: Ground Floor Layout of the hypothetical high-rise building used in Pathfinder for the study..34
Figure 4: Geometric layout of one of the floors occupying the mid-rise level offices in the building 35
Figure 5: Building geometry of the 37 floors as seen in Pathfinder 36
Figure 6: Geometric layout of one of the floors occupying the high-rise level offices in the building 37
Figure 7: Schematic Representation of the transfer floors location and the various banks of OEEs at the low-rise, mid-rise and high-rise levels...39
Figure 8: Graphical representation of the average TET for each scenario plotted against the number of occupants exiting the building...41
Figure 9: Histogram showing the TET required using Total Evacuation strategy for each Scenario..42
Figure 10: Average Evacuation time of all the runs for Base Scenario...................................57
Figure 11: Error of standard deviation (%) against number of runs (n) for Base scenario 57
Figure 13: Average Evacuation time of all the runs for Scenario 1 59
Figure 14: Error of standard deviation (%) against number of runs (n) for Scenario 1 59
Figure 15: Average Evacuation time of all the runs for Scenario 2 61
Figure 16: Error of standard deviation (%) against number of runs (n) for Scenario 2...........61
Figure 17: Average Evacuation time of all the runs for Case 3..63
Figure 18: Error of standard deviation (%) against number of runs (n) for Scenario 3...........63
Figure 19: Average Evacuation time of all the runs for Scenario 4 65
Figure 20: Error of standard deviation (%) against number of runs (n) for Scenario 4...........65
Figure 21: Average Evacuation time of all the runs for Scenario 5 67
Figure 22: Error of standard deviation (%) against number of runs (n) for Scenario 5...........67
Figure 23: Average Evacuation time of all the runs for Scenario 6 69
Figure 24: Error of standard deviation (%) against number of runs (n) for Scenario 6...........69

List of tables

Table 1: Sets of Simulations used in this study 30
Table 2: Elevator and stair usage correlation to Floor number by Heyes, Jönsson et al., and Kinsey 31
Table 3 : Population Density used on various floors for the modelled building in Pathfinder 33
Table 4: Details of walking speed data used for the agents in the simulation (Reproduced from Boyce & Shields, 1999; Gwynne & Rosenbaum, 2008) 38
Table 5: Pre-evacuation time used for the agent characteristics in Pathfinder 39
Table 6: Elevator Characteristics of the different banks of elevators employed at different levels of the modelled building 40
Table 7: Results of the Average Total Evacuation Time for the different scenarios 41
Table 8: Time for Stair evacuation Vs time for Elevator evacuation 43
Table 9: Tabulated output of the correlations by Heyes, Jönsson et al. and the average of the two for percentage of elevator usage per floor 54
Table 10: Ascending order of TET's among the scenarios modelled in Pathfinder 55
Table 11: Error % of the standard deviation for all the runs in each scenario 55
Table 12: Output for the Convergence run in the Base Scenario 56
Table 13: Base Scenario_Stair vs Elevator Evacuation time 56
Table 14: Output for the Convergence run in Scenario 1 58
Table 15: Scenario 1_ Stair vs Elevator Evacuation time 58
Table 16:Output for the Convergence run in Scenario 2 60
Table 17: Scenario 2_ Stair vs Elevator Evacuation time 60
Table 18: Output for the Convergence run in Scenario 3 62
Table 19: Scenario 2_ Stair vs Elevator Evacuation time 62
Table 20: Output for the Convergence run in Scenario 4 64
Table 21: Scenario 4_ Stair vs Elevator Evacuation time 64
Table 22:Output for the Convergence run in Scenario 66
Table 23: Scenario 5_ Stair vs Elevator Evacuation time 66
Table 24: Output for the Convergence run in Scenario 6 68
Table 25: Scenario 6_ Stair vs Elevator Evacuation time 68

1. Introduction

Buildings are being built higher and higher and this can have repercussions on evacuation design. High-rise buildings are no longer used only as commercial centers but also have multi-facility options to attract potential occupants and visitors. Shanghai tower and the Burj Khalifa are two examples of how buildings can generate income not only as means of commercial spaces but also by means of tourist attractions. Increase in the height of the buildings also come its fair share of design challenges. Arguably the greatest issue when designing ever taller buildings is vertical transportation (Noordermeer, 2010). This means, when it comes to evacuation design, alongside the regular number of occupants expected in the building such as office employees or residents of the building, the large number of tourists who visit a given high-rise building also needs to be considered.

Simple elevators are known to have been in use since ancient Rome as early as 336 B.C (TodayIFoundOut.com, 2014) but these types of elevators required someone to manually hoist the open cars to the required height. Such “elevators” were just open cars instead of the enclosed space elevators that we are used to in this day and age. It was two British architects, Burton and Homer who first designed a type of elevator that required no manual labor 1823. Their design of this early type of elevator was based on the design of the steam engine by James Watt. Calling it an “ascending room”, Burton and Homer set up their machine in London and it was used to take tourists up to a viewing platform for a view of the city skyline (TodayIFoundOut.com, 2014). Soon enough hydraulic systems replaced the steam powered elevators but due to the technical requirements of such hydraulic systems, it was not feasible to use such elevators in tall buildings. Besides, due to the high chances of having the cables snapping leading to causalities, elevators were more a novelty than actual assets in a building. This problem was solved by Elisha Otis in 1852, when he designed a safety precaution that would prevent the elevator box from plummeting to the ground in case the cable snapped. Otis successfully demonstrated this safety feature in his elevators in 1854, where he rode a platform high into the air and ordered the ropes to be cut (“Elisha Otis | American inventor,” 2019).

The most common use of high-rise buildings is for commercial purposes. Such offices tend to lead to a sedentary lifestyle. This kind of lifestyle has harmful effects on physical abilities of the general population. Studies show that the physical abilities of the general population has been gradually decreasing over the past few years (Spearpoint & MacLennan, 2012). In a well-documented research carried out by the Centers for Disease Control and prevention (CDC), it was found that in the years between 2008-2007 and 2015-2016 the rate of obesity in adults rose drastically by 5.9% (33.7% to 39.6%) and the rates of severe obesity went up by 2% during these time periods (5.7% to 7.7%) (Devito, French, & Goldacre, 2018). Health science studies carried out by He & Baker (2004), Hue et al., (2007) and Mhurchu et al., (2005) appears to establish that morbid obesity can directly affect normal day to day functions and activities such as mobility and other Activities of Daily Living (ADL’s). Although results from Peacock et al., (Peacock, Averill, & Kuligowski, 2009) do not support slowing of evacuation speeds due to obesity or fitness, Spearpoint & MacLennan (2012) note in their report that additional study is needed. Due to the lack of physical fitness or stamina, most people will be inclined to use the elevators more, instead of having to walk down dozens of flights of stairs if required.

With this in mind, the most commonly known and implemented rule of “IN CASE OF FIRE, ELEVATORS ARE OUT OF SERVICE. USE EXIT STAIRS” (Section 3002.3, International Building Code, 2018) becomes impractical and an unrealistic option as the buildings reach newer heights.

The use of elevators for the purpose of evacuation is not an entirely new concept. Elevators were commonly used for evacuation until a few decades ago. Prior to a series of fatal fires that took place in New York in the late 1960s and early 1970s elevators were quite frequently used in buildings even when an evacuation was caused by fire. But after the series of fatal fires, the message “Do not use an elevator during a fire” was formalized in 1973 (Pigg, 2013). The elevators of that generation did not have the stringent design safety features that are in place today. Eventually in the late 90’s, National Institute of Standards and Technology (NIST) worked in tandem with several federal agencies and the elevator industry to study the use of elevators as a secondary means of egress to stairs. The main outcome of this study was that the use of elevators as a means of egress was allowed in air traffic control towers by means of a change implemented in the Life Safety Code (NFPA 101) but this rule was not extended to buildings with other uses (Bukowski, 2010).

Fire related incidents in high-rise buildings are not as uncommon as one would assume. Between the years 2009 and 2013, U.S. fire departments responded to an average of 14,500 structure fires per year in high-rise buildings (NFPA, 2016). Such fires have caused and annual average of 40 civilian fatalities, 520 civilian injuries and $154 million in property damage. Larry Pigg, a retired firefighter from the Garland, Texas fire department wrote in a published article (Pigg, 2013) that each year, high rise structure fires cause 60 civilian deaths and 930 injuries. He also noted that three-quarters of high-rise fires are in residential structures, but these account only for about 25% of the monetary losses. The leading cause of all high-rise fires is cooking (38%), but these are largely dependent on the type of the property in question. Among all the high-rise fires, 69% of high-rise structure fires originate on the 4th floor or below; 60% occur in apartment buildings; 43% originate in the kitchen. Because of the nature of the building high rise fires are inherently more difficult for the fire service.

Unfortunately, even with all these statistics and data available it was the terrorist attack on September 11th, 2001 that forced the fire safety industry to re-evaluate and scrutinize the use of elevators in the case of emergencies.

After the events of the terrorist attacks on the World Trade Centers on 9/11, a number of studies were carried out with regard to the evacuation methods that were employed immediately after the incident. A majority of the evacuees used the stairs for evacuation (88%), while a smaller percentage used elevators (8%). Few chose to use the escalators (2%) while the remaining people used a combination of the available egress options (Gershon, Magda, Riley, & Sherman, 2012). The WTC towers stood at a height of more than 400m. This implies an extremely lengthy vertical travel distances for people using only stairs as a means of evacuation. Studies by Averill et al., (2005), Dunlop, Boyce, & McConnell, (1993) and Shields, Boyce, & McConnell, (2009) indicate that the two main problems faced by evacuees during the emergency evacuations in the World Trade Center (WTC) buildings were associated with the travel distance. Occupants mentioned having to deal with fatigue when evacuating using the stairs and the problems faced by occupants pertaining to mobility impairments during vertical evacuation. Fundamentally, elevators perform a basic function of accessibility in a building which makes it an essential component of any building and not just a means of convenience under normal working conditions. Use of elevators helps occupants to access higher floors with ease and swiftness, avoiding the problems related to fatigue and movement related problems on a day-to-day basis. On the other hand, during egress procedures and strategies that require a swift and efficient egress, it is unrealistic to demand that the evacuation take place only using the stairs and that the elevators not be put to use in high-rise buildings (Wong, Hui, Guo, & Luo, 2005).

The International Building Code (IBC) includes Section 3008, which is dedicated to Occupant Evacuation Elevators (OEEs). As per this section, passengers can use the elevators for evacuation purposes during emergencies, as long as specific requirements pertaining to the elevators are met. These requirements include, but are not limited to provisions such as an approved fire safety and evacuation plan for the building, requirements pertaining to the emergency recall operation (the design of the elevator use during emergencies should be such that the elevators can only be used up and until the elevator is recalled on Phase I). The building must have an emergency voice/alarm communication system to alert the occupants of the emergency and to begin the evacuation process. Section 3008 of IBC also includes the use of approved automatic sprinkler system throughout the building so that the OEE can be used during emergency evacuations. For the OEEs to be used as means of egress during a fire, the hoistways supporting the OEEs need to be constructed of materials with the required fire resistance and also have the necessary design to prevent water infiltration from the activated sprinklers in the elevator lobby. The elevator lobby should be designed to be an enclosed space with direct access to an exit stair and will have to have a smoke barrier with a minimum 1-hour fire rating. The elevator lobby should be designed taking into consideration the square foot requirement per reasonable percentages of occupant load with the door to the elevator lobby having a minimum of 45-minute fire rating (Kinateder, Omori, & Kuligowski, 2014).

Disregarding the movement capabilities of the occupants involved, typically stairways have been the primary means of escape from a building during fire emergencies. But such means of escape are not user friendly for people with mobility impairments. Mobility impaired occupants can be defined as occupants with reduced mobility, who (without assistance) cannot use or have significant difficulties using the exit stairs and egress (Kinateder et al., 2014). Even though the Americans with Disabilities (ADA) Act was passed in the year 1990 in the USA to provide equal access to public buildings for all Americans, little work was done in the way of providing a safe means of egress under fire emergencies. In the 1993 bombing at the World Trade Center, it was found that many more occupants experienced difficulties than just those with traditional disabilities. People with temporary disabilities such as broken legs, people with asthma, pregnancy, obesity all reported difficulties in mobility or stamina that limited their own evacuation abilities and that of others behind them in the stairways (Bukowski, 2005). In such cases, the use of elevators provides not only a quicker Total Evacuation Time (TET) but also a safer and more reliable means of escape for the occupants who have reduced mobility and are unable to effectively use the stairs (Kinateder et al., 2014). A recent survey by the International Organization for Standardization (ISO) TC178 Committee identified at least twelve countries that required tall buildings, usually higher than 30m, to employ firefighters' elevators which will provide access and aid to the firefighters in assisting the evacuation of people with disabilities. England is one such country which has such a requirement supported by a British Standard (BS 5588 Part 5) mandating firefighter elevators in buildings exceeding 18m (60 ft.) in height (Bukowski, 2003).

The lack of clear requirements in a lot of Codes and Standards of the past that is hindering the use of elevators in evacuation procedures. Since the formalization of the message to not use elevators in the case of fire, the idea has been so thoroughly ground into our minds that it will take a lot of training over time before people will be comfortable with the idea of elevators being the first choice of an egress route. Another possible reason for people's hesitation to use evacuation elevators in fire emergencies might be the specific risks associated with the elevators as egress alternative (Andrée, Nilsson, & Eriksson, 2015). Separate studies carried out by Francis in 2016 and Andrée et al., in 2015 discuss possible causes which can lead to disregarding the use of elevators in the case of an emergency. These reasons included the possible loss of power to the elevators. But such concern is usually addressed either by the use of a hydraulic system which lowers the elevators to the ground level when a sprinkler or smoke detector is activated, or by provision of a battery back-up to the elevators which will perform the function of transferring elevator car to the lowest floor where the occupants can disembark. There is chance of a piston effect taking place within the elevator shaft, which will basically push the entrained smoke into other sections of the building. Concerns raised regarding the fire spread into the elevators shaft or the entrainment of smoke/penetration of sprinkler water into the hoistway is addressed by the requirements of Section 3008 pf the IBC.

Decades of avoiding usage of elevators during evacuation along with skewed risk perception means that there is a significant challenge to overcome for the use of OEEs to be successfully streamlined into building evacuation strategies. Even with previous research, studies and progress in Codes and Standards, the use of OEEs is not as wide-spread as it should be for their optimal use in case of emergencies.

Especially since the events that took place on 9/11 during the World Trade Centre attacks, it became imperative that the use of elevators for evacuation be made a viable option. NIST and the US General Services Administration have been involved in research related to the use of elevators during emergencies (National Institute of Standards and Technology, 2009).

Figure 1: Warning sign to prevent occupants from using elevators during emergencies

Taken from: ("Interior Décor Sign, 2016")

In the event of a high-rise fire, firefighters face problems related to physical exertion while trying to navigate to the fire floor against the tide of the evacuees using the stairs at the same time. Evacuation via stairs also raises serious problems for the evacuees with regard to the total evacuation time and lengthy travel distances. Congestion in the stairs is to be expected during total evacuation of a tall building as opposed to the lesser number of evacuees expected during a phased evacuation at the same time as the counter flow from firefighters (Kuligowski, 2003). Though the option of increasing the stairwell width to counter the problems of congestion and counter-flow by firefighters can be addressed to some degree, this solution comes at a significant cost for new buildings, and it is an option which is all but impossible for existing buildings. The fact that elevator technology has been advancing in a range of areas makes a good argument for pushing regulatory changes with regard to elevator evacuation in high-rise buildings. Some of the advancements include carbon fiber cables which allow energy and space savings, better algorithms for elevator design which make the use of elevators more efficient, double decker elevators, potential for horizontal and diagonal travel by means of cableless elevators (Francis, 2016). Similarly, in studies carried out by Kuligowski (2003), she noted various advantages associated with the use of elevators. Tying in to the Theory of affiliation as explained by Sime (Sime, 1985), occupants who use elevators on a day to day basis will be more comfortable using the elevators for evacuation. When compared to the evacuation process involving the use of stairs, the evacuation by elevators takes far less physical effort and is a much less unpleasant experience due to the lack of congestions and long queuing. Moreover, once familiarized with the process of using elevators for exiting the building, the elderly and disabled may rely on elevators as the only option for evacuation.

In cases of total evacuation scenarios, computer aided modelling studies have indicated that the total evacuation time can be reduced by almost half with the aid of elevators when compared to the use of only stairs (Kinsey, Galea, & Lawrence, 2010). Similarly, research carried out by Ronchi and Nilsson (Ronchi & Nilsson, 2014) using Pathfinder model (Thunderhead Engineering, 2016) showed an almost four fold decrease in time required for evacuation strategies involving only elevators against the use of only stairs. It must be noted that though this is currently an ideal case since total evacuation of the entire population of a building only via elevators is not a practice that is followed, the advantages of the use of elevators combined with the use of stairs cannot be disputed. The use of Occupant Evacuation Elevators has significant advantages such as quicker evacuation of high-rise buildings, easier evacuation options for people with disabilities, and reduced need for an increased stair capacity. Though such researches are clear indications of the advantages of the use of elevators strictly from a TET point of view, obtaining objective and valid data pertaining to human behavior during such emergencies is very difficult (Kinateder et al., 2014). Collaborative efforts by the General Services Administration (GSA) and the National Institute of Standards and Technology (NIST), resulted in the 2009 editions of both U.S. model building codes (i.e., International Code Council (ICC), International Building Code, and National Fire Protection Association (NFPA) 5000, Building Construction and Safety Code) containing requirements for the installation of fire service access elevator(s) in all new buildings exceeding 36.6 m (120 ft.) in height. Such codes gives engineers and architects involved in the design of a high-rise building, the option of utilizing occupant evacuation elevators during fire emergencies (Kinateder et al., 2014).

2. Aim & Objectives

This section will explain the aims, scope and limitations & delimitations of this thesis.

2.1. Aim

This thesis aims to shed some light on the impact of the number of available elevators, number of occupants using the elevators and the maximum waiting time for elevators on the overall performance and application of the elevators for evacuation in high-rise buildings. It is also the aim of this thesis to study the impact of an unevenly zoned building on the total evacuation time.

Although this thesis focuses on the use of elevators for safe evacuation of the occupants in an emergency, the aim is not to overshadow the necessity of alternate means of escape such as stairs. As has been pointed out in the Australian Elevator Association Handbook, "The objective of safely using lifts for evacuation is not intended to diminish the importance of other evacuation measures such as emergency stairs and is not intended to reduce the number of exits, particularly the number of emergency stairways" (Australian Building Code Board, 2015).

2.2. Scope

This study focused on the use of elevators in case of fire emergencies in high-rise buildings. More specifically, the relation between various parameters in case of evacuation, i.e., number of available elevators, number of people with movement disabilities, maximum waiting time before using alternative means and the impact of elevator zoning, has been explored and analyzed with evacuation modelling using Pathfinder. Simulations were run for various scenarios and the fastest scenario was found by comparing the evacuation times. The base scenario layout deals with the use of two sets of stairs and a total of 25 OEEs with transfer floors at low-rise (Floor 5) and mid-rise (Floor 19) sections of the building.

The building used in this report is a fictional building but the design of the building was based on a possible layout of 100 Bishopsgate, as presented in the website 100 Bishopsgate Floor Plans ("100 Bishopsgate Floor Plans," 2019). This building is a development of two mixed-use buildings under construction in London, United Kingdom. The completed height of the building is expected to be 181m (155m of occupied height) with 37 floors occupying a total of 73,000 sq.m. One of the possible designs includes ten high-rise elevators, ten mid-rise elevators and five low-rise elevators.

2.3. Limitations & Delimitations

It is acknowledged that the scenarios selected for this study are not representative of all the possible variables impacting the TET. The focus of this thesis has been to conduct an exploratory study on the impact of a certain set of variables on the total evacuation of a high-rise building by means of different egress components using the Pathfinder model and elevator evacuation strategies in high-rise buildings. Evacuation of individuals with physical impairments was considered in the analysis but no fire simulations was carried out for the same. In addition, no information is derived about the times needed to evacuate each individual floor. The scope of the project and time constraints limit the analysis of the scenarios involving total occupant evacuation only. The analysis of the results has been based on evacuation times only and data regarding travel distances covered by the evacuees have not been recorded. Future studies that derive information of such type may provide additional insight useful for a more in-depth analysis of evacuation model results.

The floor plan has been developed on a layout which is similar to the layout of 100, Bishopsgate but care has been taken to emulate a generic high-rise building with a varying population density.

Use of the model: Pathfinder model include the fact that the impact of smoke on the agent has no effect on the walking speed (Thunderhead Engineering, 2016). There is no advanced sub-model for modelling the exit choice considering the evolution of the fire conditions, which means that the agent will continue using the exit choice as per the assigned behavior algorithm irrespective of the location of the fire within the building and its effects on the evacuation path. Pathfinder also does not give the control to the user over the deceleration rate of the elevators. Technical aspects of the elevator such as the deceleration jerk and motor delays are unaccounted for in the model (Ronchi & Nilsson, 2012).

Evacuation simulations have been carried out without the counter-flow actions expected due to firefighter's intervention on the stairs. Any action by the firefighters is assumed to be carried out utilizing the "Goods Elevators" which run the entire height of the building. This thesis focusses only on Total Evacuation and other egress strategies such as phased evacuation, defend in place and delayed evacuation are not considered. Other than this, one must remember that a lack of data on human behavior (especially with regard to elevator waiting time in this study) is associated with possible uncertainty associated with evacuation simulations. There is a certain level of risk perception ingrained in the minds of occupants with regard to the use of elevators in times of emergency evacuation and this is dependent on a variety of factors such as age, familiarity with the building, demographic, etc. (Jönsson & Andersson, 2014). Furthermore, out of the many evacuation models available in the market such as Exodus (Galea, Gwynne, Filippidis, & Cooney, 2006), FDS+Evac (Korhonen, 2018), Simulex (IES., 2000), STEPS (Waterson & Pellissier, 2010), etc., this study is carried out using the Pathfinder model. The results will need to be validated by replicating the study using other models. This study follows a specific configuration of a building, though an attempt has been made to have a generic layout so that, after careful consideration, the results may have a broader range of applicability.

Though the number of mobility impaired occupants was increased from 5% to 10% for Scenario 4, each of these occupants have been modelled to represent a wheelchair user. This gave an overall conservative estimate for the TET, as such occupants take up the floor area equivalent to that of 6 persons (Thunderhead Engineering, 2016).

This study also excluded the use of sky-bridges as a means of egress, hence further research is required in order to use the results of this study in a building employing sky-bridges. The design of this hypothetical building has employed the use of an unevenly distributed elevator zoning methodology which has a major impact on the results. This will be further discussed in Section 8. Furthermore, due to time constraints, a comparative study between a non-uniform elevator zoning and a uniformly distributed elevator zoning has been excluded from this study.

Human behavior is complex and the lack of sufficient data regarding human behavior during actual evacuations gives rise to uncertainties. These uncertainties directly relate to the input fed into modelling tools like Pathfinder (used in this study). These inputs include, but are not limited to, pre-evacuations times, walking speeds, choice of exit route etc.

The convergence criteria for this study have been set based on the method proposed by (Ronchi, Reneke, & Peacock, 2014), which presents a set of limitations by means of which the total number of required runs for each scenario has been set. Some methods of setting the convergence criteria employ the use of statistical estimation of the average value in a data set obtained by the repetition of the same experiment. But the proposed method uses the convergence concept in the average of a given data set and the central limit theorem. This method also assumes that the even with different behaviors occurring during different runs of one scenario, such as different occupants are reaching the exit at the same time in different runs or arriving at a different exit, the evacuation curve may be similar between the various runs. This method can be used mainly to better understand the uncertainties related to human behavior in output of a simulation. Currently, the proposed method is applicable to only simulation outputs, but once experimental data is obtained, this same method could be employed for analysis of behavioral uncertainty in experimental data as well (Ronchi et al., 2014)

3. Earlier Works on Occupant Evacuation Elevators

This section will deal with the past works related to the advantages of elevators and the risk perception with the use of elevators as carried out by various researchers.

3.1. Advantages of the use of OEEs

There have been a number of studies carried out in the past related to the benefits of using elevators as an alternative means of egress to stairs. Bazjanac developed a tool for analyzing total evacuation strategies in 1977 (Bazjanac, 1977). Later, in the year 1992, after conducting research into the use of elevators for evacuation, Klote and Alvord came to the conclusion that the use of elevators in tandem with the stairs in an evacuation procedure had a considerable effect on the total evacuation time leading to a safer design of a given high-rise building. More recently, studies related to the effectiveness of various evacuation strategies in high-rise buildings using stairs and elevators (Wong et al., 2005) have been carried out. Researchers have also carried out studies involving the impact of human factors in such studies (Kinsey, 2011).

With an aim to study the optimal evacuation strategies for total evacuation, Ronchi and Nilsson (Ronchi et al., 2014) showed that among the various evacuation strategy options available, two evacuation strategies proved to be more efficient than others, namely evacuation using only elevators and evacuation by the combined use of vertical (stairs and elevators) and horizontal (transfer floors and sky-bridges) components. It must be noted that the effectiveness of the strategies employing a combined use of elevators and stairs is dependent on the information provided to the evacuees.

Evacuation strategies involving the use of elevators coupled with stair usage must account for problems related to the design of the elevators, as well as the behavioral aspect of the occupants such as the comfort level and willingness of the evacuees to use the elevators depending on their location in the building at the time of the start of the evacuation. (Heyes, 2009; Kinsey, 2011; Nilsson & Jönsson, 2011). Not only do elevators provide an additional egress means for the entire population of a building, but it also aids people with movement disabilities evacuate the building on their own without having to wait for rescue from the intervening firefighters or help from other occupants. This impacts the total evacuation time by way of not impeding movement speeds of the entire occupant population as a whole. (Ronchi & Nilsson, 2012). Unfortunately, information related to the effects of human behavior on the use of elevators during emergency evacuations are very limited (Nilsson & Jönsson, 2011). The current best practice involves the use of the elevators along the length of the hoistway to evacuate the building (Weistmantle, Smith, & Sheriff, 2007). Another factor which plays an important role in the effectiveness of the use of OEEs is the number floors a bank of elevators will serve. This practice is known as zoning, where one group of elevators usually serves not more than 15 floors (Noordermeer, 2010).

Furthering the works mentioned above, this thesis is carried out in order to better understand the impact of a given set of variables, namely the number of elevators used, number of occupants using the elevators, the impact of maximum elevator waiting time by occupants and the impact of uneven elevator zoning on the total evacuation time.

3.2 Public Perception of Elevator Evacuation

While the advantages of the use of elevators during evacuation may be many, one of the key problems we face with its actual implementation in real-life is the fact that, for most of their lives people have been strictly instructed not to use elevators in emergency situations. Coupled with the fact that we have very little information in the way human behavior varies during actual high-rise building evacuation, the question arises as to how effective will the use of elevators actually be in a real emergency? If the elevators are considered as unsafe by the occupants who are expected to use it in emergencies, will the elevators be even regarded as an option by most people during the emergency evacuation? To answer such questions, it is necessary to examine the factors that an affect individuals decisions when choosing how to evacuate in a high-rise building (Jönsson & Andersson, 2014).

Studies by Kuligowski (2009) indicate that the decision to begin to evacuate or not is influenced by the perception of the risk involved. Keeping this in mind, it can also be argued that this perception of risk will greatly affect the egress method used for exiting the building, i.e., to use an elevator or to evacuate using the stairs (Andersson & Jönsson, 2011). Survey studies carried out also indicate that the idea of getting stuck in a que while waiting for an elevator during an evacuation procedure was perceived to be the biggest risk among the participants of the survey. Especially in buildings being used as an office, the respondent expects to be surrounded by a large number of people, hence the perceived risk of being stuck in a long que, is a reasonable one (Jönsson & Andersson, 2014). These results show a possible lack of trust in the use of elevators unless the occupants are made more aware of the current safety features in place for design and use of the elevators during emergencies. Use of elevators during mock drills, sharing of information with regard to waiting time of the elevators may better aid in the evacuation process. Human factors research clearly shows that people will generally make the right decisions when provided with the (clear and unambiguous) information upon which to base those decisions (Proulx & Koroluk, 1997). Events such as the 1993 and 2001 World Trade Center evacuations as well as evacuations and drills carried out in other tall buildings show the range of things that can go wrong when evacuating large number of people. These all demonstrate the need to actively manage evacuations, including monitoring the process to identify problems, and communications systems to give directions that resolve these problems (Bukowski, 2007).

Risk perception associated with elevator use depends on a number of factors such as floor number, use of the building and the demographic of the occupants (older occupants were more hesitant to use the elevators than the younger ones). The risk perceived with the use of elevators as a means of escape was found to be generally greater than for using stairs, though the stairs were perceived to be less safe if the respondents were located on higher floors in the building (Jönsson & Andersson, 2014). This is in line with studies carried out by other researchers which found that with the increase in the floor level, there is an increase in the percentage of people willing to use the elevators during evacuation (Heyes, 2009; Jönsson, Andersson, & Nilsson, 2012; Kinsey, 2011).

Waiting time is the time an occupant is willing to wait in the elevator lobby before the elevator begins servicing that floor. The concept of the waiting time is key in modelling evacuation scenarios as this will directly impact the TET. Waiting time is dependent on many factors such as signage and the messaging strategies adopted in the building (Kuligowski & Hoskins, 2012). Without the proper information through messaging strategies, public announcement systems, etc., the occupants will choose to use stairs instead of the elevators are waiting for a maximum waiting period (Ronchi et al., 2014). Due to the scale and scarcity of the event of an actual total evacuation in a high-rise building, there is not a lot of information available regarding waiting time for elevators. So, for the purpose of estimating a model input, all available data sets were studied and it was concluded that almost 100% of the evacuees are not willing to wait for the elevator for a time period more than 10-minutes (Ronchi et al., 2014). Similarly, another studied carried out by Andrée et al., in (2015) showed that people will wait for a minimum of 5 minutes or a maximum of 20 minutes before re-routing towards the stairs. In the Virtual Reality (VR) experimental study carried out by Andrée et al. (2015), it was found that occupants chose to re-route to the stairs instead of waiting for elevators, despite the use of voice messages informing them that they were in a safe area. This is because the participants in the experiment assumed that the elevator was not working, considering it passed by their floor a few times but did not stop to service their floor. This is due to the philosophy of evacuating a building starting from the top-most floor towards the lower floors. For such cases, an influence of the information about predicted waiting time for evacuation elevator's to arrive on people's behavior must be studied further (Andrée et al., 2015).

Studies indicate that once the key design aspects of the OEEs were explained to people with mobility impairments, OEEs were appreciated for the intent of providing a safe way out of the building. Moreover, people with mobility impairments will no longer have to rely on assisted evacuation and can evacuate the premises on their own which has psychological benefits on such a population (Butler, Furman, Kuligowski, & Peacock, 2016). The concept of a two-way communication with emergency personnel was readily accepted by the participants. Participants appreciated both that this system prioritized the people on the floors with the greatest danger and that the travel time would be much faster without stopping on intermediate floors (especially if the elevator is already full)

3.3 Elevator Zoning

Any elevator serving each and every floor of a high-rise building would amount to an excessively long travel time for the elevator users. Besides, if an elevator served the entire length of the building, it would also require a larger floor space to accommodate all the passengers who would utilize the elevator's service. In order to alleviate this problem, buildings are divided into various zones and a bank of elevators are assigned to each zone (Newell, 1998). A zone is defined as a group of mostly contiguous floors that are served by a number of elevators operating in one group. The size and composition of a zone is fixed (e.g., location of the machine room) and cannot be altered. It is usually motivated by the need to reduce the average travelling time and the need to restrict the number of elevator cars in a group. It results in reduced floor area usage on the floors above the lower zone(s). Zoning can be also be used as a means to control the flow of traffic in a building having different occupancies (Al-Sharif, Al-Sukkar, Hakouz, & Al-Shamayleh, 2016). The zones can either be static, where the elevator cars are permanently assigned to one zone or dynamic, where the cars can switch zones (Strang & Bauer, 2007). Another key advantage of employing vertical zoning in elevator shafts is the reduction in the harmful consequences of stack effect (Yu, Song, & Cho, 2017) where smoke travels up the elevator shafts with the elevator car acting as a piston, thus causing rapid smoke movement from the fire floor to other sections of the building which were unaffected by the fire.

4. Evacuation Strategies

There are many egress strategies that are used during emergency evacuations but most of the strategies employed can be broadly summarized into four main solutions: total evacuation, phased evacuation, defend-in-place, delayed evacuation. This study deals with total evacuation but the other methods of evacuation are also briefly discussed below.

Phased Evacuation: This strategy focuses on the evacuation of the population occupying the floor where the fire is detected and floors which are in close vicinity to the fire floor. The occupants present on the floors other than the prioritized floors will be evacuated only if it becomes necessary to do so. This type of strategy is mostly used when the design of the building does not make a total evacuation of the building a feasible option. Employing such a strategy not only reduces the load on stairs and elevators but also lessens the lengthy queuing time on the stairs (Ronchi & Nilsson, 2012). For the application of this strategy, the design must incorporate a robust fire safety design to prevent the fire spread from one compartment to another. These safety features should include systems such as automatic sprinkler systems, compartmentation, emergency alarm and public announcement systems, etc. The application of a phased evacuation has direct impact on the design of egress components such as the width of the stairwell. Hence, the fire safety management system in place must be highly reliable with frequent drills to ensure that the evacuation process is followed without fail. The Petronas Towers in Malaysia employs the Phased evacuation strategy as part of its "Stage 1 Evacuation" methodology (Ariff, 2003). In the Petronas Towers, when the fire is detected, occupants of that floor are evacuated to a floor, which is three levels below the affected area and there they will wait for further instructions. Occupants two floors above and below will be alerted to the fire but will not be evacuated unless it becomes necessary.

Defend-in-place: This strategy is most suited for residential buildings and hotels. It requires the occupants to shut themselves in a room by shutting doors, windows and trying to make the room air-tight to prevent the encroachment of smoke into the occupied space while awaiting support and rescue from the firefighters. This evacuation strategy relies on compartmentation to prevent the spread of fire from the location of the origin of fire to the rooms where occupants are taking refuge. Communication systems should be in place between the occupants of the refuge area and rescue teams working to evacuate the building (Ronchi & Nilsson, 2012). A well-documented case study which supports the need for this strategy is the fire at the MGM Grand in Las Vegas in 1980 which resulted in the deaths of 85 people. Investigation into this tragedy revealed that over 50% of the victims died either on the stairs, elevators or on their way to use these egress option(Best & Demers, 1982). These fatalities could have been avoided if the Defend-in-place strategy was in place (Proulx, 2001).

Delayed Evacuation: This strategy involves the use of a dedicated area or a floor as a refuge. The delayed evacuation method is most commonly employed in the rescue operations of people in wheelchairs, or for people with other mobility impairments. These impairments may be due to temporary injury, pregnancy, old age or more permanent kinds of disabilities which prevents the occupants from evacuating under their own volition. Such occupants will need aid in reaching the refuge areas where they will await further help from the rescue operators. Using such a strategy is effective when the occupancy of a high-rise building involves a considerable percentage of the population having disabilities. Such a strategy is practical in buildings where the evacuation of all the occupants at the same time may not be possible due to medical conditions, state of being bed-ridden or being too sick to exit the building on their own, for example, buildings being used as medical centers, hospitals, etc. Use of this strategy emphasizes on the training of the staff available to help the disabled occupants to reach refuge areas (Ronchi & Nilsson, 2012)

Total Evacuation: The total evacuation strategy requires all the occupants of the building to evacuate at the same time by all available means of egress available to a safe location away from the building. Depending on the design of the building in use, the means of egress could include stairs, OEEs, sky-bridges, etc. The efficiency of this strategy depends on the occupancy of the building, familiarity with the building and behavior of the occupants. The application of this strategy is usually ordered or recommended by the fire department and the design of this strategy will need to be approved by the local fire department. In some circumstances, the population of the building may decide to self-evacuate upon being alerted of an emergency, and this may be affected by the familiarity of the occupants with the building (Ronchi & Nilsson, 2012).

4.1 Egress Methods

A number of egress methods can be employed for total evacuation of a building(s). Below is a brief description of a limited list of the possible methods:

Using Stairs only: In this method, only stairs are used during the entire evacuation process. Since the message “Do not use an elevator during a fire” was formalized in 1973 (Pigg, 2013), stairs have been the default and most widely used method of evacuation in the case of fires.

Use of Occupant Evacuation Elevators only: In this method, only OEEs are used during the entire evacuation process. While the use of OEEs definitely has a positive impact on the TET, complete evacuation by this egress method is an ideal situation since large percentage of evacuees would prefer to use stairs instead of elevators (Heyes, 2009; Jönsson et al., 2012; Kinsey, 2011).

Use of Stairs and Occupant Evacuation Elevators operating at different zones: In this method, a combination of stairs and elevators are used. This strategy reduces the load on elevators as well as reduces queuing time on elevators as the total population is split between the different egress options. The number of people using the stairs and elevators varies from floor to floor and is explained further in Section 5.3. Additionally, the different banks of elevators will be serving different elevator zones. Another way of combining the use of stairs and elevators is to use the elevators to evacuate occupants from the high-rise section of the building to a mid-rise section, from where the occupants who do not have mobility impairment can use the stairs to evacuate while the disabled occupants can continue to use other elevators to continue the evacuation all the way to the ground floor of the building. According to a study carried out by Huang, Chen, & Yuan (2014), this particular method used in their study had the second shortest TET compared to other combinations of egress methods used in their study, while the shortest TET was given by the introduction of refuge floors into the evacuation philosophy. The occupants will travel to the refuge floor using the stairs, from where elevators would shuttle the occupants down to the ground floor.

Use of strategies involving shuttle elevators: This method is a combination of stairs, OEEs and shuttle elevators. Service elevators serve the transfer floors and the ground only, acting as express shuttles between the ground and the transfer floors. The philosophy can also employ the use of OEEs to serve as shuttle elevators between a designated floor and the ground floor. When zoning philosophy is used in a building, the elevators may serve as a shuttle between the ground floor and the transfer floors.

5. Methodology

The study was carried out using the Pathfinder model, developed by Thunderhead Engineering (Thunderhead Engineering, 2016), for the various simulation scenarios. Pathfinder is a continuous model program which uses two methods to simulate agent movement. One is the hydraulic model [SFPE method by Gwynne & Rosenbaum (Gwynne & Rosenbaum, 2008)] and the other is steering behavior model by Amor et al., (Armor, Murray, & Obst, 2006) which was first developed by Reynolds (Reynolds, 1999). All simulations pertaining to this study have been carried out using the hydraulic model (SFPE Method).

Pathfinder uses the agent's information in the room it is located and then uses the information of the agent in the whole building. The occupant is assumed to be familiar with the surrounding in which they are located, as well as the distance that needs to be travelled from each door to the exits. Based on this information, each door is assigned a value (known as 'Cost') and the door with the lowest 'Cost' is selected by the occupant as a means of escape (Bladström, 2017). Upon choosing the lowest costing door, the path leading towards this door is calculated using the Locally Quickest Algorithm (Thornton, O'Konski, Klein, & Swenson, 2013). This method does not calculate the full path leading to the exit of the building, rather it calculates the path only to the lowest costing door in the room where the occupant is currently present and this is repeated every time the occupant comes to a new room, eventually leading to the exit of the building.

The Pathfinder model has features to allow the agents to be set-up with commands to follow a certain route towards the exit and it also allows the users to include functions such as "*go-to*" and "*wait*" in the behavior of the agents (Thunderhead Engineering, 2016). These commands give the users better control over the behavior of the agents when it comes to actions pertaining to the use of different egress components(Ronchi & Nilsson, 2012). In the simulations carried out for this study, these commands have been used to simulate the behavioral patterns of the agents pertaining to the re-routing behavior. This is one of the key reasons for choosing Pathfinder model over the other available evacuation models. As mentioned in Section 2.2, the SFPE model has been used for simulating the movement of the agents. This model works under a given set of assumptions and calculations as explained in the Engineering Guide to Human Behavior in Fire (SFPE, 2003).

This study focused only on Total Evacuation strategy of the high-rise building. The published works used for information regarding various evacuation strategies and human behaviors under during evacuations scenarios were obtained from different online sources such as search engines like Google and websites like researchgate.net, sciencedirect.com, link.springer.com and Lund University Research Portal which have exhaustive databases of articles and journals. Two main papers which served as the basis for this research are Fire Evacuation in High-rise Buildings- A Review on Human Behavior and Modelling (Ronchi & Nilsson, 2012) and Modelling Total Evacuation Strategies for high-rise buildings (Ronchi et al., 2014). The thesis has been carried out in 4 main stages: Literature study, simulations, results and analysis & conclusions. Based on the literature review discussed in the previous sections, in order to better understand the impact of certain variables on the TET in high-rise buildings employing evacuation via stairs, elevators and transfer floors, a study was carried out taking different variables into consideration. Each parameter considered is discussed briefly below.

5.1 Convergence of evacuation model results

As in the case of most data used for simulations, evacuation data also has various uncertainty components. One of the main elements to be considered in such cases is the uncertainty that comes with the human behavior under emergency evacuations. The term behavioral uncertainty used in this report, pertains to the field of fire safety science (Ronchi et al., 2014). But may mean something else altogether when discussed in other studies. As mentioned before, there is not a lot of data pertaining to the aspect of behavioral uncertainty in evacuation studies. In studies carried out by Averill in 2011, the human behavioral uncertainty was noted to be stochastic in nature (Averill, 2011). Which means, running one simulation in a model will not encompass all possible behaviors of the occupants within the building. The study also states that evacuating a building with the same population at the same place on consecutive days could give varying results. The impact of this variation is considerable which gives rise the need of data-sets obtained from actual experiments in order to better understand the extent of the variability in the occupant behavior. But due to scarcity of such data usually only single data-set is available for one particular scenario (Kuligowski, 2013). The lack of such data could be due to the scale, time constraints and logistics involved with such an experiment. Analysis of uncertainty related to human behavior needs to be carried out by experimental methods as well as through the use of valid modelling tools. Evacuation modelling tools such as Pathfinder, consider uncertainty as a stochastic problem (Ronchi et al., 2014), i.e., uncertainty in evacuation modelling has a random probability distribution which can be analyzed by means of statistical methods, but not something that can be precisely predicted. In order to address this problem, evacuation modelling tools utilize distribution methods and stochastic variables to simulate agent movement and behavior (Capote, Alvear, Abreu, Cuesta, & Alonso, 2012; Lord et al., 2005; Peacock, 2010; Ronchi & Kinsey, 2011; Ronchi, Nilsson, & Gwynne, 2012)

In order to have suitable output from this study, an evacuation time-curve was necessary. But due to the variability in the output of different runs of the same scenario, an average value for each scenario became a requirement. To this end, the convergence of each of the run was carried out based on the method proposed by Ronchi et al., (2014). The variability of the output for every run of each scenario was analyzed until a set criterion was met. This involves meeting a predetermined value for the percentage error between standard deviations (> 5%) of the output for consecutive runs. Each scenario in this study was run until convergence was achieved. This method provided a means to quantitatively assess the variability in the output of one particular scenario, thus obtaining an 'average' value which can be used for further analysis of the scenario in question. The limitations associated with this method of convergence analysis has been discussed briefly in Section 2.3.

6. Definition of the Scenarios

Based on the Literature review carried out, the following 3 parameters have been considered for the impact analysis on the Total Evacuation Time.

- Number of elevators
- Number of disabled people/Number of elevator users
- Maximum Waiting Time

Number of Elevators: The number of OEEs available at the time of evacuation for the evacuees has a direct impact on how quickly the evacuation takes place. The number may vary for a variety of reasons, such as maintenance, loss of functionality due to smoke/water damage or due to the fact that it is in use by the firefighters for the firefighting operations. Moreover, this study is aimed at a generic high-rise building where the number of elevators may not be the same as that followed in the base scenario for this simulation.

Number of Disabled People: Disability is a broad term covering limitations on mental and physical activities. Studies show that there has been slow but gradual increase in the number of people with disabilities. Study carried out by the United Nations Department of Economic and Social Affairs estimates that around 15% of the world's population (≈1.3 billion people) deals with one form of disability or another ("Ageing and disability | United Nations Enable," 2017). USA alone there constitutes around 40 million of the disabled population. A study carried out in USA by the National Institute on Disability, Independent Living and Rehabilitation Research (NIDILRR) shows that among all the disabilities, ambulatory disabilities constitute for the highest percentage (National Institute on Disability, Independent Living, and Rehabilitation Research, 2017). The percentage of ambulatory disability increases rapidly with age. This coupled with the fact that due to better lifestyle and healthcare, people now live longer giving a rise to higher chances of an increase in the number of people having movement impairments. The use of the term disability in this study deals with movement impairments.

Taking into account the increased occurrence of obesity, the choice of using elevators as opposed to stairs is a fair assumption to consider as part of the simulation The United Nation's 2030 Agenda of 'Leaving no one behind', explicitly addresses the need to consider the accessibility for the disabled population when planning, designing and construction of a community ("Ageing and disability | United Nations Enable," 2017). Disabled occupants have been modelled in Pathfinder using the default wheelchair user profile. For the scenarios where an increased number of elevator users are expected, the increase in the elevator users population has been reflected by increasing the number of wheelchair users by 10%. This is a conservative approach as a wheelchair user occupies the space equal to that of 6 standard occupants which reduces the number of people using an elevator in a single run.

Maximum Waiting Time: A waiting time of 600s has been assumed based on the data sets provided from studies carried out by Heyes, Kinsey and Jönsson (Heyes, 2009; Jönsson et al., 2012; Kinsey, 2011). Going forward with the assumption that, given enough information and training, people will be willing to wait for a longer time for the elevators, a set of simulations will be carried out with a waiting time of 900s. It is assumed that the building does not have adequate messaging system to divulge information regarding the status of the elevator use for evacuation. Hence the re-routing of occupants occurs after a short time period of 10 minutes in some cases and 15 minutes in another. Re-routing in the occupants is based on the assigned behavior for each occupant where primarily the occupant switches from using the elevator to the use of stairs after waiting for a time period of 10 minutes or 15 minutes. A potential issue associated with the assumption of only 10 minutes as a maximum waiting time is that people's behaviors may also include waiting a longer time, i.e., wait for as long as it is necessary. In order to address this issue, one simulation was carried out with no re-routing behavior, allowing the designated agents to wait for as long as it takes in order to evacuate using the elevators.

While the impact of the above-mentioned variables were the ones short-listed for this study, there are other such factors which were not included in this study due to time constraints. These variables include, but are not limited to, different elevator zoning strategies, effect of age-group on the TET, effects of the lack of familiarity with the surroundings, combining an increased number of elevator users with a change in the number of elevators, effect of increased waiting time with lesser number of available elevators and the use of double-deck elevators.

6.1 Summary Description of Scenarios

Base scenario: The base scenario is run in order to establish a starting point of reference. In this scenario, the total number of elevators was 25, with 5% of the population expected to be mobility impaired and the elevator users had waiting time of 600 s (5 minutes) before re-routing towards the stairs. The layout of the simulated building space is shown in Figure 3 and Figure 4. Figure 3 is indicative of the layout of the ground floor where locations of the three separate banks of elevators at different levels of the building have been shown (Low-rise, Mid-rise and High-rise) It must be noted that the elevator shafts for each banks of elevators do not run the entire length of the building, rather they serve only the designated zone of the building.

Scenario 1: The occupant behavior is altered to ensure that the occupants using elevators for evacuation on each level waited as long as it took for the elevator to arrive to the floor where they are located. There is no change in the number of elevators available for use, percentage of population using the elevators and the number of mobility impaired occupants.

Scenario 2: The number of elevators was reduced by 20% (from the base scenario) in order to simulate a situation where, either the design of the building has lesser number of elevators or a situation where the elevator was unavailable for the evacuation process. This unavailability may be due to breakdown, maintenance, firefighter's intervention or any such similar reason. There was no change in the number of mobility impaired occupants and the elevator users (standard occupants) would wait for 600s before re-routing to the stairs.

Scenario 3: The number of elevators was increased by 20% (from the base scenario) in order to simulate a situation where the design of the building includes an increased number of elevators from the base scenario. There was no change in the number of mobility impaired occupants and the elevator users (standard occupants) would wait for 600s before re-routing to the stairs.

Scenario 4: The number of elevator users was increased by effectively increasing the number of wheelchair users in the building to 10%. There was no change in the number of available elevators and the elevator users (standard occupants) would wait for 600s before re-routing to the stairs.

Scenario 5: The total waiting time of the elevator users was increased to 900s (15 minutes). This in turn had an effect on the total number of elevator users without increasing the number of mobility impaired occupants modelled within the building. There was no change in the number of available elevators nor the total number of mobility impaired individuals in the building from the base scenario.

Scenario 6: In Scenario 6, the entire population of the building evacuated using the elevators. There was no change in the available number of elevators or the number of occupants using wheelchairs.

Table 1: Sets of Simulations used in this study

Scenario No.	No. of elevators	% of disabled people	Waiting time (s)	Scenario Description
Base scenario	25	5%	600	Base scenario
Scenario 1	25	5%	Indefinite waiting time	Wait as long as it takes to use OEEs for evacuation
Scenario 2	20	5%	600	Reduced number of OEEs
Scenario 3	30	5%	600	Increased number of OEEs
Scenario 4	25	10%	600	Increased number of elevator users (wheelchair users)
Scenario 5	25	5%	900	15 minutes waiting time
Scenario 6	25	5%	-	Evacuation using only OEEs

6.2 Egress Route Distribution

Heyes, Jönsson and Kinsey (Heyes, 2009; Jönsson et al., 2012; Kinsey, 2011) carried out studies to develop a correlation between the percentage of occupants who will use the elevator as a means of escape and their location in the building when the evacuation starts. While the output of Heyes's and Jönsson's studies gave a correlation that was linear in nature, Kinsey's studies provided a correlation which was exponential in nature. This could be attributed to the method of data collection employed for each of the studies. For data gathering, Jönsson et al., used on-site behavioral questionnaire while Heyes's data set was based on the responses from simulation questionnaires and collecting data from online surveys conducted from actual evacuations. Kinsey's data collection method involved the use of an online behavioral intention survey. Each correlation generated from the different data set is given in the table below:

Table 2: Elevator and stair usage correlation to Floor number by Heyes (2009), Jönsson et al. (2012), and Kinsey (2011)

Author	Correlation*
Heyes, 2009	$P = 1.14 \times F + 5.3$
Jönsson et al., 2012	$P= 0.84 \times F + 1.05$
Kinsey, 2011	$P= 0.3207 \times \ln F - 0.4403$

*Each of the correlations are suggested for above Floor Level 5

P= Percentage of occupants using the elevator; F=Floor in which the occupant is located

Given that the output of the studies carried out by Heyes (2009) and Jönsson et al. (2012) give linear correlations and percentage of people using the stairs obtained from these correlations is almost similar, the present study employed the use of the average values obtained from these two studies to dictate the choice of evacuation method employed by occupants at different levels. Such a correlation needs a correction by accounting for the percentage of occupants who will not be able to use the stairs especially in the first five floors of the building. Simply using the correlation obtained gives a value lower than what has been found to be true. Studies suggest that an approximate of 3%-5% of the population will be unable to use the stairs. Hence, as a conservative approach, the first five floors were simulated to have 5% of the population having disabilities or in need of assistance to make their way to the exit by means of the stairs. It must also be noted that, while the study by Jönsson et al., was on a building extending up to only 24 floors, the average of Jönsson's and Heyes's correlations have been extended to encompass the full length of the building in this study (i.e., 37 floors). The output of the correlations by Jönsson and Heyes and the output of the average of the two, has been shown by means of a graphical representation in Figure 2 (redrawn from (Ronchi & Nilsson, 2014)).

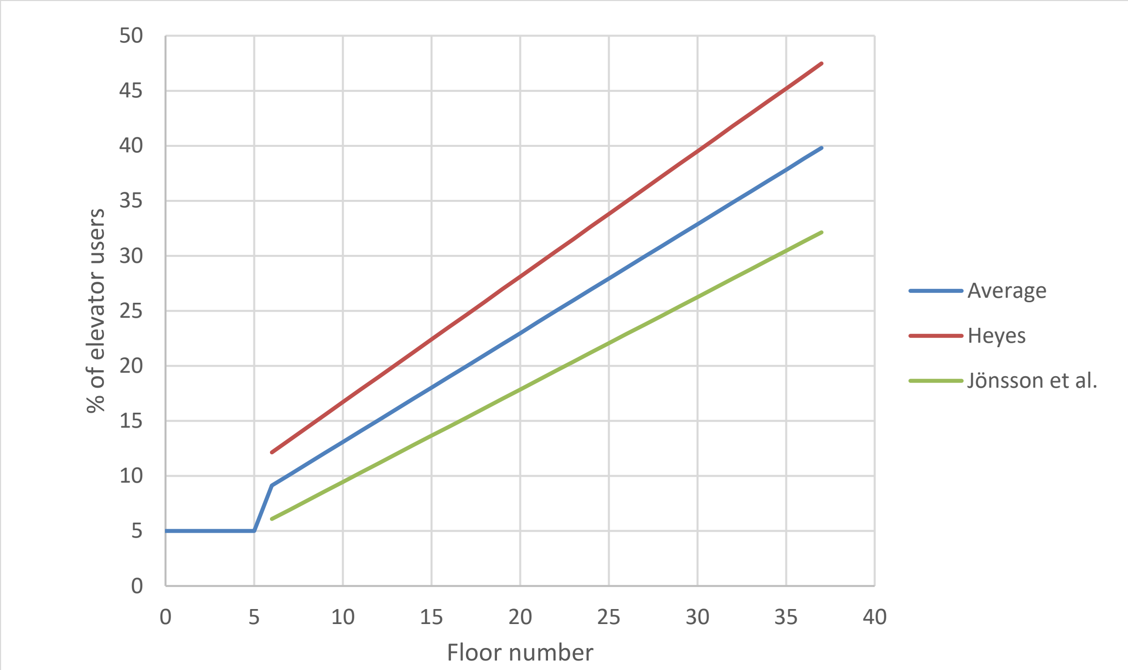

Figure 2: Graphical representation of the correlations by Heyes, Jönsson et al., and the average of the two for percentage of elevator usage per floor

7. Calibration of modelling inputs

In the following section, details of the different simulations and the various parameters varied for each simulation carried out will be discussed.

7.1 Geometric Layout

The layout considered is the financial sector of the 100 Bishopsgate ("100 Bishopsgate Floor Plans," 2019), London. This has been replicated to populate the entire 37 floors of the building. The area of each floor varies between ≈2300-2400 m^2. The ground floor consists of four exits, two sets of stairs connecting the entire length of the building and five Low-rise elevators running up till Floor 5. This floor serves as a transfer floor where occupants can switch to any of the 10 Mid-Rise Elevators running between Floor 5 and Floor 19. Floor 19 serves as the second transfer floor where the High-rise elevator can move the occupants up until Floor 37. The total population of the building stands at 7843 occupants.

The population density has been varied at different levels of the building as follows:

Table 3 : Population Density used on various floors for the modelled building in Pathfinder

Floors	**Density (m^2/p)**
1-7	8.8
8-10	8
11-15	8.8
16-18	9.5
20-34	14.5
35-37	14.5

The stairs have been modelled to in Pathfinder to have a Width of 1200 mm, tread depth of 280 mm and a riser height of 180 mm.

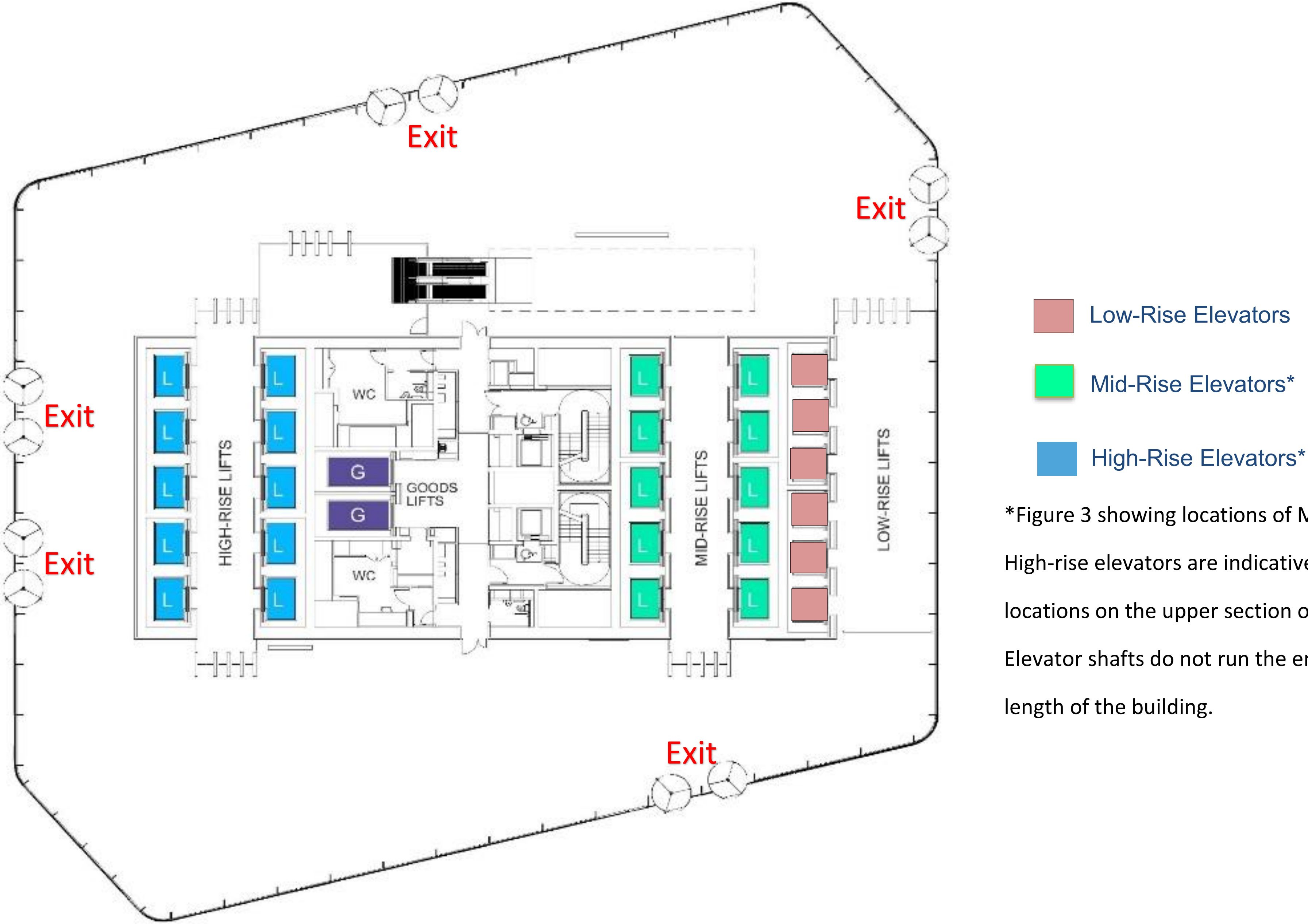

*Figure 3 showing locations of Mid-rise and High-rise elevators are indicative of their locations on the upper section of the building. Elevator shafts do not run the entire length of the building.

Figure 3: Ground Floor Layout of the hypothetical high-rise building used in Pathfinder for the study

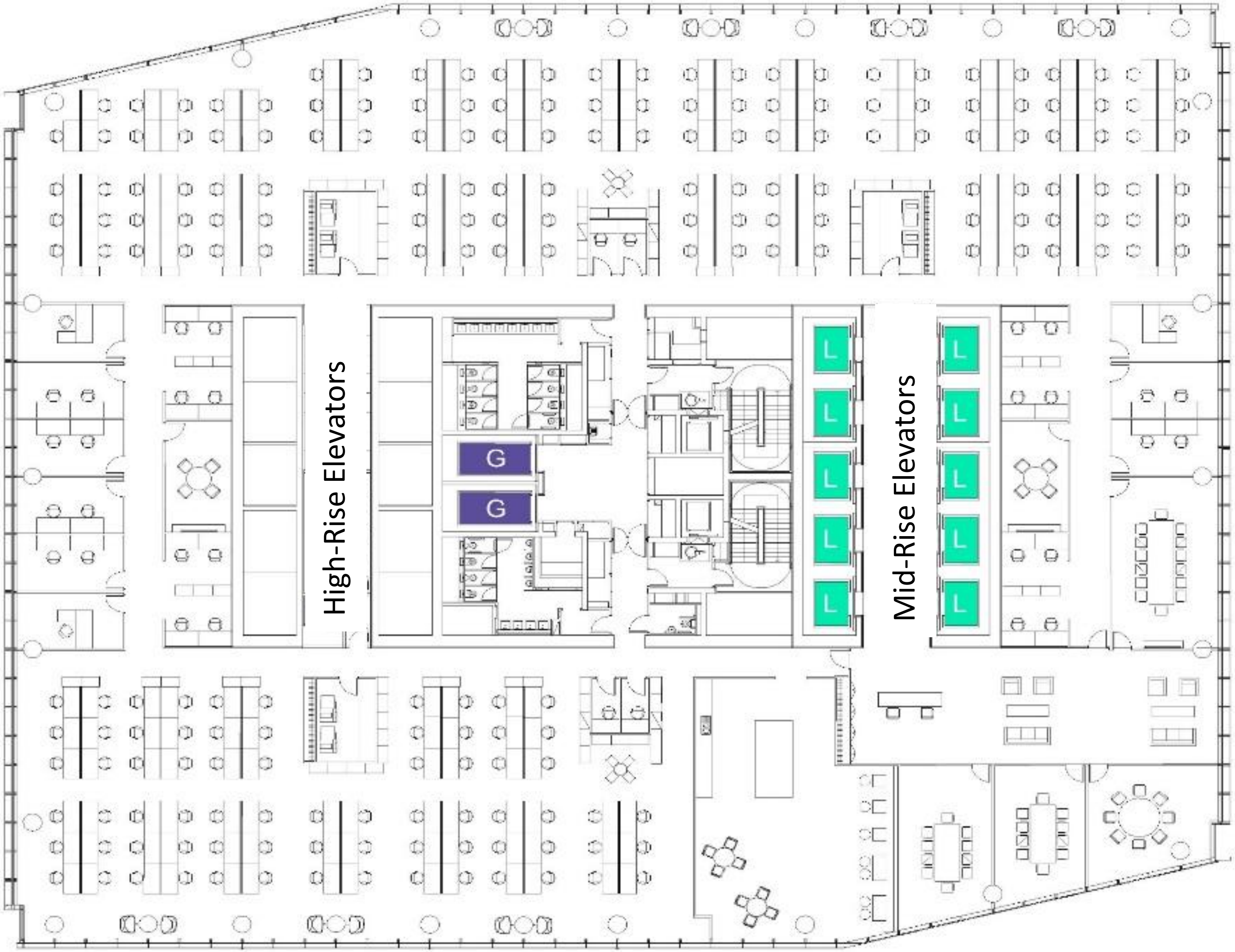

Figure 4: Geometric layout of one of the floors occupying the mid-rise level offices in the building

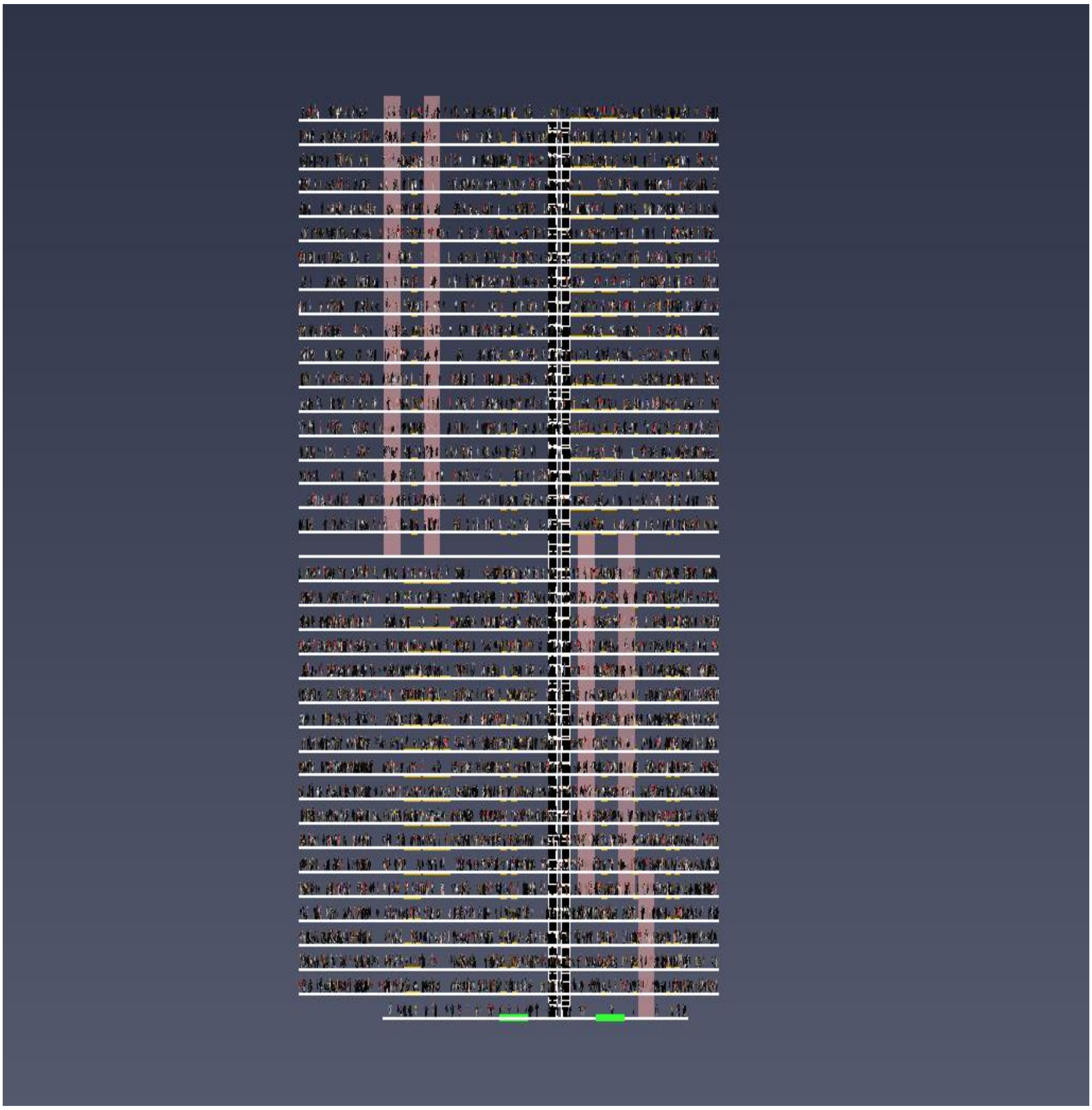

Figure 5: Building geometry of the 37 floors as seen in Pathfinder

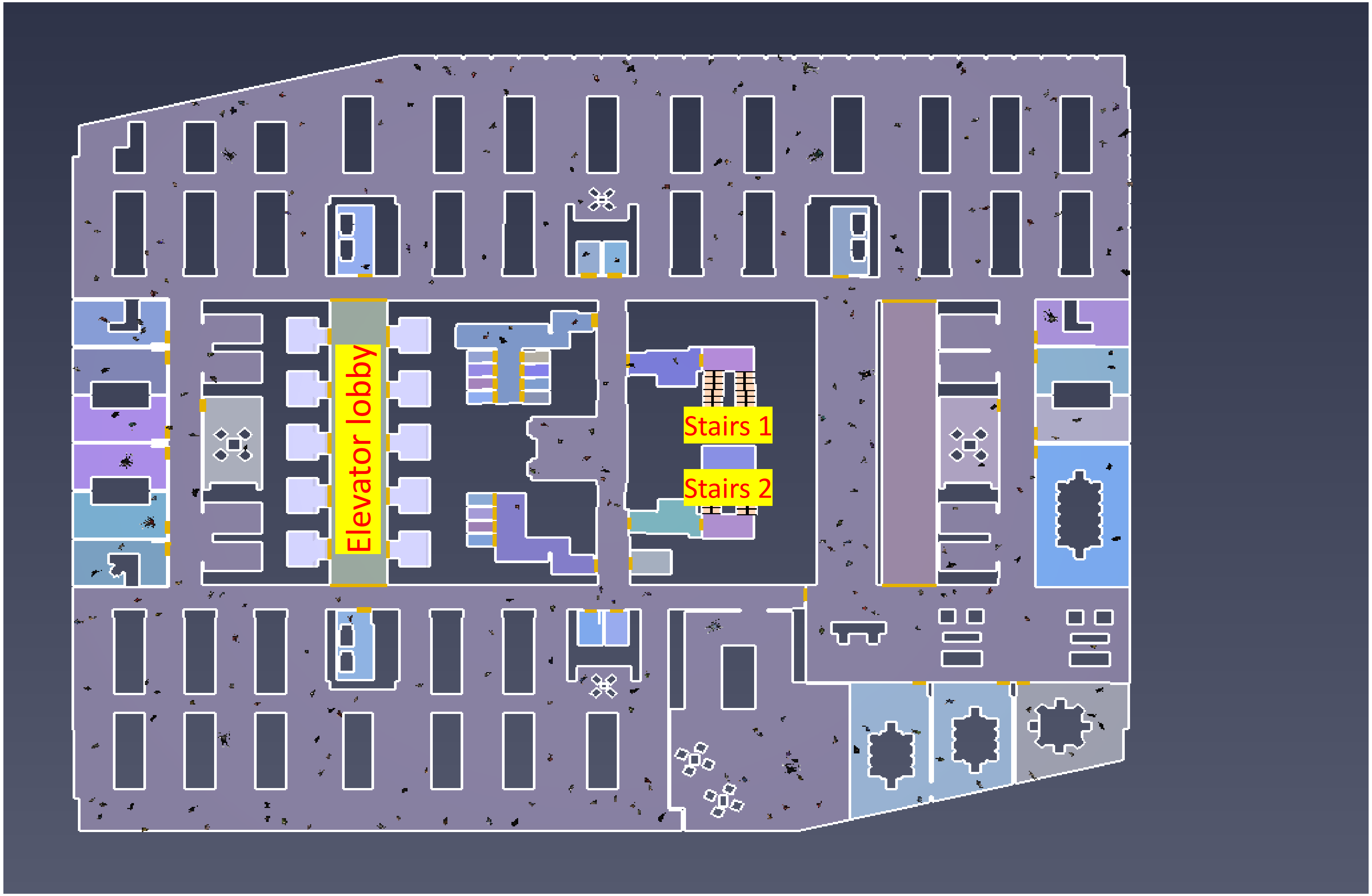

Figure 6: Geometric layout of one of the floors occupying the high-rise level offices in the building

7.2 Agent Characteristics

The simulated building has been populated with two sets of agents. One set of agents without disabilities and the other set of agents who are wheelchair users. The SFPE Handbook by Gwynne and Rosenbaum (Gwynne & Rosenbaum, 2008) provided the walking speed details for the occupants without disabilities (standard occupants) while the studies carried out by Boyce & Shields (1999) has been used for the walking speed details for occupants with movement impairments.

Table 4: Details of walking speed data used for the agents in the simulation (Reproduced from Boyce & Shields, 1999; Gwynne & Rosenbaum, 2008)

Input	Standard Occupants	Occupants having movement impairments
Minimum walking speed (m/s)	0.29	0.1
Maximum Walking speed (m/s)	2.29	1.68
Mean value of walking speed(m/s)	1.29	0.37
Standard Deviation (m/s)	1.00	0.8

The base scenario includes a total of 5% of the population having movement disabilities (Jönsson et al., 2012). This section of the population has been modelled into the scenarios by incorporating the default wheelchair user option for 5% of the total population. The agents are distributed randomly on each floor at the start of each run of the simulation. Wheelchair users have been simulated using the default feature in Pathfinder. Occupants using a wheelchair occupy an area of 1.0032 m^2 with a height of 1m. It must be noted that, though Pathfinder employs 3D elements in its visualization output, the evacuation modeling is carried out on a 2-dimensional space. Wheelchair users occupy space equivalent to that of 6 standard occupants (Thunderhead Engineering, 2016)

7.3 Modelling Pre-Evacuation Delays

Pre-Evacuation delay can be explained as the time between the sounding of the fire detection or the evacuation alarm and the actions of the occupants towards actual evacuation. No evacuation modelling can be representative of an actual scenario without taking into consideration the pre-evacuation delay. This can vary with the occupancy of the building, familiarity of the occupants with the building, efficiency of alarm and public announcement systems used during evacuations, etc. In this study, the data regarding pre-evacuation delays have been obtained from a number of studies carried out on the evacuation of the World Trade Center (Averill et al., 2005; Kuligowski & Mileti, 2009; McConnell, Boyce, Galea, Day, & Hulse, 2010; Sherman, Peyrot, Magda, & Gershon, 2011). The values used in the simulations are given in the following table (Table taken from study by Ronchi & Nilsson, 2014)

Table 5: Pre-evacuation time used for the agent characteristics in Pathfinder

Pre-Evacuation time data used as input in the Model	
Minimum delay time (s)	180
Maximum delay time (s)	600
Mean value of delay time (s)	360
Standard Deviation	120

7.4 Elevator modelling

The building used in the simulation is equipped with a total of 25 elevators. Five elevators run from the Ground Floor until the first transfer floor at Level 5. The second set of elevators, 10 in number, run from Level 5 to Level 19 where the second transfer floor is located. The third and final set of 10 elevators are located at this floor and run between Levels 19 and 37. Most commonly, elevator traffic system design follows a rule of thumb which says that the number if floors in a single zone should not exceed 18-20 floors (Al-Sharif et al., 2016). In this study, the hypothetical building is modeled after 100 Bishopsgate which consists of a Low-rise building of five floors adjacent to High-Rise building. It is assumed that this Low-Rise Building shares the use of the first bank of five elevators running from the Ground Floor to Level 5, hence the first transfer floor is located at Level 5, which under normal circumstances would have been situated at a higher level giving a more uniform zoning of the elevators.

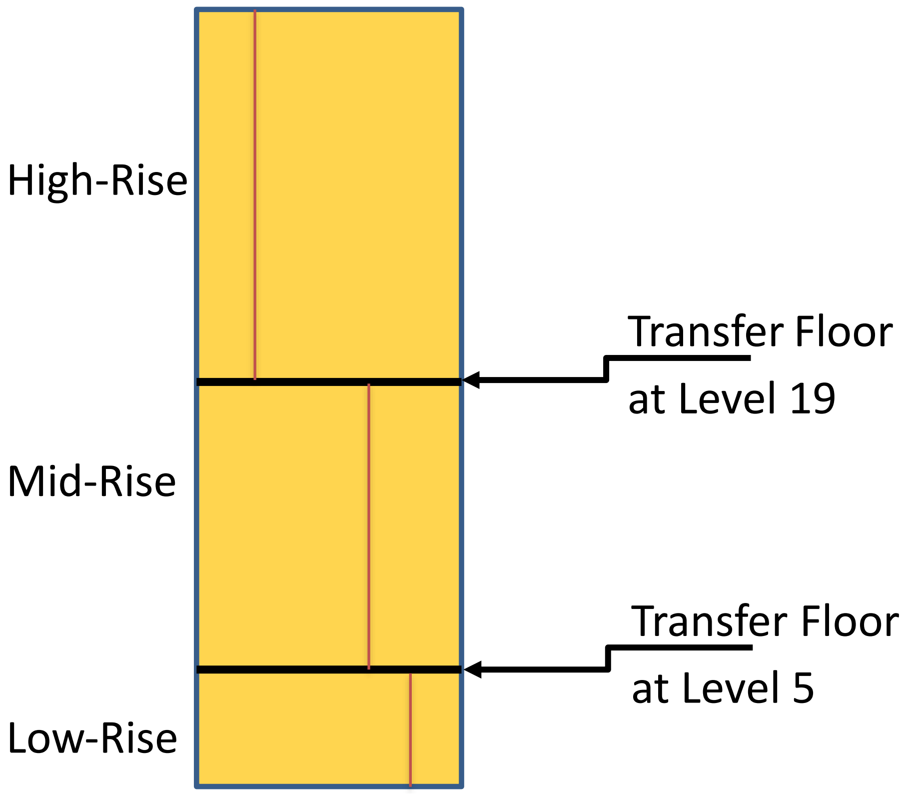

Figure 7: Schematic Representation of the transfer floors location and the various banks of OEEs at the low-rise, mid-rise and high-rise levels

The elevators modelled in these simulations are Class “A” office standard elevators from the Vertical Transportation Handbook (Starkosch & Caporale, 2010). Each elevator has a depth of 1.85 m and is 2.5 m wide. The opening of the elevator is 1.2 m wide and has a capacity of 18 persons. Static zoning has been employed in this building, meaning that the banks of elevators run only between designated floors and the elevator shafts terminate at the highest point of the zone that it serves.

Table 6: Elevator Characteristics of the different banks of elevators employed at different levels of the modelled building

Elevator Features	Low Rise Elevators	Mid-Rise Elevator	High-Rise Elevators
Number of elevators	5*	10*	10*
Maximum speed of the elevator	4	6	9
Acceleration of the elevator	1	1	1
Maximum occupancy of the elevator	18	18	18

*Not in case of Scenario 2 and Scenario 3 where the number of elevators were varied

8. Results

The output for the study carried out is depicted in a graph shown below (Figure 8). The graph is a plot of the number of occupants evacuating the building against time taken for evacuation in seconds. It must be noted that the graphs shown in the following sections indicate the average time taken for the evacuation of the occupants from multiple runs. In each run, the same occupant may or may not be the first to evacuate, nor will the evacuation process take place in the same occupant order for each run. Instead, the time of evacuation of any occupant, in the ascending order, has been plotted against time in order to obtain the results in a desired format for analysis. Each scenario was run until convergence was achieved.

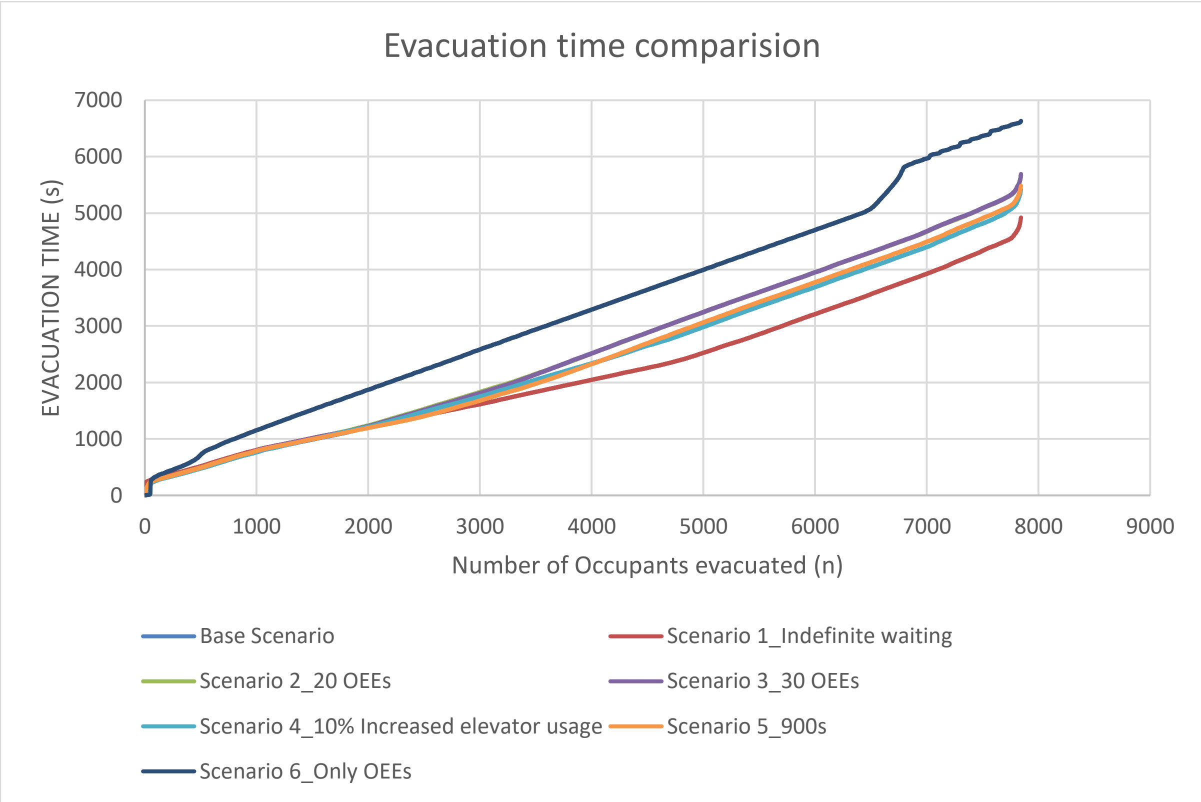

Figure 8: Graphical representation of the average TET for each scenario plotted against the number of occupants exiting the building

Table 7: Results of the Average Total Evacuation Time for the different scenarios

Scenario	No. of elevators	% of disabled people	Waiting time	Evacuation time (s)*	Evacuation time (minutes)
Base Scenario	25	5%	600s	5680	94
Scenario 1_ Indefinite waiting time	25	5%	Indefinite waiting	4929	82
Scenario 2_20 OEEs	20	5%	600s	5676	94
Scenario 3_30 OEEs	30	5%	600s	5687	94

Scenario 4_ 10% Increased elevator usage	25	10%	600s	5028	83
Scenario 5_Waiting time 900 seconds	25	5%	900s	5499	91
Scenario 6_Only OEEs	25	5%	600s	6666	111

*rounded-off values

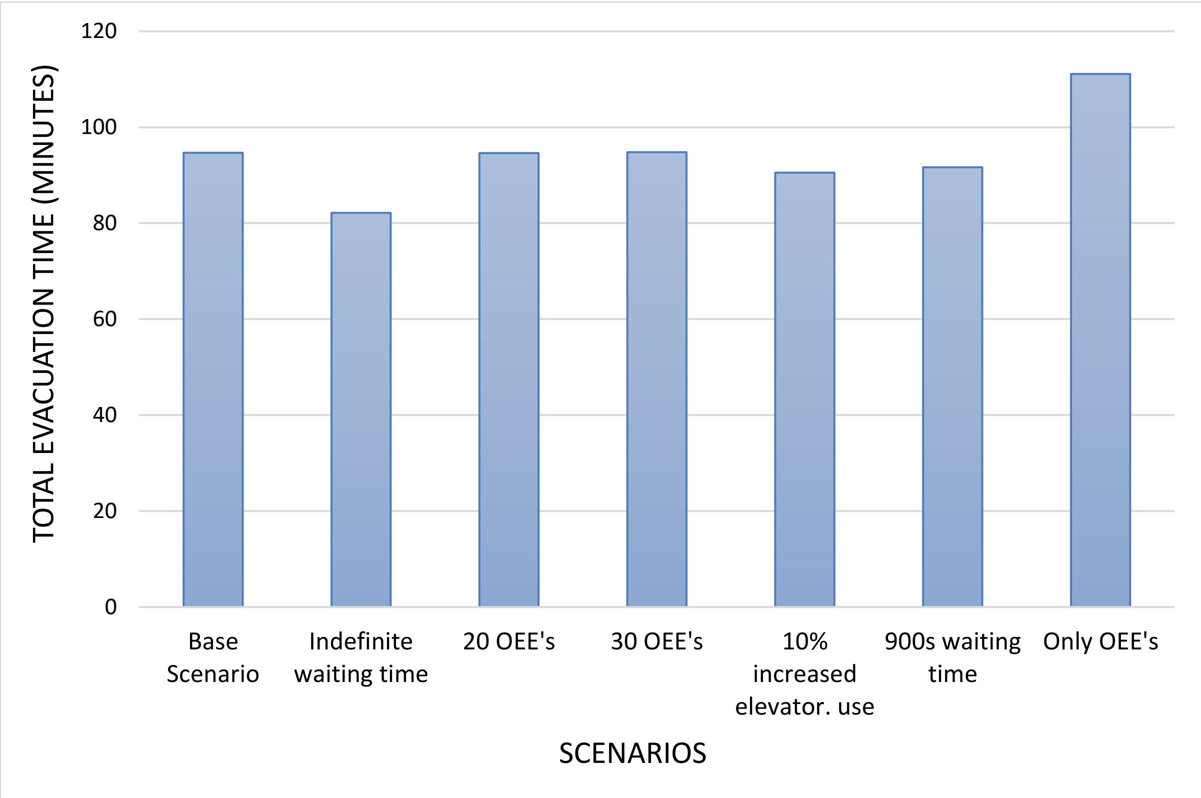

Figure 9: Histogram showing the TET required using Total Evacuation strategy for each Scenario

Results of the simulations indicate that the TET reduces as the usage of the OEEs increases. This is clearly observable with the sharp decrease of ≈13% (from base scenario) in TET for Scenario 1, where a considerable number of evacuees utilize OEEs for evacuation by waiting an indefinite amount of time for the elevator to reach their floor. Similar results are observable in Scenario 4 where there is a 5% increase in the occupants utilizing the OEEs due to the increase in the number of wheelchair users. This resulted in decreased TET of ≈11% from the Base Scenario. It must be noted that this study makes an assumption that all mobility impaired personnel using the elevators are wheelchair users. This is a conservative approach, as in reality, people with mobility impairment can range from people using a walking stick temporarily to people with more permanent forms of mobility hindrances. This means that evacuation time for elevator users would in fact be lesser (as wheelchair users occupy more space inside the elevator requiring more runs of the elevator). Therefore, in reality, there will be an increase in the number of people evacuating in a single run of the OEE.

Even an increase of waiting time for the OEEs to 15 minutes reduced the TET when compared to scenarios involving a waiting time of just 10 minutes

Results from Scenario 2 and Scenario 3 show that a variation in the number of elevators by 20% from the Base Scenario shows negligible change in the TET. This could be linked to the sub-optimal use of the elevators throughout the evacuation process. Hence, an increase in the number of the elevators may not significantly affect the TET unless a larger percentage of the population is willing to utilize the OEEs for the purpose of evacuation. With the distribution of the population between the stairs and OEEs as per Figure 2, the results of Scenario 1 gave the least TET. This indicative of the fact that if people do not re-route to the use of stairs after initially choosing to evacuate using OEEs, it would lead to shorter TET.

The use of OEEs only for complete evacuation of the building resulted in an increased evacuation time. This was counterintuitive, as studies carried out earlier indicates that the use of only elevators for evacuation should yield the quickest evacuation time (Ronchi & Nilsson, 2014). An increased congestion and longer waiting times for the elevators at the lower levels was observed. This may be due to the uneven zoning strategy employed in this scenario and is indicative of the fact that use of only OEEs in shorter buildings may not be an ideal strategy.

Time taken for stair evacuation Vs Elevator evacuation: For each case, the time taken for the last occupant using each of the egress methods was noted and is shown in the table below:

Table 8: Time for Stair evacuation Vs time for Elevator evacuation

Case	Elevator		Stairs	
	Seconds	Minutes	Seconds	Minutes
Base Scenario	2048	34	5680	94
Scenario1_ Indefinite waiting time	2795	46	4929	82
Scenario 2_20 OEEs	2236	37	5676	94
Scenario 3_30 OEEs	2081	34	5678	94
Scenario 4_ 10% Increased elevator usage	2862	47	5028	83
Scenario 5_ Waiting time 900 seconds	2159	35	5499	91
Scenario 6_Only OEEs	6666	111	-	-

As expected, it was observed that the time taken for evacuation by using stairs is much higher than the time taken for evacuation by elevators. In the case of the base scenario, for a period of 60 minutes, the elevators were not in use. In the two cases where there was increased use of the elevators, i.e., in scenario 2 where occupants waited an indefinite period of time to evacuate and in scenario 4 where there was an increased percentage of occupants using the elevators, the time taken for evacuation between the two methods of egress is 36 minutes. This indicates an optimization in the use of elevator service during evacuation.

9. Discussion

From the results of Scenario 1 (indefinite waiting time), Scenario 4 (increased elevator usage) and scenario 5 (longer waiting time) it can be inferred that with an increase in the use of elevators, there is a sharp decrease in TET. Studies by Andrée et al. (2015), indicate that the general trend is that people wait for either a limited time (<5 minutes) or a long time (>20 minutes) (Andrée et al., 2015). The waiting time period could be longer if the perception of how long the occupant has been waiting for the elevator seems shorter. When the real-time information is not made available to the waiting occupants, the perception of time is not accurate, leading the occupant to believe that they have been waiting for a longer time than the actual lapsed time period until the elevator service has reached them (Mishalani, McCord, & Wirtz, 2006). Feeling like more time has passed than actually has, can lead to an increase in the anxiety levels. By providing information pertaining to the waiting time for elevators, the wait may not seem as long because the occupants are not concentrating on the passage of time (Hui & Tse, 1996). Providing people with information on when they will be served can improve their overall comfort level with the situation and in some instances, providing information on how many people are ahead of them is even more beneficial than providing the time itself (Kuligowski & Hoskins, 2012). This may have a positive impact on the waiting time for elevators, further optimizing the use of the OEEs during evacuations. Moreover, information with regard to the safety features that are employed in the design of evacuation elevators will reinforce the level of security that occupants feel with regard to the use of elevators during emergency situations. This may help in increasing elevator usage considerably.

In order to achieve the goal of increased elevator usage, various methods can be employed. These methods include, but are not limited to, the use of suitable messaging systems, increasing the reliability on the OEEs by the occupants and reduced risk perception on the use of OEEs by means of mock drills and streamlining of the use of OEEs. This would of course need to be incorporated into the fire safety design solutions at an early stage in projects. One of the factors noted by Jönsson & Andersson (2014) was that the risk perception involved with the use of elevators for evacuation is affected by the age of the occupant. The older generation was found to be more reluctant to use elevators for evacuation when compared with the younger generation. Social influence can also play a factor in increasing the percentage of people using the elevators. If a large enough percentage of the younger generation, who are more comfortable with the use of elevators, begin to use elevators for egress, this may influence the older generation to emulate them.

The impact of increasing or reducing the number of OEEs in a given building seems to have negligible impact on the TET resulting from the sub-optimal use of the elevators. Hence, without ensuring that a higher percentage of the occupants would in fact use the OEEs during evacuations, employing more OEEs seems redundant.

Results from Scenario 6, where only OEEs were used, showed an almost 17% increase in TET from the Base Scenario. These results are contradictory to the results obtained by Ronchi and Nilsson (Ronchi & Nilsson, 2014) where employing the use of only OEEs for total evacuation resulted in the least TET among all the other egress strategies used. The difference between the two studies with regard to the use of only OEEs lies in the detail of the elevator zoning. In this study an uneven elevator zoning philosophy has been followed, whereas the aforementioned study employed a uniform elevator zoning philosophy. The results of this indicates that with uneven zoning of the elevators, the use of elevators is sub-optimal and results are counter intuitive when the zoning philosophy does not follow a relatively uniform spacing between transfer floors. On the assumption that the first bank of Low-rise elevators is employed primarily to serve the high rise building as well as the low-rise adjacent building, in the case of emergencies, it may be advantageous to have more uniformly distributed zones. While this may lead to consequences related to the stack effect, this uneven zoning of the elevators is counter-productive to evacuation.

Another option for such building designs where a bank of elevators serving adjacent buildings will cause uneven zoning, is employing a dynamic zoning philosophy. This could result in more efficient evacuation of the high-rise building. While the use of zoning is motivated by space saving on floors above a particular zone, employing dynamic zoning and use of the elevators to travel between more uniformly distributed zones only during emergencies could result in quicker evacuation.

In the case of the design considered for this study, if the Mid-rise elevators shaft were extended to serve between the Ground Floor and Floor 19 during emergency situations (effectively splitting the entire building between two almost uniform zones), it could lead to a smoother and quicker evacuation of the occupants during emergencies.

From the results shown in Table 8, where the evacuation time by occupants using different egress methods is used, it is clearly indicative that the elevators are not being used to its full potential during evacuations. In the base scenario the elevators are idle and not in use for a duration of one hour between the last elevator user and the final occupant to evacuate the building (using stairs). Due to the sub-optimal use of the elevators in this case, the TET is 94 minutes. When this result is compared to the result for scenario 1 and scenario 4 it becomes clear that with a better distribution of the occupants using the elevators and stairs the total evacuation time for scenario 1 can also be considerably reduced. Similarly, when results between scenario 2 and scenario 3 are compared, percentage of people using the elevators for evacuation take 3 minutes lesser when there are more elevators available for use, but the over-all time required for evacuation, ultimately remains the same.

9.1 Future research

Due to time constraints, some scenarios could not be simulated and discussed in this study. For a broader range of applicability of this study, it is necessary to consider the effects of the use of shuttle elevator systems which will reduce the load on OEEs, effects of counter-flow movement caused by fire-fighter's intervention, evacuation scenarios involving assisted evacuation and the effect of the lack of familiarity with the building (this study was carried out for a high-rise commercial/office building, indicating that the occupants are familiar with their surroundings. In buildings with other uses, such as high-rise hotels the validity of this study will need to be further explored). While this study has been carried out on a high-rise building used for commercial/office space, there is an underlying assumption of the age group considered for such a use of the building. In a mixed-use building, the age group will be more varied leading to a wider range of walking speeds which will directly affect the TET.

With double decked elevators providing better performance over the use of regular single-decked elevators (Shabo & Schröder, 2015) while occupying lesser building core space, the use of double decked elevators is expected to increase. The effect of such a configuration on the TET warrants further study.

As mentioned in Section 5, this study was carried out using the Pathfinder model for specific reasons. The results of this study will need to be further validated by comparing the results of similar works carried out in other available models.

10. Conclusions

Studies related to use of elevators during fire emergencies have been ongoing for quite a few years now. This study aims to shed some more light onto some of the many aspects that concern the use and applications of elevator use during emergencies.

The findings of this study can be summarized by two key points. One, in order to better optimize the use of elevators for evacuation in high-rise buildings, it is important that the percentage of population who will use the elevators needs to be increased. One of the methods to achieve this is by employing better messaging systems, employing the OEEs in evacuation drills in order to reduce the risk perception associated with the use of elevators. As is seen in the results of Scenario 1, Scenario 4 and Scenario 5, larger groups of people using the elevators for evacuation yields quicker evacuation time.

The second finding indicates a relation between total evacuation time and the elevator zoning philosophy employed. When an uneven zoning philosophy was employed in the building simulation, there was an increase in the evacuation time. These results are contradictory to results obtained from previous research that have been carried out. So far with respect to elevator zoning design, the points have mostly been related to traffic congestion, stack effects mitigation, ingress time, travel time etc. In addition to the aforementioned points, consideration may need to be given to the impact of the location of the transfer floor on the egress time needed during emergency evacuations as well. As this report does not compare results from an uneven and evenly zoned building, a future study comparing the two can better help understand the impact of zoning philosophies on total evacuation times.

11. References

1. 100 Bishopsgate Floor Plans. (2019). Retrieved March 28, 2019, from https://www.100bishopsgate.com/the-building/#soa

2. Ageing and disability | United Nations Enable. (2017, February 7). Retrieved May 19, 2019, from https://www.un.org/development/desa/disabilities/disability-and-ageing.html

3. Al-Sharif, L., Al-Sukkar, G., Hakouz, A., & Al-Shamayleh, N. A. (2016, September). *Towards a Systematic Methodology for the Design of Elevator Traffic Systems in High Rise Office Buildings*. *6*. Retrieved from https://www.researchgate.net/publication/312936707_Towards_a_Systematic_Methodology_for_the_Design_of_Elevator_Traffic_Systems_in_High_Rise_Office_Buildings

4. Andersson, J., & Jönsson, A. (2011). *Utrymning av höga byggnader – En analys av riskperception* (Thesis, Lund University). Retrieved from http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=2225923&fileOId=2225957

5. Andrée, K., Nilsson, D., & Eriksson, J. (2015). Evacuation experiments in a virtual reality high-rise building: exit choice and waiting time for evacuation elevators.

6. Ariff, A. (2003). Review of Evacuation Procedures for Petronas Twin Towers. *Proceedings of the CIB-CTBUH International Conference on Tall Buildings*, *290*. Kuaka Kumpur: CIB Publication.

7. Australian Building Code Board. (2015). *Australian Elevator Association Handbook*.

8. Averill, J D, Mileti, D. S., Peacock, R. D., Kuligowski, E. D., Groner, N., Proulx, G., … Nelson, H. E. (2005). Final Report on Collapse of the World Trade Center Towers. Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Occupant Behaviour, Egress and Emergency Communications (No. NIST NSCTAR 1-7). National Institute of Standards and Technology.

9. Averill, Jason D., Kuligowski, E. D., & Averill, J. D. (Eds.). (2011). Five grand challenges in pedestrian and evacuation dynamics. In *5th international pedestrian and evacuation dynamics conference* (pp. 1–11). New York: Springer.

10. Bazjanac, V. (1977). Simulation of elevator performance in high-rise buildings under conditions of emergency. 316–328. PA, USA.

11. Best, R., & Demers, D. (1982). *Investigation report on the MGM Grand Hotel fire, Las Vegas, Nevada*. Boston, MA: National Fire protection Association.

12. Bladström, K. (2017). *Route choice modelling in fire evacuation simulators* (Bachelor's degree thesis, Lund University). Retrieved from http://lup.lub.lu.se/student-papers/record/8903254

13. Boyce, K. E., & Shields, T. J. (1999). Towards the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and up an Incline. *Fire Technology*, *35*, 51–67.

14. Bukowski, R. W. (2007). *Emergency Egress Strategies for Buildings*. Presented at the InterFlam 2007.

15. Butler, K. M., Furman, S. M., Kuligowski, E. D., & Peacock, R. D. (2016). *Perspectives of Occupants with Mobility Impairments on Fire Evacuation and Elevators* (No. NIST TN 1923; p. NIST TN 1923). https://doi.org/10.6028/NIST.TN.1923

16. Capote, J. A., Alvear, D., Abreu, O., Cuesta, A., & Alonso, V. (2012). A Stochastic Approach for Simulating Human Behaviour During Evacuation Process in Passenger Trains. *Fire Technology*, *48*(4), 911–925. https://doi.org/10.1007/s10694-012-0251-3

17. Devito, N. J., French, L., & Goldacre, B. (2018). Trends in Obesity and Severe Obesity Prevalence in US Youth and Adults by Sex and Age, 2007-2008 to 2015-2016. *Journal of the American Medical Association*. Retrieved from https://jamanetwork.com/journals/jama/fullarticle/2676543

18. Dunlop, K. E., Boyce, K. E., & McConnell, N. (1993). Real fire emergency evacuation of disabled people. *CIB W14 International Symposium and Workshops on Engineering Fire Safety in the Process of Design Equivalency*, 157–164. University of Ulster.

19. Francis, J. (2016). To Analyse Evacuation Methods from High-Rise Buildings and Identify Fire and Life Safety Improvements for this Vertical World. The Winston Churchill Memorial Trust of Australia.

20. Galea, E., Gwynne, S., Filippidis, L., & Cooney, D. (2006). *BuildingEXODUS v4.06 User Guide and Technical Manual*. London U.K: University of Greenwich: Fire Safety Engineering Group.

21. Gershon, R. R. M., Magda, L. A., Riley, H. E. M., & Sherman, M. F. (2012). The World Trade Center evacuation study: Factors associated with initiation and length of time for evacuation. *Fire and Materials*, *36*(5–6), 481–500. https://doi.org/10.1002/fam.1080

22. Gwynne, S., & Rosenbaum, E. (2008). Employing the Hydraulic Model in Assessing Emergency Movement. In *SFPE Handbook of Fire Protection Engineering* (Fourth Edition).

23. He, X. Z., & Baker, D. W. (2004). Body Mass Index, Physical Activity, and the Risk of Decline in Overall Health and Physical Functioning in Late Middle Age. *American Journal of Public Health*, *94*(9), 1567–1573. https://doi.org/10.2105/AJPH.94.9.1567

24. Heyes, E. (2009). Human Behaviour Considerations in the Use of Lifts for Evacuation from High Rise Commercial Buildings. University of Canterbury, Christchurch, New Zealand.

25. Huang, L., Chen, T., & Yuan, H. (2014). Simulation Study of Evacuation in High-rise Buildings. *Transportation Research Procedia 2 (2014)*, 518–523. https://doi.org/10.1016/j.trpro.2014.09.069

26. Hue, O., Simoneau, M., Marcotte, J., Berrigan, F., Doré, J., Marceau, P., … Teasdale, N. (2007). Body weight is a strong predictor of postural stability. *Gait & Posture*, *26*(1), 32–38. https://doi.org/10.1016/j.gaitpost.2006.07.005

27. Hui, M. K., & Tse, D. K. (1996). What to Tell Consumers in Waits of Different Lengths: An Integrative Model of Service Evaluation. *Journal of Marketing*, *60*(2), 81–90. https://doi.org/10.2307/1251932

28. IES. (2000). *Simulex Technical Reference; Evacuation Modelling Software*. Integrated Environmental Solutions, Inc. Generic.

29. International Building Code., § 3002.3 (2018).

30. Jönsson, A., & Andersson, J. (2014). Public Risk Perception of Elevator Evacuation in High-Rise Buildings - SFPE. *SFPE Emerging Trends Newsletter*, (87). Retrieved from https://www.sfpe.org/page/FPE_ET_Issue_87/Public-Risk-Perception-of-Elevator-Evacuation-in-High-Rise-Buildings-.htm

31. Jönsson, Andersson, J., & Nilsson, D. (2012). A Risk Perception Analysis of Elevator Evacuation in High-Rise Buildings.

32. Kinateder, M. T., Omori, H., & Kuligowski, E. D. (2014). *The Use of Elevators for Evacuation in Fire Emergencies in International Buildings* (No. NIST TN 1825). https://doi.org/10.6028/NIST.TN.1825

33. Kinsey, M. (2011). *Vertical Transport Evacuation Modelling*. University of Greenwich, Greenwich.

34. Klingsch, W. W. F., Rogsch, C., Schadschneider, A., & Schreckenberg, M. (Eds.). (2009). Stairwell Evacuation from Buildings: What We Know We Don't Know. In R. D. Peacock, J. D. Averill, & E. D. Kuligowski, *Pedestrian and Evacuation Dynamics 2008* (pp. 55–66). https://doi.org/10.1007/978-3-642-04504-2_4

35. Korhonen, T. (2018). *Fire Dynamics Simulator with Evacuation: FDS+Evac*. VTT Technical Research Centre of Finland.

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

37. Kuligowski, E D. (2003). Elevators for Occupant Evacuation and Fire Department Access. *CIB-CTBUH International Conference on Tall Buildings*, 193–200. Malaysia: National Institute of Standards and Technology.

38. Kuligowski, E D, & Mileti, D. S. (2009). Modeling pre-evacuation delay by occupants in World Trade Center Towers 1 and 2 on September 11, 2001. *Fire Safety Journal*, *44*, 487–496.

39. Kuligowski, Erica D. (2009). *The Process of Human Behavior in Fires* (No. NBS TN 1632). https://doi.org/10.6028/NIST.TN.1632

40. Kuligowski, Erica D., & Hoskins, B. L. (2012). Recommendations for Elevator Messaging Strategies | NIST. *Technical Note (NIST TN) - 1730*. Retrieved from https://www.nist.gov/publications/recommendations-elevator-messaging-strategies

41. Lord, J., Meacham, B., Moore, A., Arup, O., Fahy, R., & Park, B. (2005). *GUIDE FOR EVALUATING THE PREDICTIVE CAPABILITIES OF COMPUTER EGRESS MODELS* (No. NIST GCR 06-886; p. 108).

42. McConnell, N., Boyce, K. E., Galea, E. R., Day, R. C., & Hulse, L. M. (2010). The UK 9/11 evacuation study: Analysis of survivors' recognition and response phase in WTC1. *Fire Safety Journal*, *45*, 21–34.

43. Mhurchu, C. N., Turley, M., Stefanogiannis, N., Lawes, C. M., Rodgers, A., Vander Hoorn, S., & Tobias, M. (2005). Mortality attributable to higher-than-optimal body mass index in New Zealand. *Public Health Nutrition*, *8*(04). https://doi.org/10.1079/PHN2004704

44. Mishalani, R., McCord, M., & Wirtz, J. (2006). Passenger Wait Time Perceptions at Bus Stops: Empirical Results and Impact on Evaluating Real - Time Bus Arrival Information. *Journal of Public Transportation*, *9*(2), 89–106. https://doi.org/10.5038/2375-0901.9.2.5

45. National Institute of Standards and Technology. (2009). *Summary of NIST/GSA cooperative research on the use of elevators during fire emergencies* (No. NIST SP 1620). https://doi.org/10.6028/NIST.SP.1620

46. National Institute on Disability, Independent Living, and Rehabilitation Research. (2017). *2017 Disability Statistics Annual Report* (p. 48). USA.

47. Newell, G. F. (1998). Strategies for Serving Peak Elevator Traffic. *Transportation Research Part B: Methodological*, *32*(8), 583–588. https://doi.org/10.1016/S0191-2615(98)00019-8

48. Nilsson, D., & Jönsson, A. (2011). Design of Evacuation Systems for Elevator Evacuation in High-Rise Buildings. *Journal of Disaster Research 6*, 600–609.

49. Noordermeer, R. H. J. (2010). *Usage of Lifts for Evacuation of High-rise Projects* (PhD Dissertation). Delft University.

50. Peacock, R. (2010). A Review of Building Evacuation Models: 2nd Edition. 36.

51. Pigg, L. (2013). Elevators in Emergencies: The Firefighter's Perspective. 20.

52. Proulx, G. (2001). High-rise evacuation: a questionable concept. *International Symposium on Human Behaviour in Fire*, 221–230. Retrieved from https://nrc-publications.canada.ca/eng/view/accepted/?id=2e386f19-f574-4487-9f3e-076ed6a38d17

53. Proulx, G., & Koroluk, W. (1997). *Fires Mean People Need Fast, Accurate Information* (No. NRCC-41088; pp. 17–19). Canada.

54. Ronchi, E., & Kinsey, M. (2011). Evacuation models of the future: Insights from an online survey on user's experiences and needs. *Proceedings of the Advanced Research Workshop: "Evacuation and Human Behaviour in Emergency Situations,"* 144–155. Santander, Spain.

55. Ronchi, E., & Nilsson, D. (2012). Fire Evacuation in High-rise Buildings: A Review of Human Behaviour and Modelling Research, *Fire Science Reviews*.

56. Ronchi, E., & Nilsson, D. (2014). Modelling total evacuation strategies for high-rise buildings. *Building Simulation*, *7*(1), 73–87. https://doi.org/10.1007/s12273-013-0132-9

57. Ronchi, E., Nilsson, D., & Gwynne, S. M. V. (2012). Modelling the Impact of Emergency Exit Signs in Tunnels. *Fire Technology*, *48*(4), 961–988. https://doi.org/10.1007/s10694-012-0256-y

58. Ronchi, E., Reneke, P. A., & Peacock, R. D. (2014). A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling. *Fire Technology*, *50*(6), 1545–1571. https://doi.org/10.1007/s10694-013-0352-7

59. SFPE. (2003). Engineering Guide to Human Behavior in Fire.

60. Shabo, J., & Schröder, W. (2015). *The Efficiency of Double-Decked Elevators*. 39.

61. Sherman, M. F., Peyrot, M., Magda, L. A., & Gershon, R. R. M. (2011). Modeling pre-evacuation delay by evacuees in World Trade Center Towers 1 and 2 on September 11, 2001: A revisit using regression analysis. *Fire Safety Journal*, *46*, 414–424.

62. Shields, T. J., Boyce, K. E., & McConnell, N. (2009). The behaviour and evacuation experiences of WTC 9/11 evacuees with self-designated mobility impairments. *Fire Safety Journal*, *44*(6), 881–893. https://doi.org/10.1016/j.firesaf.2009.04.004

63. Sime, J. D. (1985). Movement toward the Familiar: Person and Place Affiliation in a Fire Entrapment Setting (pp. 697–724).

64. Spearpoint, M., & Maclennan, H. (2012). The effect of an ageing and less fit population on the ability of people to egress buildings. *Safety Science*. Retrieved from https://www.researchgate.net/publication/256659506

65. Starkosch, G. R., & Caporale, R. S. (2010). *The Vertical Transportation Handbook*. Hoboken, NJ, USA: John Wiley & Sons.

66. Strang, T., & Bauer, C. (2007). Context-Aware Elevator Scheduling. *21st International Conference on Advanced Information Networking and Applications Workshops (AINAW'07)*, *2*, 276–281. https://doi.org/10.1109/AINAW.2007.131

67. Thornton, C., O'Konski, R., Klein, B., & Swenson, D. (2013). New Wayfinding Techniques in Pathfinder and Supporting Research. In *Pedestrian and Evacuation Dynamics 2012* (pp. 1315–1322). Retrieved from https://doi.org/10.1007/978-3-319-02447-9_108

68. Thunderhead Engineering. (2016). *Pathfinder User Manual*. Manhattan, USA.

69. Waterson, N., & Pellissier, E. (2010). *The STEPS Pedestrian Micorsimulation Tool - A Technical Summary*. Corydon, UK: Mott MacDonald Limited.

70. Weistmantle, P., Smith, G., & Sheriff, M. (2007). Burj Dubai: An architectural technical design case study. Structural Design of Tall and Special Buildings 16, 335–360.

71. Wong, K., Hui, M., Guo, D., & Luo, M. (2005). A Refined Concept on Emergency Evacuation by Lifts. *Fire Safety Science*, *8*, 599–610. https://doi.org/10.3801/IAFSS.FSS.8-599

72. Yu, J., Song, K., & Cho, D. (2017). Resolving Stack Effect Problems in a High-Rise Office Building by Mechanical Pressurization. *Sustainability*, *9*(10), 1731. https://doi.org/10.3390/su9101731

12. Appendices

This section consists of tables showing percentage of elevator and stair usage per floor, Error percentage of the standard deviation for the different scenarios, error of Standard Deviation (%) for each scenario run, and table indicating the evacuation time required for stairs and elevators for each scenario.

Following table shows the distribution of the occupants using stairs and elevators, based on the average value of the correlation provided by Heyes (2009) and Jönsson et al. (2012)

Table 9: Tabulated output of the correlations by Heyes (2009), Jönsson et al. (2012) and the average of the two for percentage of elevator usage per floor

Floor level	**Heyes (2009)**	**Jonsson et al.** (2012)	**Average Elevator Usage**	**Average Stair usage**
0	5.3	1.05	5.0	95.0
1	6.44	1.89	5.0	95.0
2	7.58	2.73	5.0	95.0
3	8.72	3.57	5.0	95.0
4	9.86	4.41	5.0	95.0
5	11	5.25	5.0	95.0
6	12.14	6.09	9.1	90.9
7	13.28	6.93	10.1	89.9
8	14.42	7.77	11.1	88.9
9	15.56	8.61	12.1	87.9
10	16.7	9.45	13.1	86.9
11	17.84	10.29	14.1	85.9
12	18.98	11.13	15.1	84.9
13	20.12	11.97	16.0	84.0
14	21.26	12.81	17.0	83.0
15	22.4	13.65	18.0	82.0
16	23.54	14.49	19.0	81.0
17	24.68	15.33	20.0	80.0
18	25.82	16.17	21.0	79.0
19*	~~26.96~~	~~17.01~~	~~22.0~~	~~78.0~~
20	28.1	17.85	23.0	77.0
21	29.24	18.69	24.0	76.0
22	30.38	19.53	25.0	75.0
23	31.52	20.37	25.9	74.1
24	32.66	21.21	26.9	73.1
25	33.8	22.05	27.9	72.1
26	34.94	22.89	28.9	71.1
27	36.08	23.73	29.9	70.1
28	37.22	24.57	30.9	69.1
29	38.36	25.41	31.9	68.1

30	39.5	26.25	32.9	67.1
31	40.64	27.09	33.9	66.1
32	41.78	27.93	34.9	65.1
33	42.92	28.77	35.8	64.2
34	44.06	29.61	36.8	63.2
35	45.2	30.45	37.8	62.2
36	46.34	31.29	38.8	61.2
37	47.48	32.13	39.8	60.2

*Level 19 is used only as a transfer floor

Total Evacuation time for each scenario in ascending order:

Table 10: Ascending order of Total Evacuation Times among the scenarios modelled in Pathfinder

Case Description	Evacuation time (s)	Evacuation time (minutes)
Scenario 1_ Indefinite waiting time	4929	82
Scenario 4_ Increased elevator usage	5028	83
Scenario 5_900s	5499	91
Scenario 2_20 OEEs	5676	94
Base Scenario	5680	94
Scenario 3_30 OEEs	5687	94
Scenario 6_Only OEEs	6666	111

Table 11: Error % of the standard deviation for all the runs in each scenario

Run	Base scenario Error %	Scenario 1 Error %	Scenario 2 Error %	Scenario 3 Error %	Scenario 4 Error %	Scenario 5 Error %	Scenario 6 Error %
Run 1							
Run 2	0.06614	0.37115	0.18559	0.44428	0.48430	0.19086	0.16070
Run 3	0.05876	0.26805	0.11096	0.37412	0.23112	0.12273	0.14881
Run 4	0.05355	0.24461	0.10155	0.28283	0.20363	0.10407	0.11202
Run 5	0.04879	0.14609	0.08100	0.25598	0.19782	0.09017	0.10604
Run 6	0.04707	0.11986	0.07169	0.15422	0.12008	0.07429	0.08512
Run 7	0.04100	0.10878	0.06060	0.12287	0.10320	0.07163	0.07755
Run 8	0.03514	0.09769	0.05923	0.09936	0.08435	0.07057	0.06647
Run 9	0.00000	0.08721	0.05884	0.08414	0.07267	0.06119	0.00000
Run 10	0.00000	0.07826	0.04908	0.07133	0.07032	0.05818	0.00000

Base Scenario:

Table 12: Output for the Convergence run in the Base Scenario

Base Scenario			
Run No.	**Evacuation time (s)**	**Standard Deviation**	**Error %**
Run 1	5700		
Run 2	5700	0.00265	0.00066
Run 3	5700	0.00353	0.00059
Run 4	5670	0.00535	0.00054
Run 5	5700	0.00342	0.00049
Run 6	5655	0.00235	0.00047
Run 7	5670	0.00328	0.00041
Run 8	5700	0.00316	0.00035
Run 9	5700	0	0
Run 10	5610	0	0

Average time taken for evacuation by stairs was 5680s and average time taken for evacuation by elevator users was 2048s.

Table 13: Base Scenario_Stair vs Elevator Evacuation time

Base Scenario	Elevator Evacuation (s)	Cum Avg	Stairs (s)
Run 1	1981		5700
Run 2	2013	1997	5700
Run 3	2100	2031	5700
Run 4	2091	2046	5670
Run 5	2086	2054	5700
Run 6	2088	2060	5655
Run 7	2103	2066	5670
Run 8	2071	2067	5700
Run 9	1924	2051	5700
Run 10	2026	2048	5610
Average	**2048**		**5680**

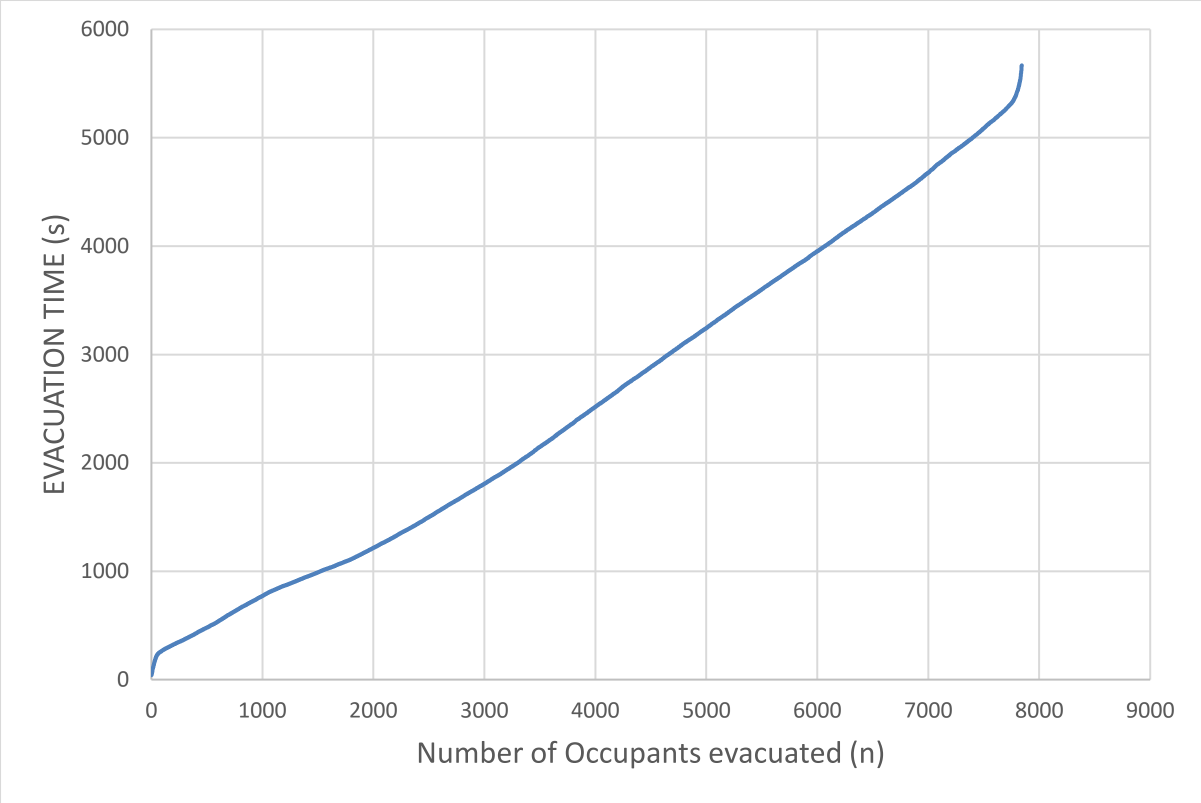

Figure 10: Average Evacuation time of all the runs for Base Scenario

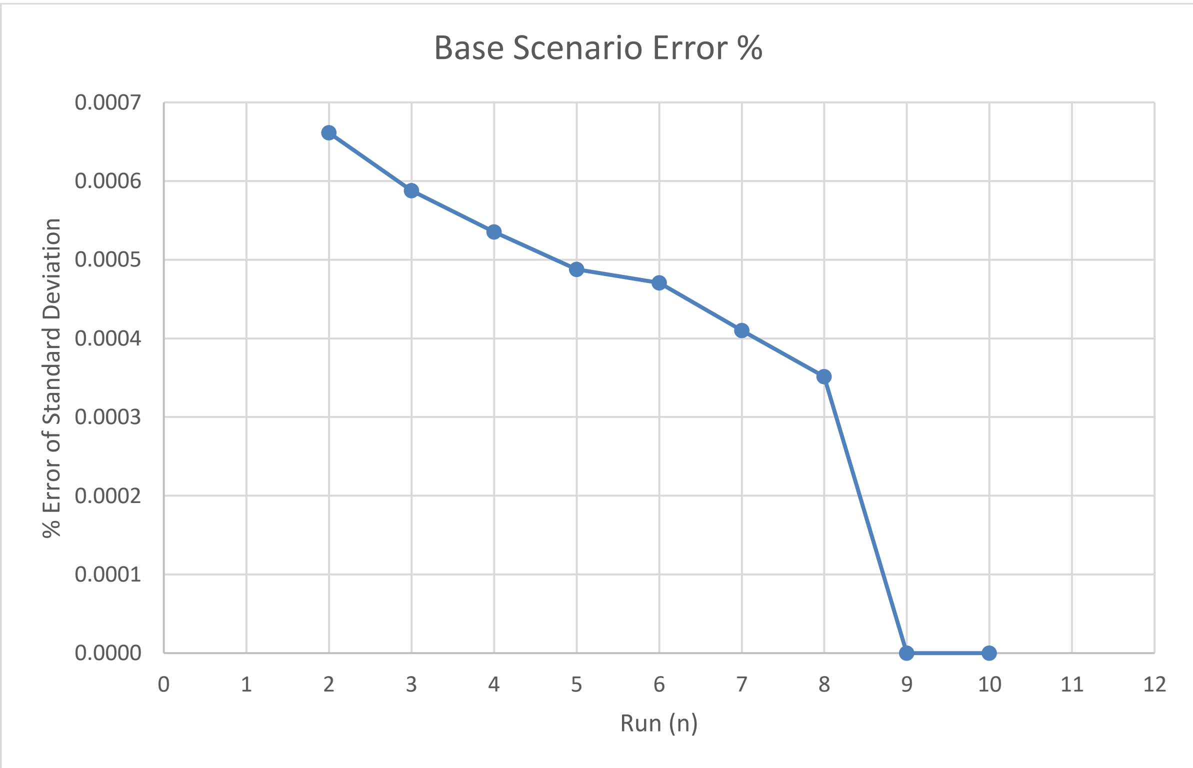

Figure 11: Error of standard deviation (%) against number of runs (n) for Base scenario

Scenario 1_Indefinite waiting time:

Table 14: Output for the Convergence run in Scenario 1

Scenario 1_Indefinite waiting			
	Evacuation time (s)	Std Dev	Error %
Run 1	4860		
Run 2	4875	0.01113	0.00371
Run 3	4935	0.00804	0.00268
Run 4	4980	0.00978	0.00245
Run 5	4920	0.00877	0.00146
Run 6	4920	0.00839	0.0012
Run 7	4950	0.00218	0.00109
Run 8	4920	0.00782	0.00098
Run 9	4965	0.00785	0.00087
Run 10	4965	0.00783	0.00078

Average time taken for evacuation by stairs was 4929 s and average time taken for evacuation by elevator users was 2795 s.

Table 15: Scenario 1_ Stair vs Elevator Evacuation time

Scenario 1	**Elevator Evacuation**	**Cum Avg**	**Stairs**
Run 1	2805		4860
Run 2	2760	2783	4875
Run 3	2852	2806	4935
Run 4	2790	2802	4980
Run 5	2820	2805	4920
Run 6	2852	2813	4920
Run 7	2775	2808	4950
Run 8	2835	2811	4920
Run 9	2714	2800	4965
Run 10	2747	2795	4965
Average	**2795**		**4929**

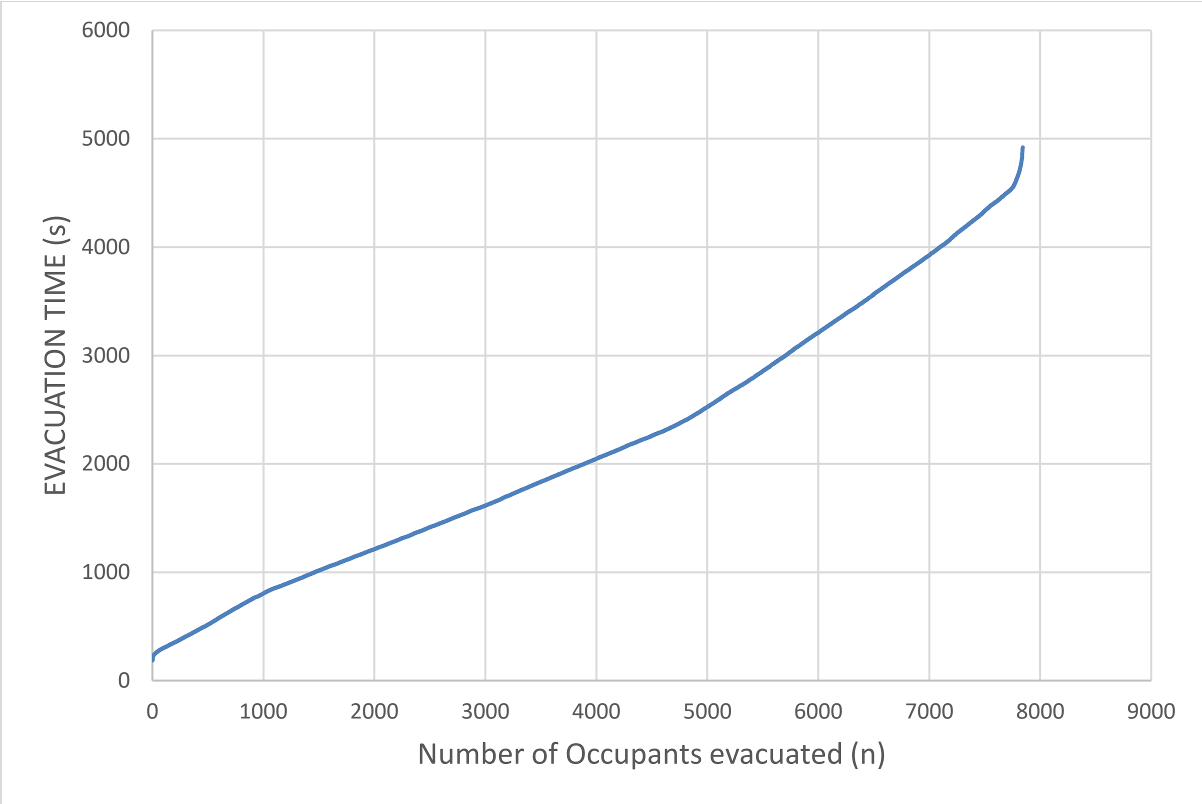

Figure 12: Average Evacuation time of all the runs for Scenario 1

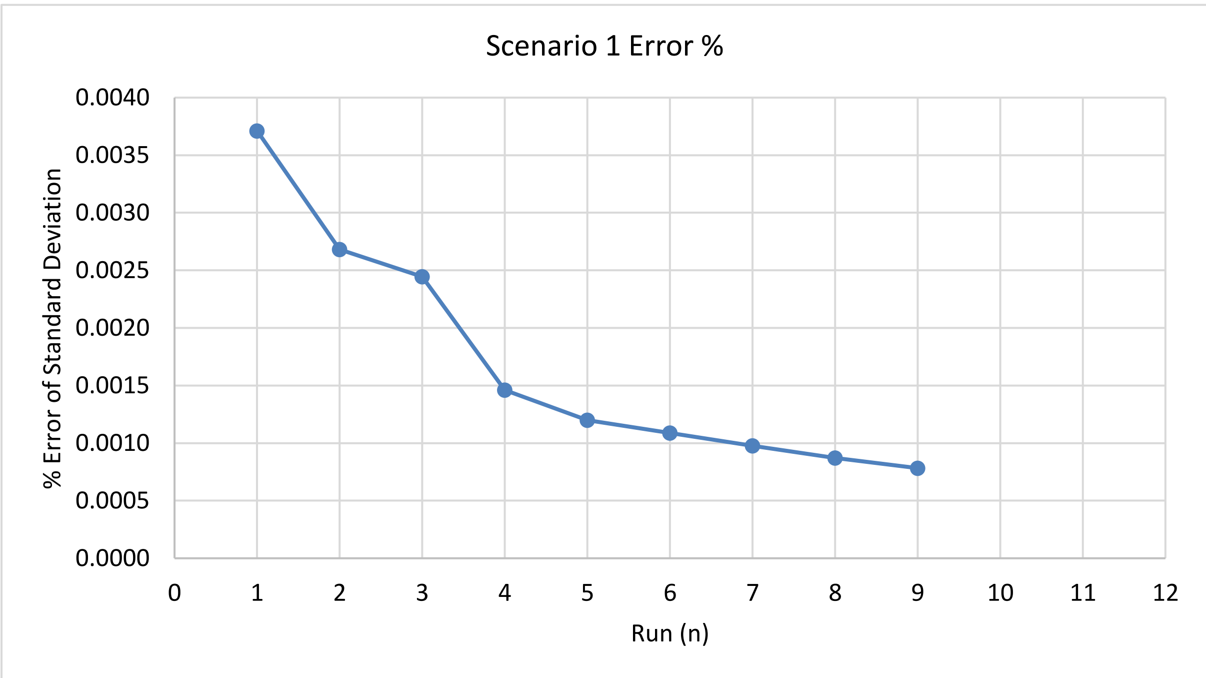

Figure 13: Error of standard deviation (%) against number of runs (n) for Scenario 1

Scenario 2_20 OEEs:

Table 16:Output for the Convergence run in Scenario 2

Scenario 2_20 OEEs			
	Evacuation time (s)	Std Dev	Error %
Run 1	5685		
Run 2	5715	0.00371	0.00186
Run 3	5685	0.00305	0.00111
Run 4	5670	0.00333	0.00102
Run 5	5670	0.00324	0.00081
Run 6	5730	0.00430	0.00072
Run 7	5670	0.00424	0.00061
Run 8	5685	0.00393	0.00059
Run 9	5625	0.00530	0.00059
Run 10	5625	0.00592	0.00049

Average time taken for evacuation by stairs was 5676s and average time taken for evacuation by elevator users was 2236s.

Table 17: Scenario 2_ Stair vs Elevator Evacuation time

Scenario 2	**Elevator Evacuation**	**Cum Avg**	**Stairs**
Run 1	2087		5685
Run 2	2205	2146	5715
Run 3	2265	2186	5685
Run 4	2175	2183	5670
Run 5	2234	2193	5670
Run 6	2280	2208	5730
Run	2358	2229	5670
Run 8	2230	2229	5685
Run 9	2298	2237	5625
Run 10	2234	2237	5625
Average	**2237**		**5676**

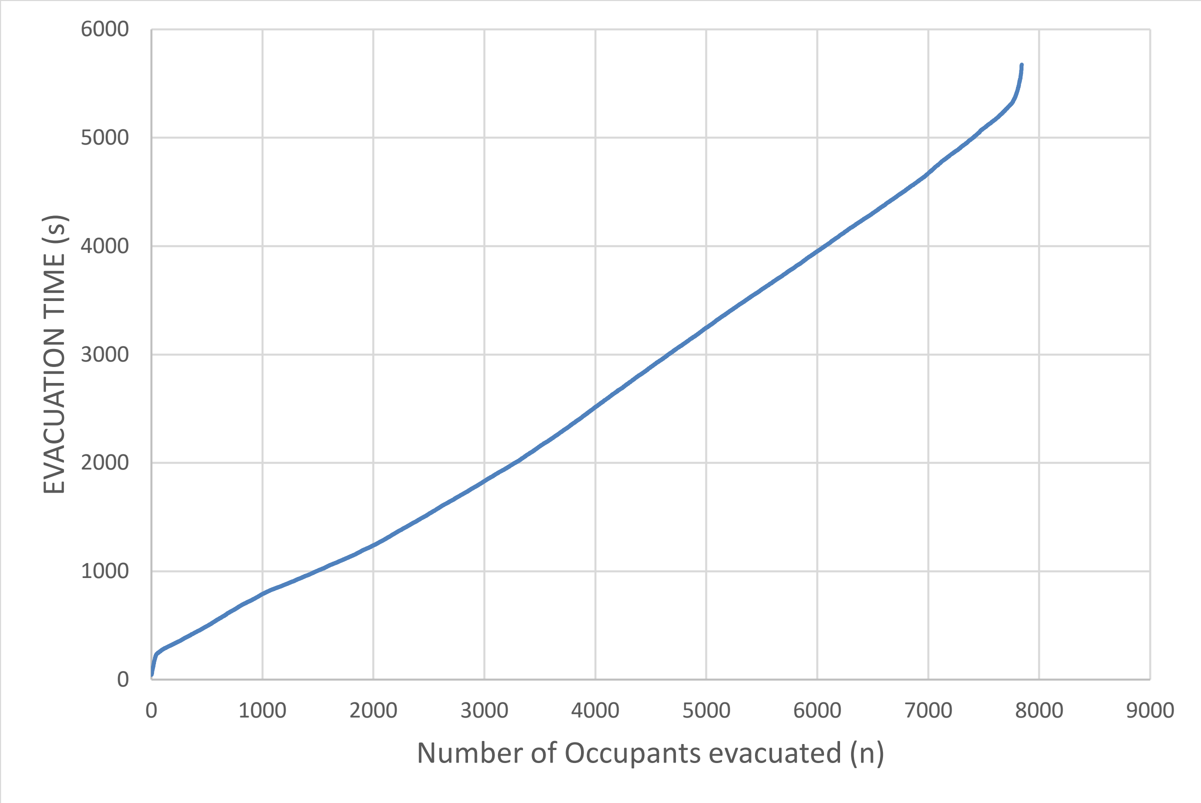

Figure 14: Average Evacuation time of all the runs for Scenario 2

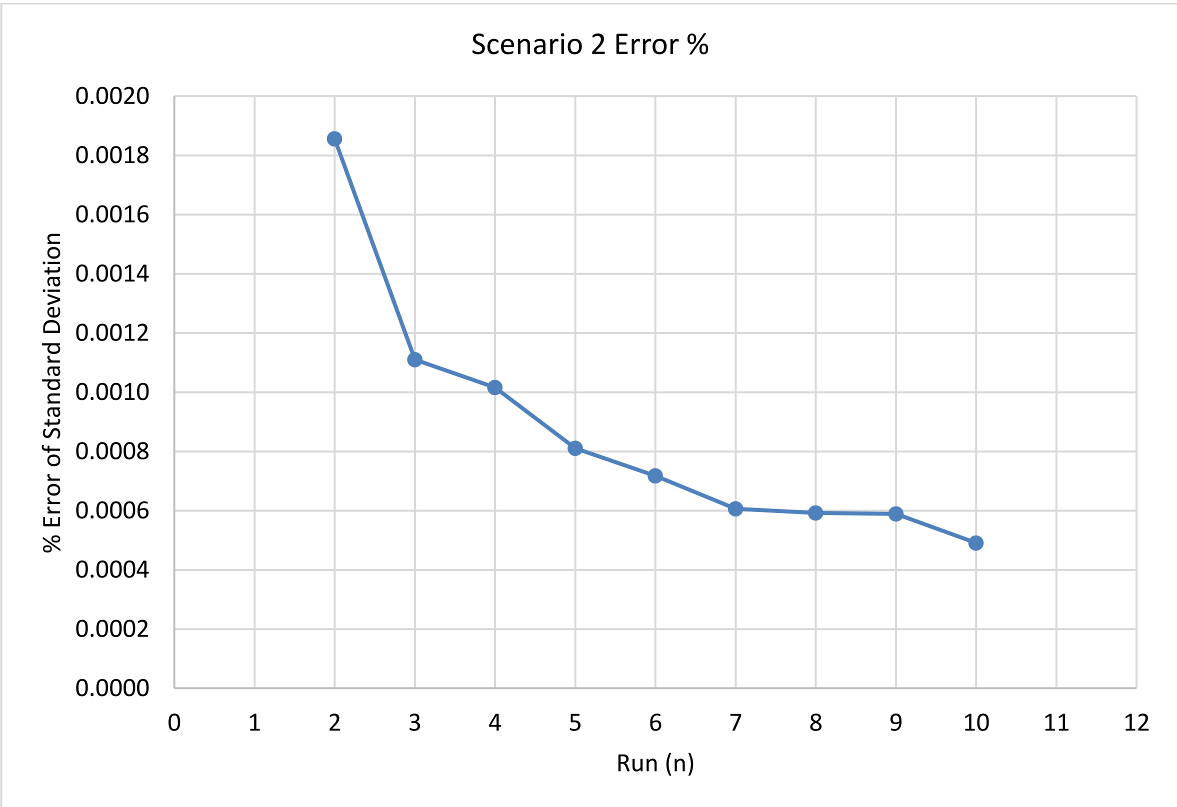

Figure 15: Error of standard deviation (%) against number of runs (n) for Scenario 2

Scenario 3_30 OEEs:

Table 18: Output for the Convergence run in Scenario 3

Scenario 3_30 OEEs			
	Evacuation time (s)	Std Dev	Error %
Run 1	5670		
Run 2	5625	0.00566	0.00444
Run 3	5775	0.01333	0.00374
Run 4	5670	0.01122	0.00283
Run 5	5730	0.01024	0.00256
Run 6	5685	0.00925	0.00154
Run 7	5670	0.00860	0.00123
Run 8	5700	0.00795	0.00099
Run 9	5670	0.00757	0.00084
Run 10	5682	0.00713	0.00071

Average time taken for evacuation by stairs was 5687s and average time taken for evacuation by elevator users was 2081s.

Table 19: Scenario 2_ Stair vs Elevator Evacuation time

Scenario 3	**Elevator Evacuation**	**Cum Avg**	**Stairs**
Run 1	2003		5670
Run 2	2191	2097	5625
Run 3	1936	2043	5775
Run 4	2205	2084	5670
Run 5	2056	2078	5730
Run 6	2073	2077	5685
Run 7	2085	2078	5670
Run 8	2170	2090	5700
Run 9	2080	2089	5670
Run 10	2011	2081	5682
Average	**2081**		**5687**

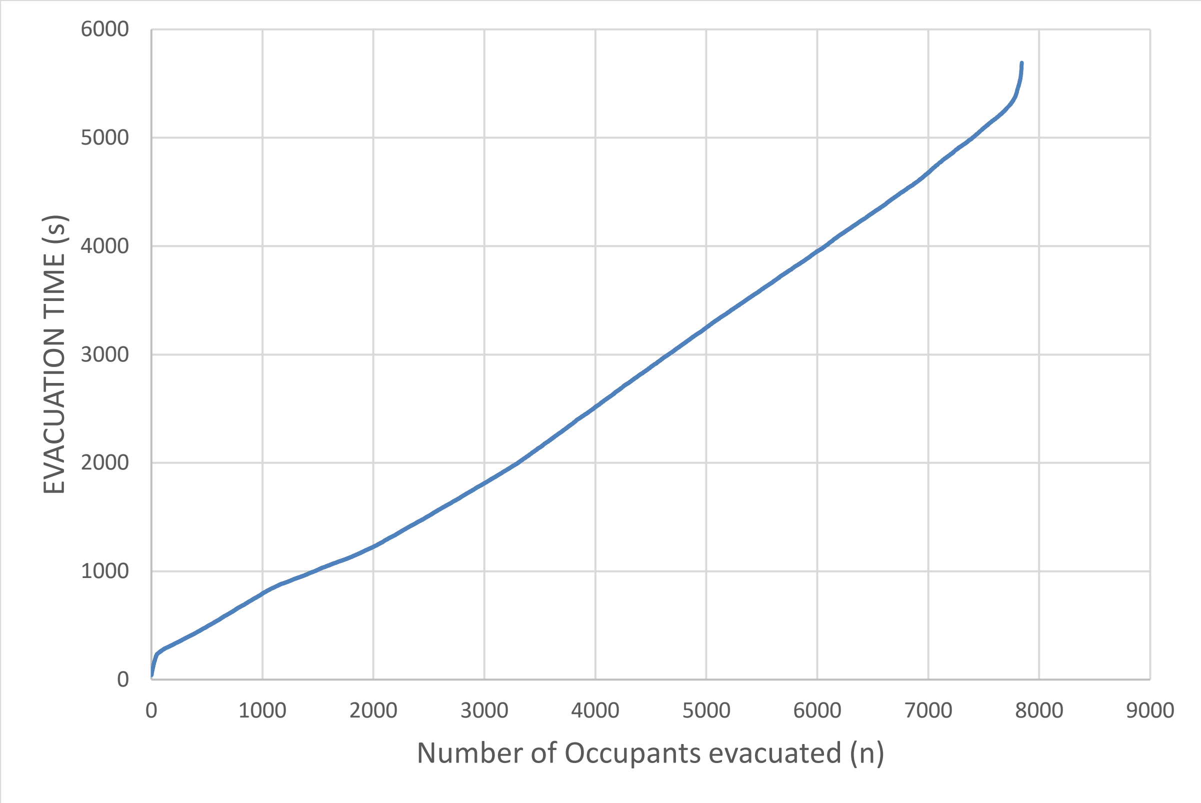

Figure 16: Average Evacuation time of all the runs for Case 3

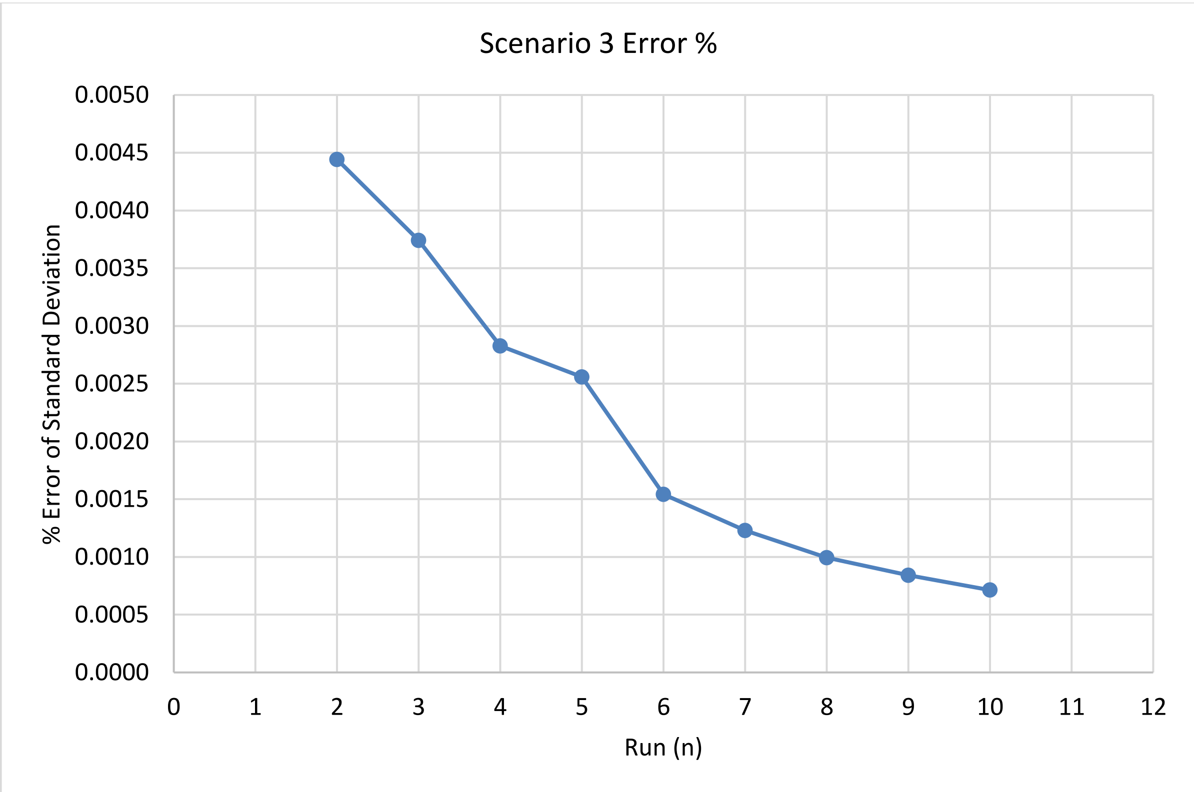

Figure 17: Error of standard deviation (%) against number of runs (n) for Scenario 3

Scenario 4_10% Increased elevator usage:

Table 20: Output for the Convergence run in Scenario 4

Scenario 4_10% Increased elevator usage			
	Evacuation time (s)	Std Dev	Error %
Run 1	5400		
Run 2	5475	0.00969	0.00484
Run 3	5445	0.00693	0.00231
Run 4	5460	0.00593	0.00204
Run 5	5370	0.00815	0.00198
Run 6	5430	0.00720	0.00120
Run 7	5475	0.00722	0.00103
Run 8	5445	0.00675	0.00084
Run 9	5445	0.00633	0.00073
Run 10	5370	0.00727	0.00070

Average time taken for evacuation by stairs was 5432s and average time taken for evacuation by elevator users was 2863s.

Table 21: Scenario 4_ Stair vs Elevator Evacuation time

Scenario 4	**Elevator Evacuation**	**Cum Avg**	**Stairs**
Run 1	2971		5400
Run 2	2760	2866	5475
Run 3	2865	2866	5445
Run 4	2880	2869	5460
Run 5	2820	2859	5370
Run 6	2808	2851	5430
Run 7	2880	2855	5475
Run 8	2925	2864	5445
Run 9	2880	2866	5445
Run 10	2835	2863	5370
Average	**2863**		**5432**

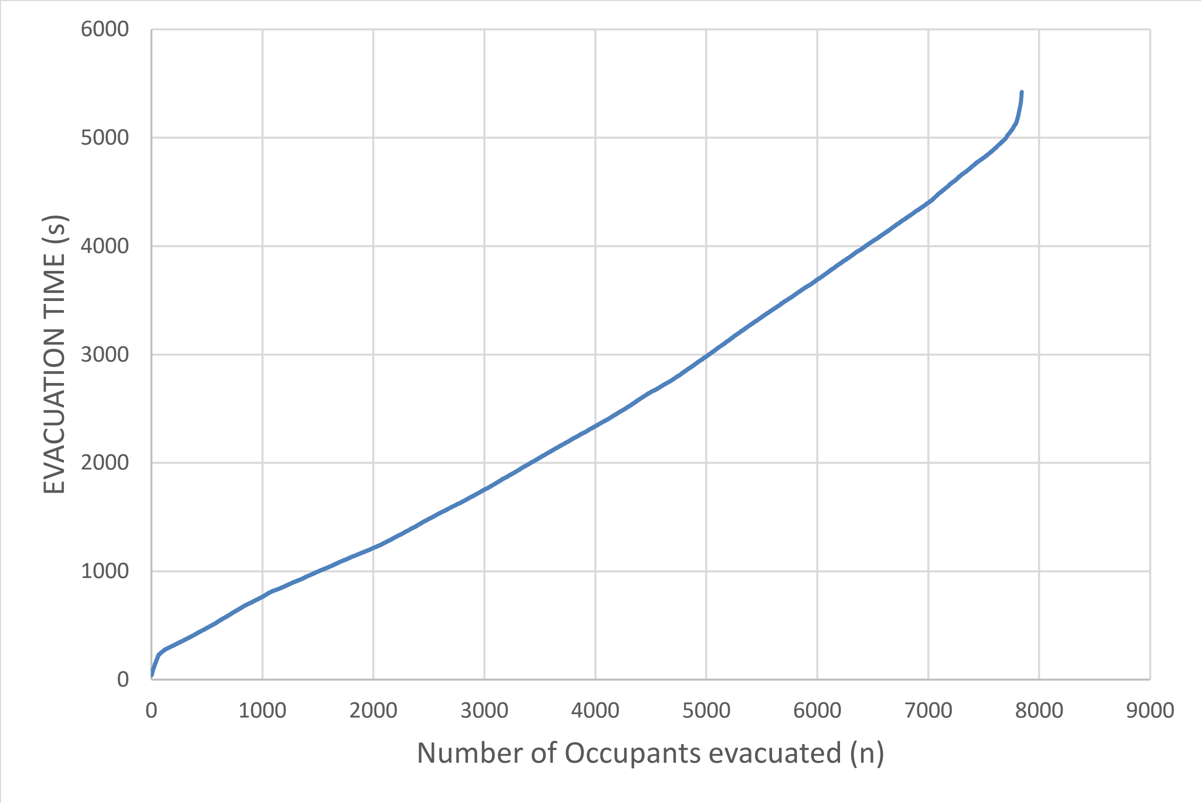

Figure 18: Average Evacuation time of all the runs for Scenario 4

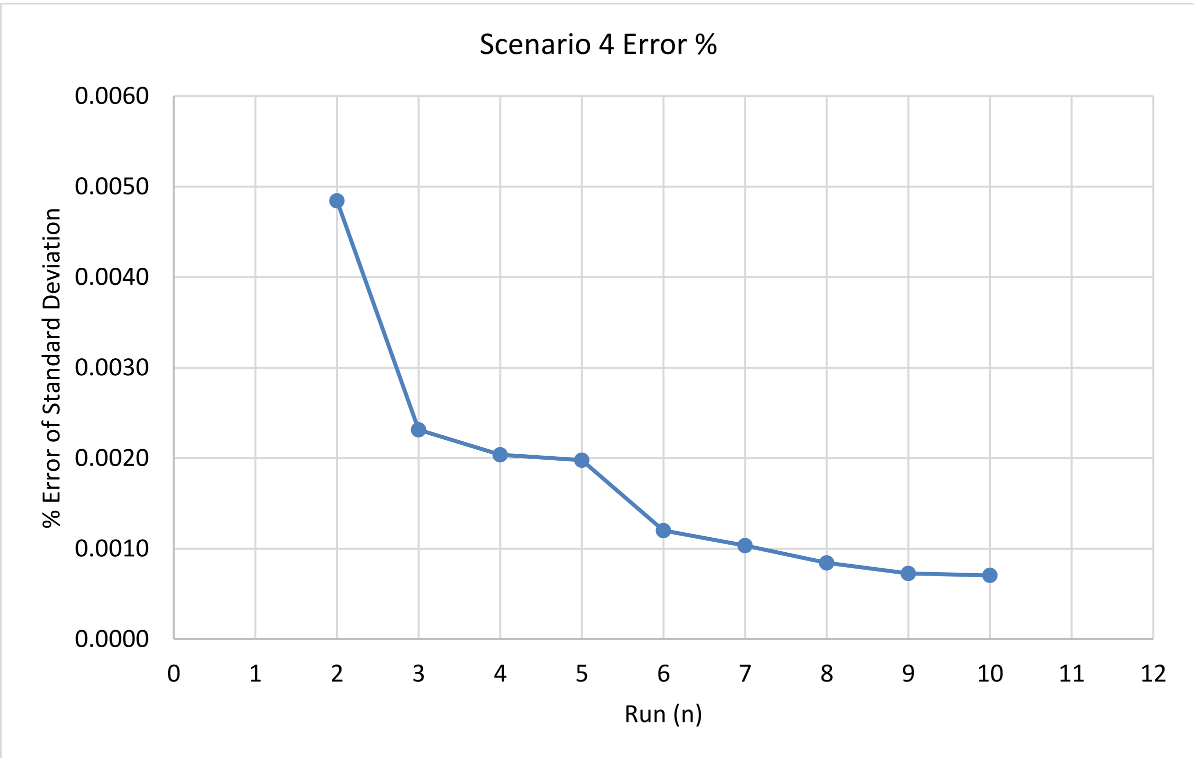

Figure 19: Error of standard deviation (%) against number of runs (n) for Scenario 4

Scenario 5_900 seconds waiting time:

Table 22: Output for the Convergence run in Scenario

Scenario 5_900s			
	Evacuation time (s)	Std Dev	Error %
Run 1	5490		
Run 2	5520	0.00382	0.00191
Run 3	5520	0.00312	0.00123
Run 4	5520	0.00271	0.00104
Run 5	5460	0.00491	0.00090
Run 6	5490	0.00446	0.00074
Run 7	5460	0.00494	0.00072
Run 8	5550	0.00573	0.00071
Run 9	5520	0.00551	0.00061
Run 10	5460	0.00582	0.00058

Average time taken for evacuation by stairs was 5499s and average time taken for evacuation by elevator users was 2160s.

Table 23: Scenario 5_ Stair vs Elevator Evacuation time

Scenario 5	**Elevator Evacuation**	**Cum Avg**	**Stairs**
Run 1	2100		5490
Run 2	2220	2160	5520
Run 3	2130	2150	5520
Run 4	2190	2160	5520
Run 5	2250	2178	5460
Run 6	2100	2165	5490
Run 7	2155	2164	5460
Run 8	2160	2163	5550
Run 9	2160	2163	5520
Run 10	2130	2160	5460
Average	**2160**		**5499**

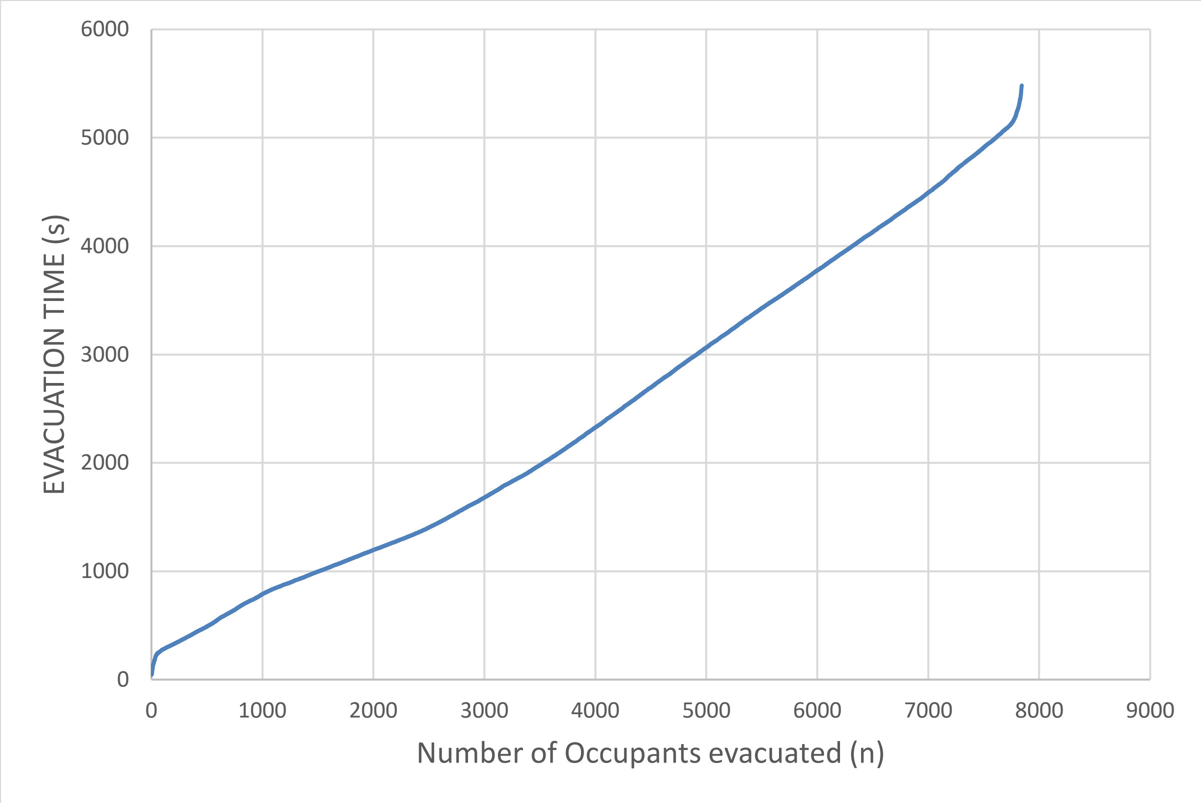

Figure 20: Average Evacuation time of all the runs for Scenario 5

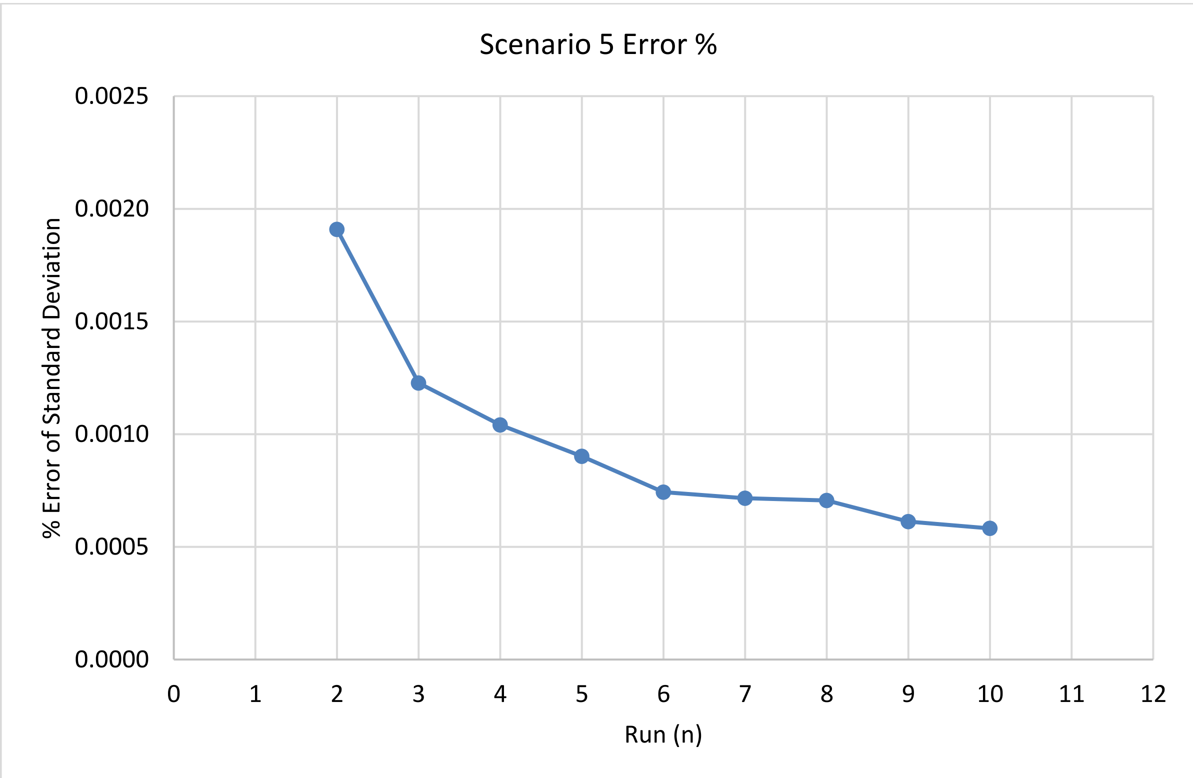

Figure 21: Error of standard deviation (%) against number of runs (n) for Scenario 5

Scenario 6_Only OEEs:

Table 24: Output for the Convergence run in Scenario 6

Scenario 6_Only OEEs			
	Evacuation time (s)	Std Dev	Error %
Run 1	6660		
Run 2	6660	0.00000	0.00000
Run 3	6660	0.00000	0.00000
Run 4	6720	0.00446	0.00149
Run 5	6600	0.00643	0.00161
Run 6	6720	0.00672	0.00112
Run 7	6600	0.00742	0.00106
Run 8	6660	0.00681	0.00085
Run 9	6720	0.00698	0.00078
Run 10	6660	0.00665	0.00066

Average time taken for evacuation by elevator users was 6666s.

Table 25: Scenario 6_ Stair vs Elevator Evacuation time

Scenario 6	**Elevator Evacuation**	**Cum Avg**	**Stairs**
Run 1	6660		-
Run 2	6660	6660	-
Run 3	6660	6660	-
Run 4	6720	6675	-
Run 5	6600	6660	-
Run 6	6720	6670	-
Run 7	6600	6660	-
Run 8	6660	6660	-
Run 9	6720	6667	-
Run 10	6660	6666	-
Average	**6666**		

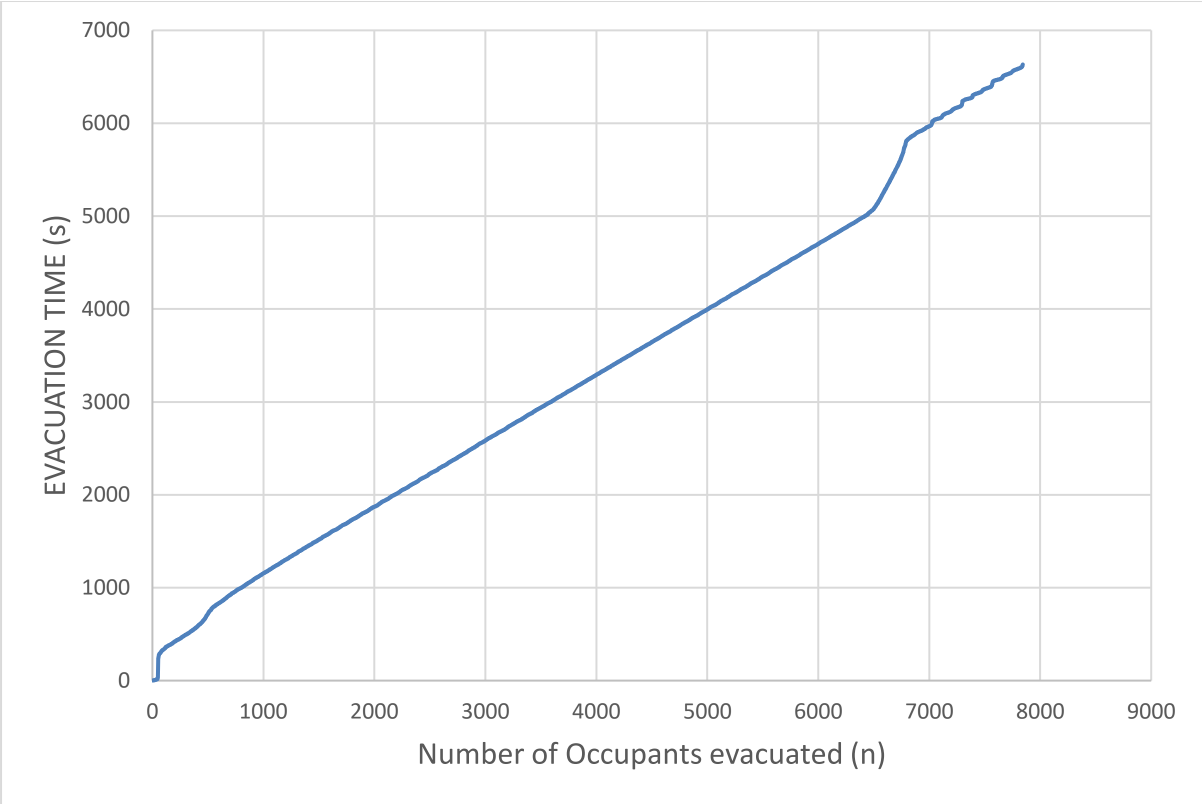

Figure 22: Average Evacuation time of all the runs for Scenario 6

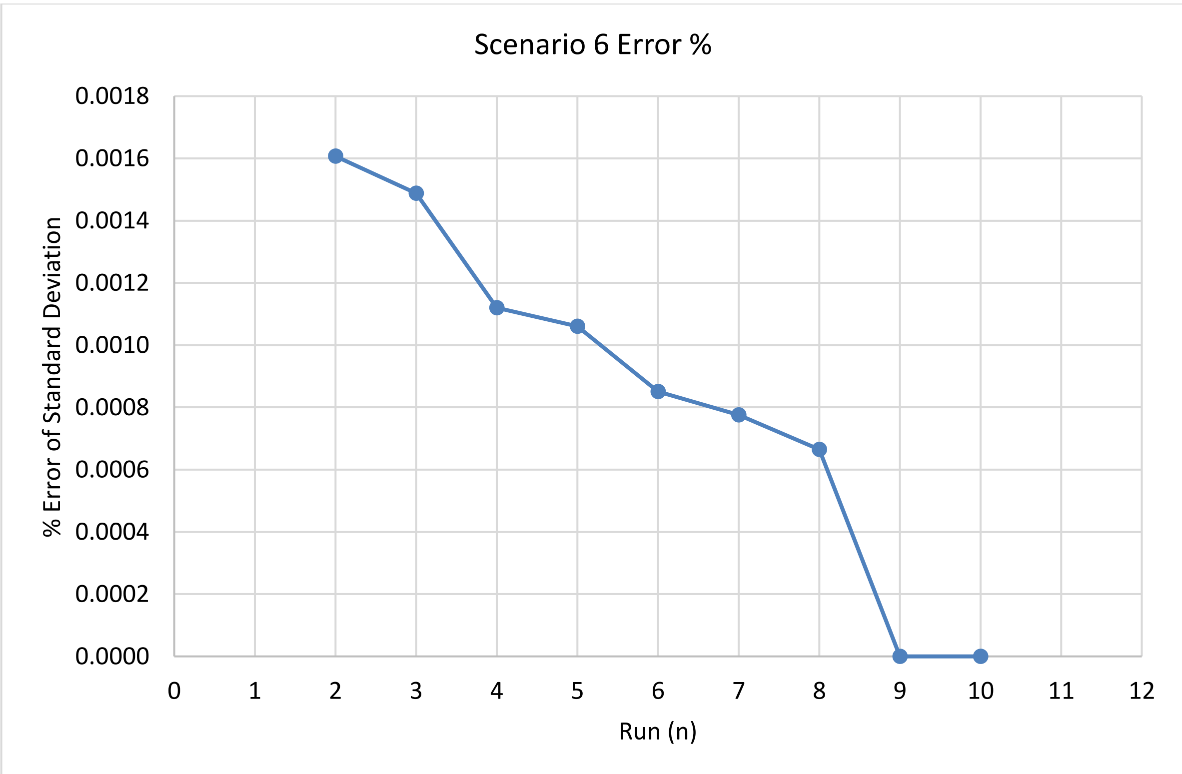

Figure 23: Error of standard deviation (%) against number of runs (n) for Scenario 6