

**EFFICIENT EVACUATION OF TALL BUILDINGS IN FIRES USING LIFTS**

**A thesis submitted to the University of Manchester for the degree of Master of  
Philosophy in the Faculty of Engineering and Physical Sciences.**

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## CONTENTS

1.0	CHAPTER 1 - INTRODUCTION .....	15
1.1	Code Compliant Means of Escape.....	15
1.2	Use of Lifts for Evacuation .....	17
1.3	Research Objectives .....	19
1.4	Theoretical Building .....	20
1.5	Thesis Layout.....	21
2.0	CHAPTER 2 - LITERATURE REVIEW.....	23
2.1	Impact of the World Trade Centre Attacks (2001).....	23
2.2	Evacuation of Disabled Persons .....	24
2.3	Existing Lift Evacuation Systems .....	26
2.3.1	Eureka Place Tower, Melbourne.....	26
2.3.2	Stratosphere Tower, Las Vegas.....	26
2.3.3	Petronas Twin Towers, Kuala Lumpur .....	28
2.3.4	Summary .....	30
2.4	Concern of the Use of Lifts for the Evacuation of Building Occupants..	30
2.5	Protection of Refuge Area's.....	32
2.5.1	Fire Resisting Construction .....	33
2.5.2	Ventilation.....	33
2.5.3	Provision of Refuges.....	34
2.5.4	Summary .....	35
2.6	Lift Technology.....	35
2.6.1	Lift Controls.....	36
2.6.2	Lift Speeds.....	38
2.6.3	Lift Acceleration .....	39
2.6.4	Multiple Deck Lifts .....	39
2.6.5	Summary of Lift Performance Values .....	41
2.7	Occupant Behaviour.....	42
2.7.1	Escape via Entry Route.....	42
2.7.2	Waiting Times .....	43
2.7.3	Panic Behaviour.....	44
2.7.4	Summary of Information.....	45
2.8	Summary .....	46
3.0	CHAPTER 3 - METHODS OF ANALYSIS .....	47
3.1	Introduction.....	47
3.2	Calculation of Evacuation Time Using Stairs .....	47

3.2.1	Method detailed by Nelson and Mowrer .....	49
3.2.2	Method by Pauls .....	50
3.2.3	Method Based on Approved Document B .....	52
3.2.4	STEPS Assessment of Stair Conditions .....	53
3.2.5	Occupant Fatigue .....	55
3.2.6	Summary .....	57
3.3	Calculation of Evacuation Time Using Lifts .....	58
3.3.1	Introduction .....	58
3.3.2	Calculation Developed By Siikonen.....	59
3.3.3	Calculation Procedure Developed By Japanese Researchers .....	61
3.3.4	STEPS.....	66
3.3.5	ELVAC .....	70
3.3.6	ELEVATE .....	84
3.4	Summary of Methods of Analysis .....	85
4.0	CHAPTER 4 - PREVIOUS SIMULATIONS .....	87
4.1	Bazjanac V. (1977) .....	87
4.1.1	Summary of Study.....	87
4.1.2	Summary .....	88
4.2	Pauls (1977) .....	89
4.2.1	Summary of study .....	90
4.2.2	Results of Simulation .....	91
4.2.3	Summary .....	92
4.3	Siikonen (2003) .....	93
4.3.1	Summary of Comparative Assessment .....	93
4.3.2	Summary of Studies .....	95
4.3.3	Summary .....	97
4.4	Wong et al (2005) .....	98
4.4.1	Summary of Study.....	98
4.4.2	Results of Simulations.....	98
4.4.3	Summary .....	101
4.5	BRE Research .....	102
4.5.1	Introduction .....	102
4.5.2	Summary of Study.....	103
4.6	Summary .....	105
5.0	CHAPTER 5 - CALCULATION VARIABLES .....	106
5.1	Introduction.....	106

5.2	Lift Specification .....	106
5.2.1	Lift Speed .....	106
5.2.2	Lift Acceleration .....	107
5.2.3	Door Opening and Closing Time .....	107
5.2.4	Lift Car Capacity .....	107
5.3	ELVAC Inefficiencies.....	107
5.4	STEPS Variables .....	108
5.4.1	Dwell Time .....	109
5.4.2	Motor Delay .....	109
5.4.3	Summary .....	109
5.5	Refuge Floor Location.....	110
5.6	Stair/Lift Evacuation Ratio .....	110
5.7	Occupancies .....	111
5.8	Summary .....	112
6.0	CHAPTER 6 - STEPS MODELLING .....	114
6.1	Introduction.....	114
6.2	Sensitivity Study .....	114
6.2.1	Cell Grid Size.....	115
6.2.2	Walking Speed.....	117
6.2.3	Patience.....	118
6.2.4	Summary .....	121
6.3	Results.....	121
6.3.1	Comparison of Phased and Simultaneous Evacuation.....	122
6.3.2	Space per Person.....	123
6.3.3	Number of Occupants Evacuated .....	124
6.3.4	Stair Flow Rate .....	126
6.3.5	Lift Waiting Times .....	128
6.3.6	Effects of Reduced Occupancy .....	128
6.3.7	Summary .....	129
7.0	CHAPTER 7 - ANALYSIS OF RESULTS.....	130
7.1	Code Compliant Evacuation .....	130
7.2	Evacuation via Lifts Only .....	132
7.2.1	Refuge Floor.....	132
7.2.2	Evacuation Zone.....	136
7.3	Evacuation via Stairs and Lifts (75% Lift Usage).....	142
7.3.1	Introduction .....	142

7.3.2	Refuge Floor .....	143
7.3.3	Evacuation Zone.....	146
7.4	Evacuation via Stairs and Lifts (50% Lift Usage).....	151
7.4.1	Refuge Floor .....	152
7.4.2	Evacuation Zone.....	157
7.5	Analysis of Combined Lift Performance Values.....	163
7.6	Comparison of Calculation Methods and Lift Variables on the Evacuation Time	165
7.6.1	Refuge Floors .....	165
7.6.2	Evacuation Zone.....	166
7.6.3	Summary .....	167
7.7	Analysis of Results.....	167
8.0	CHAPTER 8 - CONCLUSIONS AND RECOMMENDATIONS.....	169
8.1	Comparison of Refuge Floors and Evacuation Zones.....	169
8.2	Calculation Methods.....	171
8.2.1	Stair Evacuation .....	171
8.2.2	Lift Evacuation.....	172
8.3	Application of Lift Evacuation Strategy .....	173
8.4	Conclusion .....	174
9.0	REFERENCES.....	177
10.0	APPENDIX.....	181

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## List of Figures

Figure 1.2 (a) – Evacuation of occupants from floor of origin	18
Figure 1.2 (b) – Evacuation from a refuge floor	19
Figure 1.4 – Plan of upper floor level of theoretical building	21
Figure 2.3.2 – Stratosphere Tower	27
Figure 2.3.2 (a) – Lower refuge floor level of Stratosphere Tower	28
Figure 2.6.4 – Simulated evacuation times with Single Deck, Double Deck and Triple Deck lift systems	41
Figure 2.7.2 – Comparison of occupant traces	44
Figure 3.2.1 - Effective Width and Clear Width	49
Figure 3.2.3 – Predicted and observed total evacuation times for tall office buildings	51
Figure 3.2.3 (a) – Predicted and observed total evacuation times from tall office Buildings	52
Figure 3.2.4 - Occupant flow rate during simultaneous evacuation	54
Figure 3.2.4 (a) - Occupant flow rate during phased evacuation	54
Figure 3.2.5 – Comparison of time for evacuation using fatigue sub-model	57
Figure 3.3.3 – Graphical representation of single lift trip	62
Figure 3.3.3.1 – Section of building used in Sekizawa’s calculations	65
Figure 3.3.5.3 – Velocity of lift reaching normal operating velocity	76
Figure 4.2 – Trace of occupant movement for a 15 storey building	90
Figure 4.2.2 – Occupant trace for lift evacuation of 40 storey office building	91
Figure 4.3.1.3 – Evacuation time for scenarios 1, 2 and 3	95
Figure 4.3.2 – Egress times with stairs and lifts	97
Figure 4.4.2 – Cumulative percentage of occupants evacuated	99
Figure 4.4.2 (a) – Number of occupants evacuated	100
Figure 4.4.2 (b) – Percentage of occupants contained on refuge floor at high level	100
Figure 4.4.2 (c) – Percentage of occupants contained on refuge floor at mid level	101
Figure 4.5.2 – People inside building at set time	103
Figure 6.2.1 – STEPS stair flow rates based on different grid sizes	117
Figure 6.2.2 – Evacuation times based on walking speeds	118
Figure 6.2.3 – Number of occupants evacuated via Stair 1	119
Figure 6.2.3 (a) – Number of occupants evacuated via Stair 2	120
Figure 6.2.3 (b) – Time for evacuation based on patience level	120

Figure 6.3.1 – Comparison of simultaneous and phased evacuation	122
Figure 6.3.3 – Evacuation time lines	125
Figure 6.3.4 – Stair flow rate serving 10 <sup>th</sup> floor level	127
Figure 6.3.6 – Flow rate in stair serving 30 <sup>th</sup> refuge floor	128
Figure 7.1 – Time for evacuation using stairs only	131
Figure 7.2.1.2 – Summary of lift and stair evacuation times	134
Figure 7.2.1.2 (a) – Evacuation from refuge floors at 10 storey intervals compared to code compliant evacuation time	134
Figure 7.2.1.2 (b) – Evacuation from refuge floors at 15 storey intervals compared to code compliant evacuation time	135
Figure 7.2.1.2 (c) – Evacuation from refuge floors at 20 storey intervals compared to code compliant evacuation time	136
Figure 7.2.2.1 – Indicative diagram of stair evacuation times for comparison to evacuation zone lift times	137
Figure 7.2.2.2 – Summary of evacuation from evacuation zones at 10 storey intervals	140
Figure 7.2.2.2(a) – Summary of evacuation from evacuation zones at 15 storey intervals	141
Figure 7.3.2.2 – Evacuation from refuge floors at 10 storey intervals compared to code compliant evacuation time	144
Figure 7.3.2.2 (a) – Evacuation from refuge floors at 15 storey intervals compared to code compliant evacuation time	144
Figure 7.3.2.2 (b) – Evacuation from refuge floors at 20 storey intervals compared to code compliant evacuation time	146
Figure 7.3.3.2 – Comparison of code compliant stair evacuation time with lift evacuation from 10 storey evacuation zones	148
Figure 7.3.3.2 (a) – Comparison of code compliant stair evacuation time with lift evacuation from 15 storey evacuation zones	149
Figure 7.3.3.2 (b) – Comparison of code compliant stair evacuation time with lift evacuation from 20 storey evacuation zones	150
Figure 7.4.1.2 – Comparison of lift evacuation time with stair evacuation times	154
Figure 7.4.1.2 (a) – Comparison of code compliant evacuation time with lift evacuation at 10 storey intervals	154
Figure 7.4.1.2 (b) – Comparison of code compliant evacuation time with lift evacuation at 15 storey intervals	155
Figure 7.4.1.2 (c) – Comparison of code compliant evacuation time with lift	

evacuation at 20 storey intervals	156
Figure 7.4.1.2 (d) – Comparison of code compliant evacuation time with lift	
evacuation at 25 storey intervals	156
Figure 7.4.2.2 – Comparison of lift and stair evacuation from 10 storey	
evacuation zones	159
Figure 7.4.2.2 (a) – Comparison of code compliant evacuation time with lift	
evacuation at 10 storey intervals	159
Figure 7.4.2.2 (b) – Comparison of stair evacuation time with lift	
evacuation at 15 storey intervals	160
Figure 7.4.2.2 (c) – Comparison of code compliant evacuation time with lift	
evacuation at 15 storey intervals	161
Figure 7.4.2.2 (d) – Comparison of stair evacuation time with lift evacuation	
at 20 storey intervals	161
Figure 7.4.2.2 (e) – Comparison of code compliant evacuation time with lift	
evacuation at 25 storey intervals	162



## List of Tables

Table 2.2 – Estimated percentage of building occupants unable to evacuate via stairs	25
Table 3.2.1 - Maximum Specific Flow	51
Table 3.2.5 – Summary of fatigued stair evacuation times	57
Table 3.3.3.1 – Lift details	66
Table 3.3.3.1 (a) – Comparison of Evacuation Times	66
Table 3.3.5.3 – Door operating time and transfer inefficiency	75
Table 3.3.5.4 – Lift trip and evacuation time calculated by ELVAC computer program	79
Table 3.3.5.4 (a) – Summary of lift evacuation times using STEPS programme	81
Table 3.3.5.5 – Impact of variable inefficiency factors from a refuge floor	83
Table 3.3.5.5 (a) – Impact of variable inefficiency factors from an evacuation zone	83
Table 3.3.5.5 (b) – Result of people transfer time on value of start-up time	84
Table 3.4 – Summary of Calculation Methods	86
Table 4.5.2 – Clearance time for each storey	104
Table 5.8 – List of input values	112
Table 7.2.1.1 – Time for evacuation by stairs from refuge floor based on AD-B flow rates	132
Table 7.2.2.1 (a) - Time for evacuation by stairs from 10 storey evacuation zone	137
Table 7.2.2.1 (b) - Time for evacuation by stairs from 15 storey evacuation zone	137
Table 7.2.2.1 (c) - Time for evacuation by stairs from 20 storey evacuation zone	138
Table 7.2.2.1 (d) - Time for evacuation by stairs from 25 storey evacuation zone	138
Table 7.3.2.1 – Time for evacuation by stairs from refuge floor (AD-B)	143
Table 7.3.3.1 (a) - Time for evacuation by stairs from 10 storey evacuation zone	147
Table 7.3.3.1 (b) - Time for evacuation by stairs from 15 storey evacuation zone	147
Table 7.3.3.1 (c) - Time for evacuation by stairs from 20 storey evacuation zone	147
Table 7.3.3.1 (d) - Time for evacuation by stairs from 25 storey evacuation zone	147
Table 7.4.1.1 - Time for evacuation by stairs from refuge floor (AD-B)	152
Table 7.4.2.1 (a) - Time for evacuation by stairs from 10 storey refuge zone	157
Table 7.4.2.1 (b) - Time for evacuation by stairs from 15 storey refuge zone	157
Table 7.4.2.1 (c) - Time for evacuation by stairs from 20 storey refuge zone	157
Table 7.4.2.1 (d) - Time for evacuation by stairs from 25 storey refuge zone	157
Table 7.5 - Comparison of evacuation times based on the use of refuge floors	164
Table 7.5 (a) - Comparison of evacuation times based on the use of evacuation zones	164

**ABSTRACT OF THESIS** submitted by: Ian Hall

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The objective of this thesis is a study into the feasibility of lift evacuation within high-rise buildings during a fire, in particular, those buildings used as office accommodation. Lift evacuation has been debated theoretically by a number of researchers. A summary of the main methods of evacuation discussed can be summarised as follows:

- Evacuation from a dedicated refuge floor
- Evacuation from an occupied floor, which is within a zone of floors provided with lift evacuation.

Whilst some researchers have sought to assess the suitability of these methods by conducting simulations and devising calculations to determine the evacuation time from a building, there is limited information available with regards to the assumptions made in these assessments to allow the reader to determine its applicability. Furthermore, the assessments noted above focus on a single method of evacuation and do not compare the different evacuation strategies available.

The aim of this thesis is to compare evacuation times achieved in a theoretic building which is designed in accordance with current design codes (i.e. Approved Document B), with those achieved when the building is provided with either of the lift evacuation methods discussed above. This will allow the most efficient evacuation time to be determined.

Based on the simulations conducted as part of this thesis it can be demonstrated that the simultaneous evacuation of a high rise office building may be achieved in less time when occupants escape via code compliant stairs designed for phased evacuation rather than using lifts provided in accordance with current design guidance to evacuate. However, these simulations also demonstrate that once the percentage of occupants using the lifts for evacuation decreases, or the lift performance values are increased, the evacuation time from a number of refuge floors or evacuation zones is less than the evacuation time achieved using code compliant stairs.

Based on the findings of this assessment, it was considered necessary to develop a programme for preliminary design which is capable of determining if the use of lifts for evacuation is more efficient than a code compliant design, and which evacuation strategy is the most effective.

## **Declaration**

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## Nomenclature

$a$  = constant = 0.266

$D$  = density in persons/m<sup>2</sup>

$f$  = mean evacuation flow (persons/second/metre effective stair width)

$H_{ij}$  = vertical distance between  $i$ th floor and  $j$ th floor (m)

$j$  = number of lifts

$k$  = constant = 1.08

$L$  = vertical distance for the lift movement (m)

$m$  = is the number of round trips

$N_{dw}$  = the number of people entering the lift during the dwell time

$N_{elv}$  = flow factor of lift doors (persons/m/s)

$p$  = actual evacuation population per metre of effective stair width

$P_{fi}$  = number of occupants on the  $i$ th floor

$P_{stri}$  = number of evacuees by stairs on the  $i$ th floor

$S$  = speed along line of travel

$T$  = minimum time in minutes

$T_1$  = acceleration time (s)

$T_2$  = constant velocity time (s)

$T_3$  = deceleration time (s)

$t_a$  = lift start up time

$T_{cl}$  is the closing time of lift doors (s)

$t_d$  = time for the doors to open and close once

$T_e$  = time for evacuees to get on and off a lift (s)

$t_i$  = time for people to enter the lift

$t_{io}$  = the average time for one person to enter the lift

$T_m$  is the lift transfer time (s)

$t_o$  = the travel time from the lift lobby to the outside or to another safe location

$T_{op}$  = opening time of the lift doors (s)

$t_{r,j}$  = time for round trip  $j$

$t_s$  = standing time

$t_T$  = the travel time for the lift car to go from the furthest floor to the discharge floor

$t_u$  = the time for passengers to leave the lift

$V_{elv}$  = lift velocity (m/s)

$V_{max}$  = maximum lift velocity (m/s)

$W_{\text{elv}}$  = available lift door width (m)

$\alpha$  = basic transfer inefficiency (generally 0.1)

$\alpha$  = lift acceleration ( $\text{m/s}^2$ )

$\beta$  = lift deceleration ( $\text{m/s}^2$ )

$\gamma$  = other inefficiencies in people transfer into or out of lifts

$\varepsilon$  = door inefficiency

$\eta$  = trip inefficiency

$\mu$  = is the total transfer inefficiency

$\rho$  is the evacuation population (persons per metre effective stair width)

## CHAPTER 1 - INTRODUCTION

The means of escape in new buildings in England and Wales should be designed in accordance with Approved Document B<sup>[1]</sup> of the Building Regulations. This Approved Document defines a very tall building as any with a top floor level more than 45m in height.

It is proposed to review all code compliant means of escape assessments in accordance with the guidance of Approved Document B<sup>[1]</sup> (AD-B), which is applicable in England and Wales. Where necessary to support this study, additional reference will be made to the building codes of other countries.

Whilst there are numerous buildings within England and Wales that exceed this limit, the number of super-tall buildings is limited. The tallest building in the UK is currently 1 Canada Square, which is approximately 235m in height and provided with 50 storeys. However, due to the development of a number of city skylines in the UK this height will be exceeded in the near future.

### 1.1 Code Compliant Means of Escape

High rise buildings often contain thousands of persons over many floor levels. However, due to the limited plan area of these buildings, high rise buildings often contain only a few stairs. Whilst it is noted that the occupancy of a stair increases with the number of storeys it serves, due to the additional 'stacking capacity' within the stair, the number of occupants entering the stair generally significantly exceeds this additional 'stacking capacity'.

For example, based on the theoretical building used as part of this study (as described in Section 1.4), and assuming an entire stair is discounted due to fire fighting operations in accordance with Section 4.27 of AD-B, each stair is required to be 3100mm wide based on the guidance of Section 4.25 of Approved Document B to provide sufficient escape and stacking capacity within the notional evacuation period.

However, to allow a reduction in the required escape width of the stairs, current guidance in the UK<sup>[1]</sup> recommends that a high rise building is provided with phased evacuation and compartment floors separating each storey, as well as the provision of sprinklers throughout.

Phasing the evacuation of a high-rise building allows only a handful of storeys to evacuate at any one time. Therefore, the escape routes, such as stairs and doorways, can be designed based on the relatively low number of occupants using them compared to those during the simultaneous evacuation of the building, reducing the required width.

Phased evacuation generally requires the floor of fire origin to evacuate upon detection, then after a set time delay, usually of two and a half minutes, the next two floors above will evacuate. Once the floors above the floor of fire origin evacuate, those below commence evacuation. However, based on a two and a half minute interval of the evacuation of floor levels, and a fire on the 20<sup>th</sup> floor level of the theoretical building used as part of this study, the time for the final floor of the building to evacuate is 62.5 minutes (i.e. final stage of phased evacuation occurs after 62.5 minutes).

In addition to the time taken for evacuation to commence, it is also necessary to include the additional time required to descend the stairs.

For example, based on a 4m floor to floor height, the fiftieth floor is approximately 200m above Ground floor level. Based on a riser dimension of 182mm and a going dimension of 270mm, the total horizontal travel distance is approximately 297m (270mm x 22 steps per floor x 50 storeys) while the total vertical travel distance is approximately 200m (182mm x 22 steps per floor x 50 storeys). Therefore, the hypotenuse (travel distance down the centre line of the stair) can be calculated as 358m. If it is assumed that occupants will travel 350mm from the central handrail<sup>[2]</sup> an additional 1.4m is added for every level to account for the travel distance on the landings. On this basis, the total travel distance down the stairs is approximately 428m.

Based on a speed of 0.95 m/s for travel down a stair<sup>[3]</sup>, the time taken to descend the centreline of the stair is equal to 451 seconds, or approximately seven and a half minutes. However, this speed is for a person with an un-impeded flow. However, in reality, there will be multiple merging flows of occupants within in the stair, as well as fatigue of the occupants descending the stair, which will increase the evacuation time.

Nevertheless, based on the provision of good internal Fire Service access and passive fire protection, it is likely that the fire will be confined to a single floor and will not require the simultaneous evacuation of the buildings occupants. Kinsey et al<sup>[4]</sup> notes that 'since the



wide scale adoption of sprinkler systems in high rise buildings, there has been an expectation that there would rarely, if ever, be a need to undertake full building evacuations'. Whilst this may be a concern in the event of a bomb threat, the risk of a fire in a high-rise building, which requires the simultaneous evacuation of the whole building, is unlikely.

However, there has been an increased interest in the simultaneous evacuation of high-rise buildings since the World Trade Centre attacks in 2001<sup>[4]</sup>. Lane et al<sup>[5]</sup> states that "many people are now unwilling to stay in a building on fire even if it is remote from their location and want to be reassured that they can evacuate in a timely fashion."

## **1.2 Use of Lifts for Evacuation**

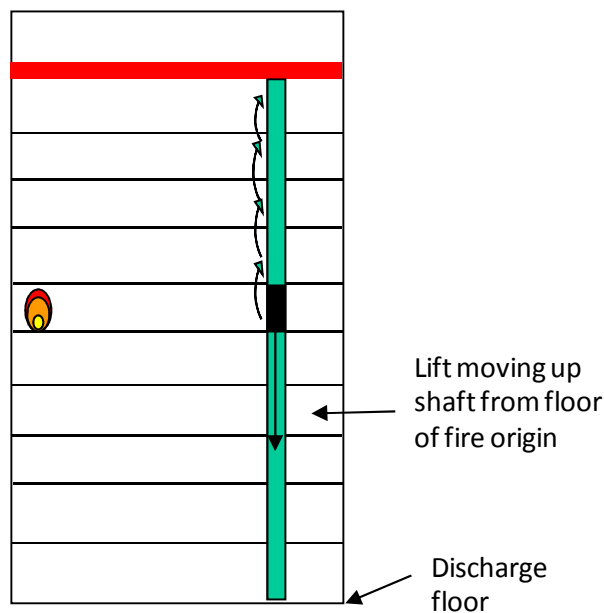
Notwithstanding the above, it is necessary to provide a suitable means of escape for building occupants located at high level. The physical effort for some of the occupants to evacuate from the 50<sup>th</sup> storey may be too strenuous. This is recognised by design guidance in Hong Kong<sup>[6]</sup>, which requires refuge floors to be provided a minimum of every 25 storeys from any other refuge floor, or above street level, to provide occupants with a place to rest in relative safety. The provision of these refuge floor may be supplemented with lift evacuation to assist those occupants from the upper storeys evacuate within a reasonable time and without undue stress.

The use of lifts and stairs for evacuation of a high rise buildings is supported by experiences from the World Trade Centre attacks<sup>[7]</sup> in 2001, which have shown that occupants of a high rise building are prepared to use the lift for evacuation irrespective of the risk posed from a fire on a floor level below.

The use of lifts for evacuation has been reviewed by a number of researchers since the 1960's, using a number of different operation modes, which can generally be summarised as follows:

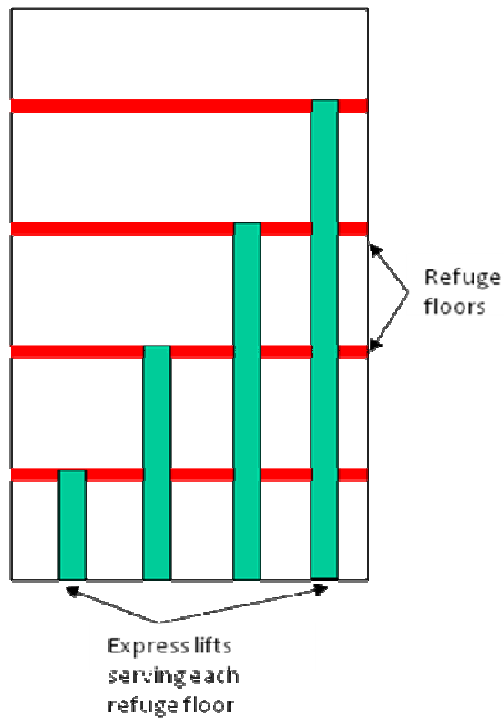
- Evacuation from the floor of origin, within an evacuation zone (Figure 1.2(a))
- Evacuation from a dedicated refuge floor (Figure 1.2 (b))

The evacuation from the floor of origin is considered to be the most simplistic evacuation to manage, on the basis that occupants are required to assemble in the lift lobby of their floor of origin and exit via a route they used to enter the building, and are, therefore, familiar with. This will allow a relatively small protected lobby to be provided at each floor level, based on the requirement to accommodate the occupants of that floor level only, rather than dedicating a whole floor as a refuge floor level to accommodate the occupants of multiple floor levels, as required for evacuation from a refuge floor. However, this method of evacuation is considered to require a greater overall evacuation time, based on the increased distance the lift is required to travel to evacuate the higher floors within the zone it serves.



**Figure 1.2 (a) – Evacuation of occupants from floor of origin**

Evacuation from a refuge floor requires occupants to descend the stairs to a dedicated floor, which is served by evacuation lifts. Whilst this may require a larger floor area to be provided as a protected refuge, this is considered to be a more efficient evacuation method based on the lower overall travel distance of the lifts, and a lower number of partially full round trips.



**Figure 1.2 (b) – Evacuation from a refuge floor**

### 1.3 Research Objectives

Whilst these evacuation strategies have been discussed by previous researchers, none of the previous research studies has directly compared the evacuation times of a building using both of these evacuation strategies to identify the most suitable method, or to determine the effectiveness against a code compliant escape time.

The purpose of this thesis is to review the information available with regards to the use of lifts for evacuation, including previous research on lift evacuation strategies, to determine the most effective of both possible methods of providing lift evacuation. This will be conducted using existing calculation methods to determine the evacuation time of each method from a theoretical building and by comparing the results of the lift evacuation simulations and with those achieved when escape is provided via the code compliant method (i.e. escape stairs). The evacuation time of the escape stairs assumes that all occupants seek to simultaneously escape, as may be accommodated by lift evacuation, in a building designed to accommodate phased evacuation.

In addition to assessing the overall building evacuation times for comparison to the equivalent stair evacuation times, comparison will be made to ascertain whether the

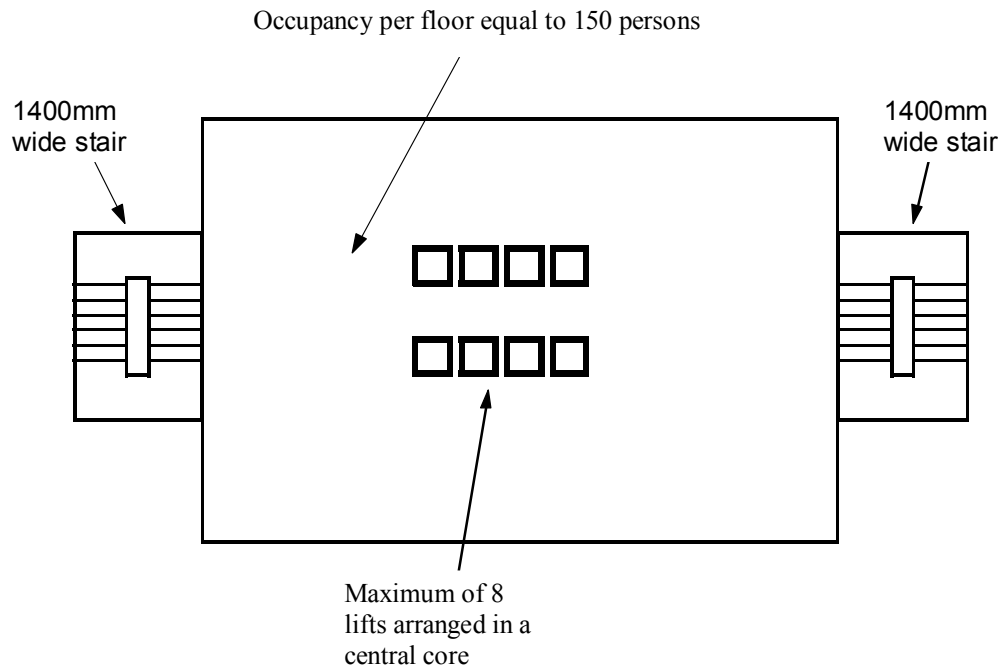
conditions within the building during the means of escape would be feasible for building occupants to use lifts for evacuation. Details of this assessment are provided in Chapter 6. In addition, this thesis will review the information available with regards to human behaviour in fire and how it relates to the use of lifts for evacuation as well as the design and performance of the lift system required to achieve a reduction in the code compliant evacuation time.

Based on the results and findings of this thesis, a computer programme will be created to calculate the most effective evacuation strategy for a conceptual building based on various lift performance values and occupant ratio, using Microsoft Excel and Visual Basic. This will allow the user to determine the effectiveness of lift evacuation compared to the code compliant evacuation time and therefore, determine which strategy to implement.

#### **1.4 Theoretical Building**

The calculations will be performed for a theoretical building with the following details:

- The building is provided with 51 storeys of accommodation (i.e. Ground – Fiftieth). Based on a floor to floor height of 4m, the top floor is 200m above the discharge level.
- The occupancy of each floor level (with the exception of Ground) is equal to 150 persons. On this basis, the total building occupancy is equal to 7500 persons. However, refuge floor are assumed to not contain a permanent occupancy.
- In accordance with Table 3 of Approved Document B, it is necessary to provide a minimum of two storey exits for a storey level with an occupancy greater than 60 persons, and less than 600 persons. Therefore, the building is provided with two stairs serving each floor level.
- In accordance with Section 4.27 of Approved Document B, it is assumed that a single stair is discounted due to fire fighter operations as a conservative assumption. Therefore, the occupancy of each floor level is required to escape via a single stair. In accordance with Table 8 of Approved Document B, each stair is provided with a clear width of 1400mm.



**Figure 1.4 – Plan of upper floor level of theoretical building**

## 1.5 Thesis Layout

Chapter 1 is a brief introduction to the issues of evacuation from high rise buildings for fire and non fire events.

Chapter 2 is a literature review with regards to lift performance values and concerns with using lifts for evacuation, disabled evacuation, existing lift evacuation systems and occupant behaviour during evacuation, in particular, panic behaviour and occupant queuing times, which are considered to be most relevant to this study.

Chapter 3 is a review of the methods of analysis which assess the analytical and simulation assessments used as part of this study and includes validation studies, for the simulation programmes used as part of this study, including STEPS and ELVAC, and assesses how these may be accurately applied to this study.

Chapter 4 provides the reader with a brief overview of previous studies into lift evacuation, from the initial simulations of Bazjanac and Pauls in the late 1970's, through to the most recent studies by the BRE. The chapter highlights the relevant parts of these studies to this research.

Chapter 5 details the variables used in the calculations conducted for this study and the sources these have been selected from.

Chapter 6 details the results of the STEPS modelling assessment and compares these values with previous assessment detailed in the Literature Review.

Chapter 7 contains an analysis of the results and compares the lift evacuation times with the associated stair evacuation times and code compliant stair evacuation times.

Chapter 8 contains the Conclusions and Recommendations based on the analysis of the results, as listed in Chapter 7.

## CHAPTER 2 - LITERATURE REVIEW

### 2.1 Impact of the World Trade Centre Attacks (2001)

The 2001 attacks of the World Trade Centre provided an insight into the complications involved in the simultaneous evacuation of a high rise building. Media reports showed crowded conditions within the stairs, as some occupants reportedly queued for hours to evacuate. Whilst it is acknowledged that the conflicting flow of fire fighters up the stairs reduced the flow rate, it is noted that the limited escape capacity of the stairs, which had been designed to accommodate a much smaller flow of occupants, was significantly under sized to accommodate the simultaneous evacuation of the building.

Based on the recommendations of Approved Document B<sup>[1]</sup>, it is likely that the evacuation of the World Trade Centre towers would have been phased to limit the required width of the escape stairs. However, due to the impact of a passenger airliner, multiple floor levels were involved in the fire, which is not considered in Approved Document B for a building provided with phased evacuation. Whilst a 1400mm wide stair may accommodate additional occupants to those that evacuate during the initial phase, who may queue on the stair, the escape width provided in a phased building is considered unlikely to provide sufficient escape width for those occupants of the affected floors (i.e. impact floors and above) to simultaneously evacuate the building, therefore, leading to substantial crowding within the stairs.

Galea et al<sup>[8]</sup>, estimates that there was a total building population of between 10,000 – 14,000 persons, occupying the towers at the time of impact. Based 110 occupied floors, this equates to between 90 and 127 persons per floor level. However, the maximum building occupancy is considered to be equal to 25,000 persons.

Following a review of a large number of survivors of the 2001 attacks of the World Trade Centre Fahy and Proulx, as quoted by Murphy<sup>[7]</sup> noted that a number of occupants used lifts as their only means of escape, or to supplement their escape, once conditions in the staircases deteriorated. Of the occupants who evacuated using just stairs, the time to exit the building ranged from 20 to 53 minutes depending on the location of the occupant.

However, evacuation of the occupants using the lifts took between 14 and 24 minutes to reach a place of safety remote from the building from their floor of origin.

Further evidence of the enhanced escape capacity of a building supplemented with lift evacuation is provided in BRE research<sup>[9]</sup>, which notes that 'in the 16 minutes before the impact of the aircraft, 27% of those who evacuated used the lifts for part of their escape route. In addition, the investigation found some evidence that the flow rate from WTC2 during those 16 minutes was approximately twice that for WTC1 (where only stairs were available for evacuation).'

Based on the above references one can only assume that the use of lifts to supplement evacuation reduces the overall evacuation time. However, in this scenario, the lifts were used by a limited number of persons and did not result in the optimum reduction of the evacuation time via the stairs. Therefore, as well as comparing the evacuation times of the theoretical building using stairs and lifts, it is necessary to assess the impact on the overall evacuation time using a combination of stairs and lifts.

## **2.2 Evacuation of Disabled Persons**

It is a functional requirement of the Building Regulations that adequate means of escape are provided, which includes provisions of disabled persons, without the requirement for Fire Service assistance. This may be achieved using a number of methods, which includes the provision of evacuation lifts. In low rise buildings the provision of evacuation lifts are designed to accommodate non-ambulant occupants only. However, the lift evacuation system in a high-rise building will also be required to accommodate ambulant patients. On this basis, it is necessary to assess the impact to the lift system when evacuating disabled occupants with ambulant occupants. Disabilities are defined by Proulx<sup>[10]</sup> as people who have limitations in the following:

- Mobility
- Agility
- Intellectual
- Hearing
- Seeing
- Speaking



People who have hearing or speaking limitations are not included in the group known as disabled occupants, as these occupants may escape via conventional means using simple management procedures. However, occupants with other limitations will require the evacuation strategy to be adjusted according to their needs. For example, a blind occupant will be able to evacuate in a lift, which is fully occupied, whereas an occupant using a large wheel chair may fully occupy a single lift.

The evacuation of a building should include provisions for disabled occupants. These occupants are quoted as consisting of different percentages of the building occupancy, which vary between 1% and 15%. Whilst it is noted that these occupants may have difficulties walking multiple flights of stairs, the number of occupants who may require additional space within the lift, such as wheelchair users, is less than the quoted percentage of occupants considered to be disabled.

Researcher	Percentage of occupants
Lane et al <sup>[5]</sup>	15%
Charters et al <sup>[9]</sup>	11%
Pauls <sup>[11]</sup>	6%
Pauls <sup>[12]</sup>	3%
Smith <sup>[13]</sup>	1%

**Table 2.2 – Estimated percentage of building occupants unable to evacuate via stairs**

It is recommended that disabled occupants are given priority to escape. This will ensure that should occupants be required to evacuate via the stairs, the maximum flow rate will be achieved in the stair, based on the use of the stairs by able bodied occupants only.

If the evacuation is from a refuge floor it is unlikely that any disabled occupants will be the first to arrive at the refuge floor. Therefore, to ensure that the evacuation time of these occupants is minimised it is recommended that disabled occupants should be located as close to the refuge floor as possible to reduce the travel time required to reach the lifts.

Based on the number of wheelchair based occupants contained within a building, it may be necessary to include a single round trip for each occupant to account for the additional space occupied by this person in a lift.

## 2.3 Existing Lift Evacuation Systems

Lift evacuation is currently used in a small number of buildings worldwide for the evacuation of a building. Three notable examples are described below:

### 2.3.1 Eureka Place Tower, Melbourne

The Eureka Place tower is an 88 storey building located in Melbourne, Australia. Details of the lift evacuation strategy are provided by Kuligowski<sup>[[14]</sup>.

‘The Eureka Place Tower is separated, according to the lift arrangement, into vertical evacuation zones. The plan states that occupants within the vertical zone that indicates the fire floor would evacuate via the stairs until they reach the next transfer floor. At the transfer floors, which are located on levels 24 and 52 of the Eureka Place tower, the occupants would then take the express lift to the Ground floor. The express lifts will be located in separate shafts in order to avoid water and smoke damage, and will be accompanied by the other lifts provided for fire fighter access.’

It is noted that the Eureka Place Tower uses the transfer floor or refuge floor method of lift evacuation, first proposed by Pauls<sup>[[12]</sup>, despite having a relatively low occupancy compared to an office building of the same height. Whilst it is not stated within the reference, this is assumed to be the result of a requirement for a high efficiency evacuation system as a result of the relatively low number of lifts generally provided in a residential building, such that a suitable lift evacuation time is achieved, which does not require the lifts pick up small numbers of occupants on different floor levels.

### 2.3.2 Stratosphere Tower, Las Vegas

The Stratosphere Tower is located in Las Vegas in the United States of America and is essentially an eleven storey building sited atop a 250m tower. Details of the lift evacuation strategy for the building is provided by Quiter<sup>[[15]</sup> as summarised below.

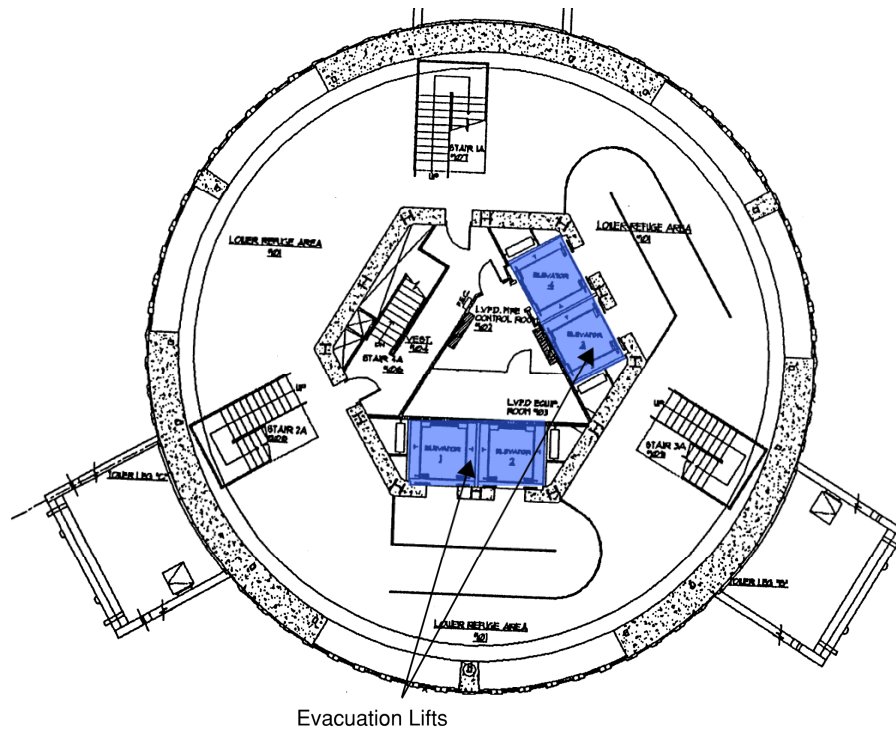


**Figure 2.3.2 – Stratosphere Tower**

Some floors of the building may include an occupancy of more than 500 persons. Strict compliance with the building codes at the time would require the provision of three remotely located escape stairs. However, based on the restricted plan area of the tower it was not considered possible to meet this requirement.

The primary evacuation method for this building is the use of stairs for the occupied floors, which discharge into an area of refuge on the lowest two floors of the pod. These two areas of refuge are used for no other purpose and are completely non-combustible. A diagram of a refuge floor level is shown below.

From the area of refuge, a single stair leads down through the shaft of the tower to Ground floor level. However, the primary evacuation route from the area of refuge involves the use of lifts. These lifts are double deck lifts which travel at 1800 feet per minute (approximately 9m/s) and can discharge either within the main casino (at podium level) or at two specially designed discharge levels at the roof of the podium building. These discharge levels are enclosed in two hour, fire rated, construction in accordance with NFPA 5000, from the roof to grade, and are separated from all other areas by two hour, fire rated, construction.



**Figure 2.3.2 (a) – Lower refuge floor level of Stratosphere Tower**

The high level accommodation is provided with the two lowest floors as refuge floor levels. This is based on the use of double deck lifts to evacuate the upper storeys of accommodation within a reasonable time. However, to ensure that lift evacuation is economically feasible it is necessary to limit the area of refuge floor required within a building. Therefore, it is necessary to determine the level of lift performance required to ensure that only a single level of refuge floor accommodation is required to accommodate occupants waiting for the lifts to arrive.

### 2.3.3 Petronas Twin Towers, Kuala Lumpur

The Petronas Twin Towers were originally designed to accommodate evacuation by stairways only. However, following the attacks on the World Trade Centre, the evacuation strategy of the building was modified to accommodate lift evacuation<sup>[16]</sup>.

During Stage 1 of the previous evacuation strategy occupants of the fire floor and a single floor above and below were required to evacuate their floor and re-enter 3 floors lower. Occupants of the two floors above and below the affected floor would have been put on alert. If the Stage 1 event could not be contained (i.e. fire and smoke spread to multiple

floors), the Stage 2 evacuation would be implemented, which necessitated the simultaneous evacuation of the whole building via the following procedure:

- Low Zone (Level G to 37) – Down the stairs to Concourse and exit building
- Middle Zone (Level 40 to 60) - Down the staircase to Level 41, cross over sky bridge to adjoining tower, use shuttle lifts to Ground and exit building.
- High Zone (Level 61 to 77) – Down the staircase to Level 42, cross over sky bridge to adjoining tower, use shuttle lifts to Mezzanine and exit building.
- Top Zone (Level 78 to 86) – As similar to High Zone evacuation

This was amended such that in the event of both towers being affected, each tower would be provided with independent means of escape, as follows<sup>[16]</sup>:

- Low Zone (Level G to 37) – Down the stairs to Concourse and exit building
- Middle Zone (Level 40 to 60) - Down the staircase to Level 41, use the designated shuttle lifts in the same tower to Ground and exit building.
- High Zone (Level 61 to 77) – Down the staircase to Level 42, use the designated shuttle of the same tower lifts to Mezzanine and exit building.
- Top Zone (Level 78 to 86) – As similar to High Zone evacuation

A fire drill was conducted to assess the implementation of lift evacuation. The total building evacuation time was equal to 32 minutes. Based on the information available, it is not possible to determine the exact reduction in the evacuation time as a result of the provision of lift evacuation. However, this is considered to be a significant reduction in the 'several hours' quoted by Bukowski<sup>[17]</sup> prior to the implementation of the amended strategy.

Occupants of the 'Top Zone' are required to travel 44 floors to reach the refuge floor level. This is considered to be an excessive travel distance for occupants of the Top Zone and is

likely to require large refuge floors to accommodate the occupants of 44 storeys waiting for the lift.

#### 2.3.4 Summary

Lifts are currently in use as a means of escape route from a few high rise buildings in different countries worldwide. Case studies of these buildings have shown that the number of floor levels, or number of occupants per floor level, may exceed those used in this study based on the provision of lifts with a higher performance value than those stated in Chapter 5.

### 2.4 **Concern of the Use of Lifts for the Evacuation of Building Occupants**

Occupants of buildings throughout the world have previously been told to not use the lifts in the event of a fire.

“The danger of lift failure, the need for the emergency personnel to get to the area in danger without delay, and the opinion that existing lift configurations cannot evacuate people fast enough are reasons given most frequently for the elimination of lift service.”<sup>[18]</sup>

A number of situations, which could render a lift evacuation system inoperable are considered by Klote et al<sup>[19]</sup>. Additional issues were raised by Klote et al<sup>[20]</sup> at a later date. A summary of these concerns and possible solutions are listed below:

*Doors Opening into the Fire* - One of the main causes of fatalities when using lifts in a fire is due to the lift doors opening onto a fire floor due to the call button being activated due to the high levels of heat. However, this is considered to be a result of the lift doors opening directly onto the floor plate, and therefore, not being provided the protection of a dedicated lobby. The recommended method of preventing lift doors from warping due to exposure to high temperatures is to provide access to the lift doors via a protected lobby with compartment construction.

*Lift System Activation* - Identification of the fire location is important for lift evacuation from an evacuation zone to the extent that the lift system must respond differently to the

fire floor (i.e. lift evacuation from an evacuation zone should answer calls from the fire floor first).

*Lift doors jamming open* - Lift doors may be jammed open during a fire due to the changes in pressure created by a fire. When a lift door is jammed open the lift will not move. However, in the event that lift doors are jammed open, occupants will be able to add the small additional amount of closing force required to close the doors.

*Fire or Heat Penetration of Lift System Barriers* - An approach for the selection of the fire resistance rating of these assemblies is that the lift evacuation system should be able to withstand fire exposure for long enough to allow for relocating or evacuating people to safety. However, based on the provision of sprinklers and protected lobbies accessing the lifts, it is considered reasonable to assume that heat will have a minimal impact on the lift system barriers.

*Water Damage of Lift System Components* - A building which is evacuated using lifts is likely to be in excess of 30m in height and therefore, in accordance with Approved Document B, will be required to have sprinklers<sup>[1]</sup>. In addition, large amounts of water may be released within the building during fire fighting operations. Water from fires away from the lift system can flow into the shaft and damage system components. However, there are currently lifts operating throughout the world on the outside of buildings where the system components are exposed to water in the form of rain. Therefore, the provision of water resisting components has shown that this issue can be overcome. A number of alternative methods may also be provided to prevent water from flowing into a lift shaft including the use of sloping floors to include floor drains. This method is considered more suitable as it requires much less maintenance and therefore increases reliability.

*Reliability of Electrical Power* - This is not considered to pose a significant problem to the design of the lift evacuation system. Under current guidance<sup>[21]</sup>, fire-fighting shafts are required to be provided with an alternative power source which is achieved using a number of methods which are above the scope of this study.

*Fire in the Evacuation System* – lifts which are protected from smoke and fire by protected lobbies can be considered to be a place of relative safety. On this basis, the evacuation system should be maintained as a fire sterile place. Proulx<sup>[22]</sup> recommends that smoke and

heat detectors are provided in the lift lobby. Once the detectors have been activated a recorded message could be played telling occupants that the lift will not stop at that floor and to move to the appropriate floor below.

*Smoke in the Evacuation System* - The main reason that it is recommended that occupants do not escape via lifts in the event of a fire is the risk of fire and smoke causing malfunctions in the lift motor room which can trap people in a potentially smoke filled lift shaft. Lift systems should not operate when significant levels of smoke are in a lift lobby, hoistway or machinery room.

*Trapped Lifts* - Under the guidance of BS EN 81 73<sup>[23]</sup> in the U.K, lifts are required to return to the discharge floor once the alarm has sounded. This allows the Fire and Rescue Service to identify the locations of all the lifts and prevents people from becoming trapped in a lift during the evacuation. Nevertheless, it is considered reasonable to keep the lifts in operation if the lifts are protected against the effects of a fire as mentioned above.

*Myth of Panic* - Klote<sup>[20]</sup> states that “panic behaviour is rare even among people aware of an ongoing fire, and he indicates that the most frequent mode of behaviour during fire emergencies is deliberate and purposeful”. Further review of occupant behaviour has shown that people act in a calm and deliberate manner during a fire evacuation.

*Fire Spread Via Lift Shafts* - There is large concern based on past experiences of fire spread via lift shafts and of fire fighter and civilian deaths in lifts over the use of lifts for evacuation. However, these have generally been in buildings without protection to the lift shafts (i.e. protected lobbies etc).

Although the concerns are many, they can be considered to be minor technical issues, which may be overcome in a correctly designed building. Therefore, there is no reason why lift evacuation should not be used.

## **2.5 Protection of Refuge Area's**

Whilst early studies into lift evacuation assessed the use of unprotected lifts, in relatively low rise buildings, during the early stages of a fire evacuate the floors immediately affected by the fire. This study assumes that, due to the longer times associated with evacuating



multiple floor levels, occupants may be required to wait for a significantly greater time before boarding a lift. Therefore, the lift evacuation simulations conducted as part of this thesis assumes that the following level of protection is provided to the areas of refuge where occupants are assumed to wait for a lift to arrive.

#### 2.5.1 Fire Resisting Construction

The refuge area should be maintained as a place of relative safety during the period of evacuation. To ensure that the refuge area is maintained as a tenable space for occupants to wait for the lift car to arrive, it is considered necessary to provide the refuge area with fire resisting construction.

Bukowski<sup>[17]</sup> recommends that the level of fire resistance provided to the structure forming the escape route is equal to twice of that required for occupants to escape the building. Based on the evacuation times achieved as part of this study, this would require in excess of 120 minutes fire resistance to be provided.

#### 2.5.2 Ventilation

It is noted from the STEPS assessment detailed later within this study that occupants located on refuge floors may be required to wait on a refuge floor for between four and a half minutes to ten minutes for a lift to arrive. Whilst the occupants waiting in these places of relative safety are protected from the immediate effects of a fire, they may become exposed to high concentrations of smoke. This may be via a number of different scenarios such as smoke flow into the refuge area during the escape phase. Based on this prolonged time within the refuge, it is considered necessary to prevent the ingress of smoke into the refuge. This may be achieved using one of the methods listed below:

- Provide extract ventilation to the refuge area
- Provide ventilated lobbies between the refuge area and adjacent accommodation,
- Pressurise the lift shaft and/or refuge area to prevent smoke movement into the refuge.

Stroup<sup>[24]</sup> details experiments carried out by Tamura and Klote at the NRCC on lift operations during a building fire, which concluded that without mechanical pressurization,

lethal concentrations of carbon monoxide were reached on all levels of the building 45 minutes after ignition. With lift shaft pressurization, the lift shaft was free from smoke; however, the lift lobbies were still above the critical level 15 minutes after ignition. On this basis, it is noted that the best results were obtained with both lift shaft and lobby pressurization.

### 2.5.3 Provision of Refuges

The design of the refuge area is considered to be a critical component of the evacuation lift system design. The refuge is required to be suitably large enough to accommodate the number of occupants required to wait for the lift in relative comfort, but also be of a sufficient size to be accommodated within the building floor plan without significantly affecting the cost. Building designers and owners are unlikely to implement lift evacuation if this will affect the rentable space of the building.

The refuge occupancy will increase based on the arrival of passengers at the refuge floor who cannot be transported down by the express lifts at the same time as they arrive, such that congestion will occur on the refuge floor.

The results of this study have shown that the refuge floor is required to accommodate a large percentage of occupants during the evacuation. It is noted that the refuge floor will not be required to accommodate all of the zones occupants, as some of the will be required to travel from their floor of origin to the refuge floor (i.e. occupants will be 'stacked' in the stair), while some will have exited the building.

As the first occupants reach the refuge floor they will be immediately evacuated by the lift. However, the refuge floor should be sized to accommodate the occupants that may be required to wait there due to the higher flow rate of stairs on to the refuge floor compared to that of occupants escaping via lifts. Based on the work by Wong et al<sup>[50]</sup> and the results of this study, it is considered necessary for a refuge floor to be able to accommodate approximately 70% of the occupants it serves. A lift lobby in an evacuation zone is required to accommodate all the occupants of the floor level it serves.

In an article in the Fire Prevention and Fire Engineers Journal<sup>[25]</sup>, Taylor recommends a floor space factor in lift refuges of between 0.6m<sup>2</sup>/person and 0.7m<sup>2</sup>/person based on research

and the Fruin levels of service. However, Lay<sup>[26]</sup> recommends that this may be reduced to 0.5m<sup>2</sup> per person, which is the same floor space factor recommended for a bar.

Lay<sup>[26]</sup> states that the use of a floor space factor of 0.5m<sup>2</sup> allows conditions to be achieved in the refuge area which will allow occupants to move in the refuge area and allow fire fighters to exit through the lobby if required.

The conditions on the refuge floor are considered to be a significant factor in the comfort of occupants waiting for the lifts to arrive and therefore the percentage of occupants who may use the stairs as an alternative means of escape. Suitable floor space factors have been suggested in the latest BRE design guidance<sup>[9]</sup> similar to the area within 2m of a crowded bar<sup>[1]</sup>. However, this is considered to create unsuitable conditions for occupants to wait for relatively prolonged periods of time for the lift to arrive. On this basis, it is considered that 0.5m<sup>2</sup>/person is the lowest limit for a refuge floor.

#### 2.5.4 Summary

It has been demonstrated from the event of the World Trade Centre attacks that stairs designed for phased evacuation become congested when occupants attempt to simultaneously evacuate. Whilst lift evacuation may help to reduce this congestion it is important that the lift system is designed to accommodate the building occupants likely to use the system in comfort. This include adequate provisions for the likely numbers of disabled persons that will use the system, as well as enough space to hold the occupants required to wait for the lift before evacuating.

## 2.6 **Lift Technology**

The simulations conducted as part of this assessment use default values as a base case, which are based on current design guidance<sup>[27]</sup>. Sections 2.6.1 to 2.6.4 below discuss the selection of these values.

### 2.6.1 Lift Controls

In the event that the lifts are required to be used for evacuation, the activation of the lifts may be automatic (i.e. on activation of the fire alarm), or manually by the Fire Service, as discussed below<sup>[28]</sup>.

Manual Control is to have persons in a command centre direct lifts to where they are most immediately needed. The co-ordinators would communicate with and direct these operators.

Automated control with human oversight is to use a computer programme to set priorities, send lifts to the appropriate floor and determine which floors should be evacuating into the stairwells. Depending on how the evacuation decision rules, additional input could be provided by co-ordinators. Whilst Groner and Levin<sup>[28]</sup> note that monitors would not be assigned to operate lifts, to ensure an acceptably high level of reliability it is assumed that some sort of human oversight over the computer programme will be needed.

Barlund<sup>[29]</sup> recommends that if evacuation time is critical then an automatic evacuation mode of the group controller is necessary. Manual dispatching, as in a fireman's drive mode can never compete with the efficiency of automatic dispatching.

Charters and Fraser-Mitchell<sup>[9]</sup> note that peak down mode is used at the end of the working day in office buildings to facilitate the efficient egress of most occupants over a relatively short period of time. This mode may provide a good starting point for the development of a lift operating mode for emergency evacuation. However, peak down mode still allows occupants to access the building from the ground floor travel up the building and move between floors. Therefore, Charters and Fraser-Mitchell recommend the peak down mode should be modified for emergency evacuation. Examples of the modified modes of operation are as follows.

- Ignore up calls
- Top call first
- Non-stopping on the way down, and/or
- Non-stopping at the fire floor

### 2.6.1.1 *Ignore all up calls*

Ignore all up calls means that the evacuation lifts will not respond to any up calls. This should increase the quality and quantity of service for floors with a down call. It may mean that if someone places an up call only, they may be waiting for a lift that will not arrive. This can be addressed through training and/or programming the lift to respond, but only travel down to ground floor once the occupant has entered.

### 2.6.1.2 *Top call first*

Top call first means that the lifts will prioritise lift calls from the top floors. When a floor has been evacuated, the lifts will then prioritise the next top call and so on. This method of operation is similar to that used in the BRE studies<sup>[9]</sup>. This is a very efficient way of reducing the evacuation time for those at the top of the building, but may lead to;

- Extended waiting times for those on lower floors using lifts and/or
- Lack of service for all floors, except the top floor.

This may be improved by having the one lift from each bank serve adjacent floor levels, in the same manner as the STEPS lift operation mode. However, this is considered to be effective only if the occupancy on each floor level is approximately equal. An unequal occupancy on different floor levels will require some lifts to make a greater number of round trip times, therefore, increasing the time taken to evacuate a floor level which may not have access to a lift that has completed the evacuation of the floor levels it serves

### 2.6.1.3 *Non stopping on the way down*

Non-stopping on the way down can be a way of avoiding delays due to the lifts stopping at additional floors until it is full. This may improve the quantity of service because lift door opening and closing times can form a significant proportion of a lifts journey time. However, this may also mean that on the last call for a floor, the lift may travel to the ground floor with only a partial load of occupants, therefore, increasing the inefficiency factor of the lift.

Whilst this is not considered an issue for evacuation from a refuge floor, due to the limited number of inefficient trips, this significantly increase the time to evacuate from an evacuation zone due to the increased number of inefficient round trips required.

#### 2.6.1.4 *Non stopping at the fire floor*

If lifts are used for means of escape from fire, they may be programmed not to travel to any floor where the fire alarm system has operated. This should mean that the lift will not stop at a fire floor and so will prevent occupants being exposed to fire hazards. It may also mean that people on the fire floor are waiting in a lift lobby for a lift that will not arrive. This also applies to people on other floors where smoke leakage is sufficient to activate detectors or where occupants see smoke and operate a manual call point. This can be addressed through training, and programming the lift to avoid only those floors where automatic detectors have been activated.

Whilst it is not possible to specify a method of operation in the computer simulation programmes or the analytical calculations, it is noted<sup>[40]</sup> that the lift efficiency during evacuation may be improved on compared to the times calculated as part of this assessment.

#### 2.6.2 Lift Speeds

Guidance provided in CIBSE Guide D “*Transportation Systems in Buildings*”<sup>[27]</sup> recommends a rated speed of 6m/s and an acceleration rate of 1.2m/s<sup>2</sup> for a lift car in a shaft that is 120m or more in height.

However, the lifts used for the evacuation of the Stratosphere Tower in Las Vegas are provided with a rated speed of 1800 feet per minute<sup>[15]</sup>, which is approximately equal to 9.1m/s.

The fastest lifts in the world are provided in the Taipai 101 building and are provided with a rated speed of approximately 17m/s<sup>[30]</sup>. However, these lifts were specially designed for use in this building and included may additional features, including a pressurised and aerodynamically shaped lift car. For lifts to be a more feasible means of evacuation it is considered necessary to assess the evacuation based on commercially available lifts.

Fortune<sup>[31]</sup> states that a lift with a descent speed which exceeds 7m/s or the vertical travel distance which exceeds 300m will cause passenger discomfort if the lift is not pressurised.

Therefore, it is proposed to assess the evacuation times based on the maximum speed recommended by CIBSE Guide D, Fortune<sup>[31]</sup>, and 16m/s to approximately represent the fastest lift in the world. A sensitivity study will also be conducted using a lift with a lower speed of 5m/s.

### 2.6.3 Lift Acceleration

Whilst it is proposed to carry out the study using a number of different lift speed to find the most efficient scenario it is recognised that the maximum lift speed is governed by the acceleration of the lift and the number of floors the lift car is required to travel before achieving maximum velocity.

The guidance contained in Table 3.5 of Guide D<sup>[27]</sup> recommends that a lift serving a building of 120m should be provided with a lift speed of 6m/s and an acceleration rate of 1.2m/s<sup>2</sup>. However, the guidance provided in CIBSE Guide D<sup>[27]</sup> recommends that passengers are uncomfortable when subjected to values of acceleration greater than about one sixth of the acceleration due to gravity (approximately equal to 1.5m/s<sup>2</sup>).

On this basis, the evacuation times will be assessed based on an acceleration and deceleration value of the 1.2m/s<sup>2</sup> and 1.5m/s<sup>2</sup> to determine the impact on the evacuation time.

### 2.6.4 Multiple Deck Lifts

The most effective method of increasing the lift capacity without increasing shaft area is to provide double deck lifts. There are a number of buildings throughout the world that utilise double deck lifts which serve as shuttle lifts between an access floor and sky lobbies.

This concept may also be applied to evacuation where occupants are expected to evacuate to the refuge floor or floors, where they can board a double deck lift to ground floor.

The benefits of using double deck lifts is discussed by Fortune<sup>[32]</sup> and includes:

- Reduction in the number of lifts required compared to single deck lifts which will save expensive lettable space within the building.
- Double deck lift arrangements save approximate 30% of the core space compared to a single deck lift group.
- Individual lift cars may be provided with a reduced capacity in a double deck lift system due to the stacking of cars within a single shaft.

However, when used as express lifts in an evacuation, double deck lifts require two levels of entry and exit.

This may be accommodated by providing an increased floor to ceiling height, which allows both lifts to discharge into the same zone, which is provided with a mezzanine level for the top lift car.

Whilst it is recognised that the size of these refuge levels will be smaller when compared to a single refuge level it is considered unlikely that this method will be adopted due to the reduction in the amount of lettable space over two levels when compared to a single level for a building provided with single deck lifts. However, this may be effective for evacuation from the floor of fire origin, based on a limited floor to floor height, such that two lifts may serve two separate floors.

It is currently not possible to accurately calculate the evacuation time using any of the computer simulation programmes or analytical calculations discussed in this paper. However, an approximate comparison is provided by Siikonen et al<sup>[33]</sup> using the Building Traffic Simulator (BTS) programme, which demonstrates that the times required for a building to be evacuated using single, double and triple deck lifts, as shown in Figure 2.6.4.



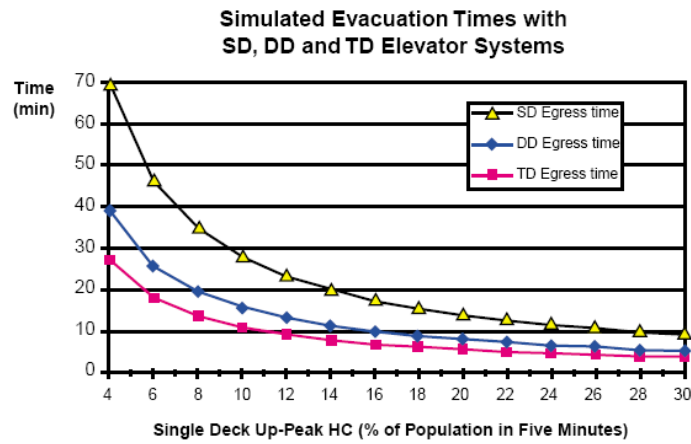


Figure 3: Simulated passenger egress times with single-deck (SD), double-deck (DD) and triple-deck (TD) elevators requiring the same shaft space

**Figure 2.6.4 – Simulated evacuation times with Single Deck, Double Deck and Triple Deck lift systems**

According to Figure 2.6.4 the evacuation time with double deck lifts are 50% to 60% of the time taken using single deck lifts while the time for a triple deck lift is about 40% of the time of double deck lifts.

**2.6.5 Summary of Lift Performance Values**

The highest rated speed currently recommended in design guidance is  $6\text{m/s}^{[27]}$ . However, these speeds have been exceeded in certain buildings throughout the world, particularly those where lifts are used to supplement evacuation. On this basis, it is proposed to use this speed as the base case during the simulations, as well as conduct additional assessments using alternative lift speeds to assess the impact on the total building evacuation time.

The assessments of the lift acceleration value will be conducted using the value of  $1.2\text{m/s}^2$  recommended by CIBSE Guide D<sup>[27]</sup> as the base case. An additional assessment will also be undertaken for the maximum tolerable lift acceleration value of  $1.5\text{m/s}^2$  for an unpressurised lift.

Whilst it is noted in Section 2.6.4 that a double deck lift will reduce the evacuation time, it is not proposed to include for the provision of these lifts in the simulations due to the inability to accurately simulate the movement of these lifts.

## 2.7 Occupant Behaviour

There are multiple signs within modern buildings of all heights warning occupants not to use lifts in the event of a fire. Therefore, based on an occupant's behaviour to avoid the lifts when evacuating, it is considered necessary to assess the likely human behaviour when occupants are required to wait for the lift to evacuate, as discussed below.

### 2.7.1 Escape via Entry Route

There are a number of documented cases, where occupants have tried to escape via the route which they entered the building despite documented cases of occupants passing a number of well signed alternative exits. This has caused a number of fatalities due to crushing of large numbers of people trying to escape via a single exit, or, via smoke inhalation caused by an increased evacuation time.

Johnson<sup>[34]</sup> notes that "this reluctance to follow emergency signage and instead retrace the path back to an initial entrance is a common feature in many accidents. It does not represent 'irrational' behaviour given that many fire exits can be blocked or alarmed. Arguably, individuals exhibit a preference to follow what they believe to be a 'sure route' to safety rather than take a chance on following fire exit signs in a direction they are not familiar with.

This theory is supported by Smith<sup>[13]</sup> who states that people "will do this even if this route is smoke filled or other alternatives and safe routes are available."

However, based on the use of the general circulation lifts as evacuation lifts, which are therefore provided with additional protection, it is considered reasonable to assume that occupants will be familiar with the escape route, when compared to escape stairs, which is considered to reduce occupant anxiety during means of escape, and reduce the need to provide distributed lifts throughout a building, therefore allowing a greater grouping of lifts, and improving the performance of the lift evacuation system.

## 2.7.2 Waiting Times

As a result of lift evacuation, building occupants will be required to wait for a lift to arrive in a protected lobby or refuge floor. This lack of movement is considered to cause agitation with the awaiting occupants.

There is currently no guidance on the acceptable waiting times in protected lobbies or refuge floors. In the study carried out by Lane et al<sup>[5]</sup> a waiting time of eight minutes is proposed based on the time taken to evacuate a stadium as it is assumed that this will meet the patience levels of the occupants.

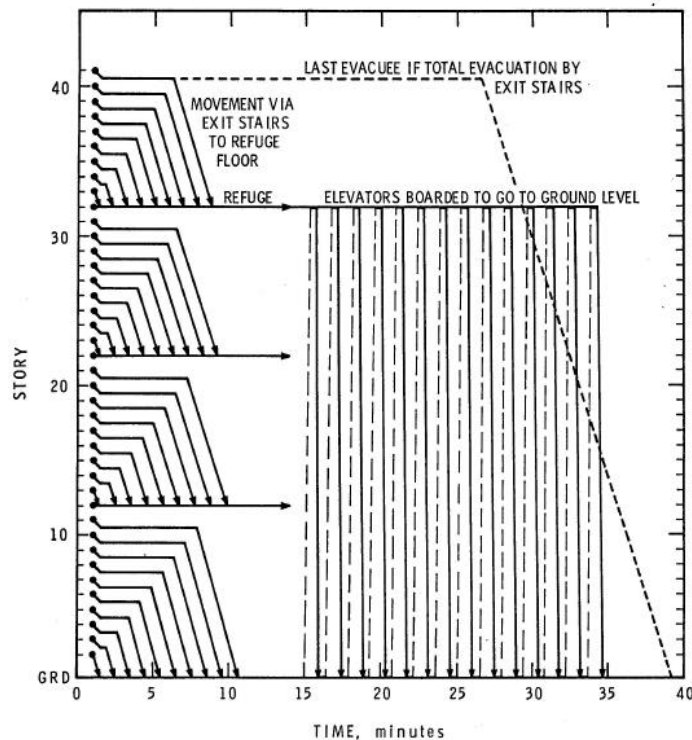
However, it is not considered unreasonable to provide a longer waiting time if the occupants are located in a place of relative safety and provided with a continuous update of the evacuation procedure. Whilst the work by Charters and Fraser-Mitchell<sup>[9]</sup> also notes that there is very little research in this area, some high rise office occupants have been noted to wait for up to 30 minutes or more for an evacuation lift during evacuation exercises.

Notwithstanding the above, Heyes<sup>[35]</sup> notes that an implicit assumption [of lift evacuation strategies] is that occupants will be willing to wait indefinitely for a lift until it arrives, which may not reflect the actual behaviour of people in such situations.

Research by Heyes<sup>[35]</sup>, shows that between approximately 5% to 15% of occupants will seek to find an alternative means of escape after waiting five minutes for a lift. It is considered worth noting that these results were collected by research from a number of participants for a hypothetical building. Therefore, these values are not considered to be the results of actual occupant waiting times but rather a perception of a number of occupant groups with regards to how long they feel they will be willing to wait for a lift before seeking an alternative.

The research of Pauls<sup>[2]</sup> recognises that occupants may be required to wait at a certain floor level for longer than required when using stair evacuation. However, as noted in Figure 2.7.2 the overall lift evacuation time is less than that via stairs despite a prolonged waiting time. Whilst this information may be known to the building designers and fire safety managers, this will not be available to the general building occupants. Therefore, to reduce

occupant stress while waiting for the lift it is recommended that information is provided to the refuge floor occupants with regards to the lift location, such that a decision can be made to wait for the lift to arrive or seek an alternative escape route via the protected escape stairs.



**Figure 2.7.2 – Comparison of occupant traces**

Based on the above, it is considered necessary to calculate the lift waiting times for the most onerous situations and assess the likely impact this will have on occupant behaviour during the evacuation.

### 2.7.3 Panic Behaviour

It is widely believed that panic is the most common response to an emergency situation, but studies by social scientists argue that panic behaviour in a fire is rare. This is supported by Fahy<sup>[36]</sup> who notes that “today, it is largely unknown that in the face of the extreme stress of a disaster, there is an absence of widespread, irrational antisocial and dysfunctional behaviour that has often been described as panic”. Thus, the false but common belief that people will panic in disaster situations is a myth. In human behaviour fire research, it is found that panic behaviour is extremely rare.

This is supported by Groner and Levin<sup>[28]</sup> who state that:

*“studies of behaviour during actual fire emergency situations have shown that social norms are not generally abandoned, and people do care and assist one another. However, fear and the desire to avoid pain, injury and death are great motivators and will affect the decisions of the occupants. Normally, people will follow a fire plan only if they believe that it will provide them with personal safety....Therefore, we would anticipate that occupants will willingly wait their turn to use the lift or stairs if they believe that they still would be able to safely evacuate and the delay permits an orderly evacuation for all and a more rapid evacuation for those closer to the fire.”*

Based on observations within the Post War Building Studies<sup>[37]</sup>, which recommends that a “crowd which is not in immediate danger, especially a disciplined crowd, may not show any great urgency in the use of exit” it is assumed that all code compliant means of escape provisions are designed based on the assumption that occupants do not behave in an irrational manner.

On this basis, it is assumed that occupants will behave in an orderly fashion during evacuation and lift boarding will occur with minimum delays. This is considered to be an important assumption as door opening and closing times make up a large percentage of the round trip time. Therefore, an increase in this time is considered to significantly increase the overall evacuation time.

This is considered to support the recommendations of the BRE research, which considers occupants are willing to wait approximately 30 minutes for a lift to arrive.

#### 2.7.4 Summary of Information

Based on the above research, the assumption that occupants may be required to wait on a refuge floor for approximately 30 minutes is not considered to be unreasonable based on known occupant behaviour research with regards to evacuation.

Based on occupants escaping via the route they entered the building, and waiting for the lift in an area which is not in immediate danger, it is considered that occupants will not suffer increased anxiety and make irrational decisions.

Nevertheless, it is recognised that prolonged waiting times increases the discomfort amongst passengers wanting to evacuate. Therefore, based on previous research it is recommended that the lift waiting time does not exceed 30 minutes.

## **2.8 Summary**

Based on the accounts of a number of survivors of the World Trade Centre attacks in 2001, it has been demonstrated that the use of a combination of stairs and lifts, can significantly reduce the overall evacuation time. However, as demonstrated by the review of the evacuation strategy for the Petronas Twin Towers<sup>[16]</sup>, the proposed evacuation strategy should contain some redundancy in the system to allow for the safe evacuation in the event of certain lifts or staircases becoming unsafe.

The provision of building specific lift evacuation strategies has been included in a small number of tall buildings worldwide. It is noted that the two buildings with a high density of occupants are provided with lift performance values which exceed the design guidance used as the basis of this thesis, to ensure that the round trip time is sufficiently low enough to evacuate the building before conditions become untenable. On this basis, additional simulations have been conducted using higher lifts speeds of 7m/s and 16m/s to assess the impact on the total building evacuation time.

Each of the existing buildings utilising lifts for evacuation are provided with refuges that are constructed from high levels of fire resisting construction and maintained as a place of relative safety. On this basis, lift evacuation is provided to serve all of the floors within the zone of fire origin, rather than those floor levels immediately affected by the fire, as discussed by early researchers.

Therefore, the simulations conducted as part of this assessment are based on the assumption that occupants will be provided with an area of relative safety where they may wait for the lift to arrive. This refuge area will be provided with a number of active and passive fire protection systems that will ensure tenable conditions are maintained in the refuge area, allowing occupants to wait for up to 30 minutes before boarding a lift.

It is also assumed that occupants will be provided with access to the protected escape stair from this refuge area.

## CHAPTER 3 - METHODS OF ANALYSIS

### 3.1 Introduction

Evacuation in the UK is provided in accordance with the guidance contained in Approved Document B (AD-B), based on a notional two and a half minute evacuation time. This requires exit routes to be provided with a sufficient width to allow the occupants located on any floor to flow through the available escape routes to a place of relative safety within this evacuation period. However, the place of relative safety may be the enclosure of an escape stair. Therefore, the total evacuation time (i.e. the time to travel the flight of stairs) will exceed the notional evacuation time of two and a half minutes.

Therefore, this study assesses the total evacuation time from the theoretical building discussed in Section 1.4, based on the assumption that occupants use stairs, lifts or a combination of both to escape.

A number of methods exist to calculate total evacuation time. This chapter will review these methods in order to identify the most suitable ones.

### 3.2 Calculation of Evacuation Time Using Stairs

The calculation of the evacuation time via stair is based on a number of different components which can be briefly summarised as follows:

- Fire alarm sounds and evacuation commences.
- Occupants exit their floor of origin via storey exits into a protected staircase. The rate at which occupants enter the staircase is dependent on the width of the stair.
- Occupants descending in the stair merge with occupants from the lower levels simultaneously entering the stair. The speed at which the merged crowd of occupants descends the stair is based on the occupant density in the stair which is itself controlled by the width of the stair.

- Once the occupant density decreases to a certain level within the stair, the flow of occupants within the stair stops. The escape capacity in the stair is limited to the standing area within the stair, also known as the 'stacking capacity'.
- Occupants from the lowest floor levels will continue to evacuate due to the higher density of the floor levels immediately adjacent to the final exit. Once those occupants of the lowest floor levels have evacuated the density of occupants in the stair above these floor levels slowly decreases allowing the flow rate of occupants to increase.
- Once the density within the stair exceeds approximately  $1.85 \text{ m}^2/\text{person}$  occupants will move at their own pace and the optimum stair flow rate will be achieved.

Advanced guidance on calculating the evacuation time of a building is provided in BS 7974-6<sup>[38]</sup>, which makes reference to two articles contained in the SFPE Handbook<sup>[3, 10]</sup> when calculating the total evacuation time of a whole building.

Based on the results of the evacuation time calculations using these two calculation methods, it is proposed to assess the lift evacuation times against those calculated in accordance with the flow rate of Approved Document B.

Based on the provision of lift evacuation in a building in the UK, it is considered necessary to demonstrate a reasonable evacuation time when compared to the times achieved using the flow rates in Approved Document B. Therefore, to ensure that a suitable strategy is selected, the lift evacuation times will be assessed against the stair evacuation times from the relevant building code.

Additionally, the assessment of the stair evacuation times using flow rates from Approved Document B is considered to provide a conservative escape time for comparison to the lift evacuation times, as a result of the faster evacuation time, when compared to the stair evacuation times calculated in accordance with Nelson and Mowrer, such that the stair evacuation times will be lower based on the use of this flow rate.

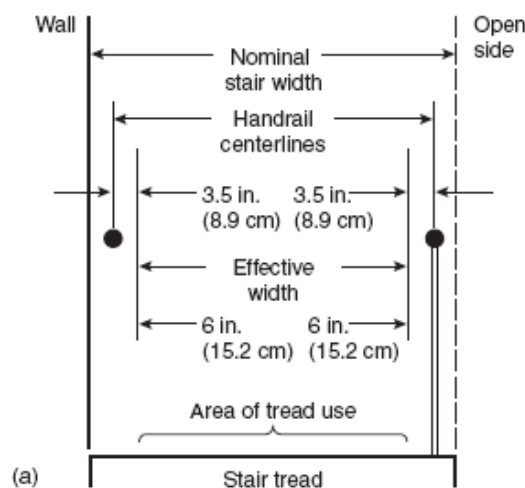


### 3.2.1 Method detailed by Nelson and Mowrer

In the article by Nelson and Mowrer<sup>[3]</sup> the time to evacuate a building may be calculated using one of two methods, a first order assumption and a more detailed analysis. For the purpose of this study it is considered reasonable to apply the calculation procedure of the first order assumption to calculate the approximate evacuation time by stairs. This is reasonable on the basis of a simple building layout, which will provide an overall time for the total building evacuation time rather than detailed evacuation times for each level.

#### *Estimate the flow capacity of the stairway*

The effective width ( $W_e$ ) of the stair is taken as the clear width of the stair minus the boundary layer of that stair, as shown in Figure 3.2.1. Therefore, the effective width of the 1400mm wide stair in the theoretical building is considered to be 1160mm (i.e.  $1400 - 150 - 90$ )).



**Figure 3.2.1 - Effective Width and Clear Width**

#### *Calculate the Specific Flow*

The specific flow is the flow of evacuating persons past a point in the exit route per unit of time per unit of effective width. The Maximum Specific Flow is tabulated<sup>[3]</sup> for different stair tread dimensions, as shown in Table 3.2.1.

Based on an assumed tread dimension of 11 inches, the maximum specific flow may be taken as 1.01 persons/second/metre of effective width. Therefore, the notional maximum specific flow may be calculated as 1.172 persons/second (i.e. 1.01 x 1.16).

Exit Route Element	Maximum Specific Flow	
	Persons/min/ft of Effective Width	Persons/s/m of Effective Width
Corridor, Aisle, Ramp, Doorway	24.0	1.3
Stairs		
Riser (in.)	Tread (in.)	
7.5	10	17.1
7.0	11	18.5
6.5	12	20.0
6.5	13	21.2

**Table 3.2.1 - Maximum Specific Flow**

### *Building evacuation time*

Based on the assumption that the occupancy of the building is required to evacuate via a single stair as required by AD-B, each stair is required to accommodate approximately 7500 persons (150 persons x 50 storeys). Based on a flow rate of 1.17 persons/second, the total evacuation of the building takes approximately 6410 seconds. Therefore, the total evacuation time can be calculated as 1 hour and 47 minutes.

### 3.2.2 Method by Pauls

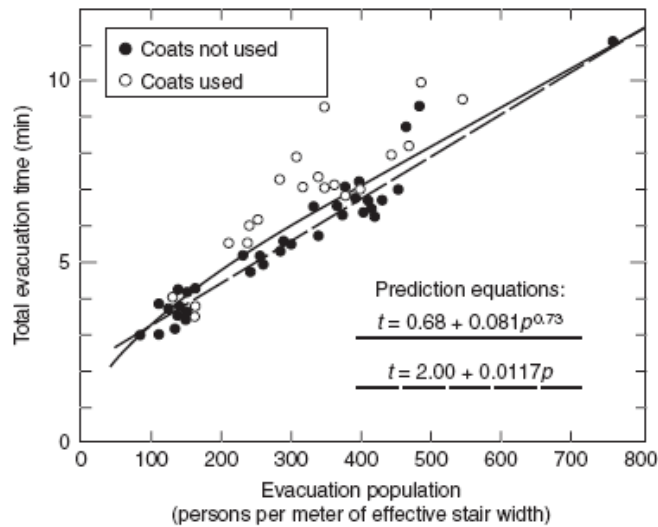
After carrying out a number of studies of simultaneous evacuations of office buildings in Canada, Pauls<sup>[10]</sup> noticed that the mean evacuation flow of the effective stair width approach (per metre of effective stair width) varies in a non-linear fashion with evacuation population. This regression equation is represented by Equation 1 and can be used to calculate the mean flow rate based on the density of occupants per metre of escape width.

$$f = 0.206\rho^{0.27} \quad \text{Equation 1}$$

Where: f is the mean evacuation flow (persons/second/metre effective stair width)  
 ρ is the evacuation population (persons per metre effective stair width)

However the calculation above is valid for occupancies of no more than 800 persons/m of effective stair width. Based on the requirement for 7500 persons to use the stair, this validity limit is significantly exceeded.

However, two prediction equations are presented by Pauls which calculate the total evacuation time and are shown in the figure below compared to a number of results obtained by Pauls for a number of observed evacuations.



**Figure 3.2.3 – Predicted and observed total evacuation times for tall office buildings**

For buildings with more than 800 persons per metre of effective stair width the following equation is presented by Pauls which is stated as “providing a good basis for predicting times for uncontrolled total evacuations in tall office buildings”.<sup>[10]</sup>

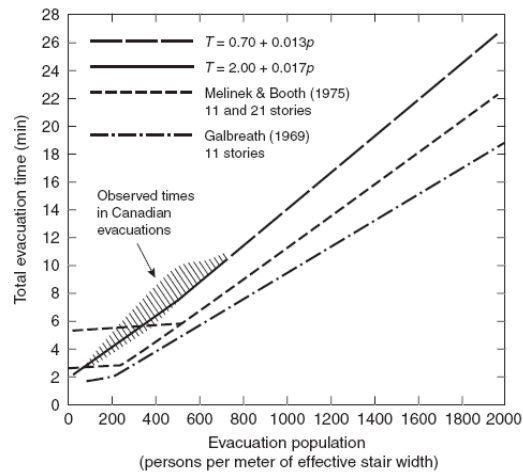
$$T = 0.7 + 0.0133p \quad \text{Equation 2}$$

Where:  $p$  is the actual evacuation population per metre of effective stair width

Therefore, based on an effective stair width of 1160mm, the total simultaneous evacuation time for the exemplar building used in this study may be considered to be 1 hour and 25 minutes.

To assess the accuracy of Equation 2, the results obtained from using this equation were plotted and compared to other calculation procedures by Pauls, as shown in Figure 3.2.3 (a)

below. The cross hatched area of the graph shows the observed times, as shown in Figure 3.2.3 above. It can be seen from these results that this equation produces results that are similar to those observed in actual building evacuations.



**Figure 3.2.3 (a) – Predicted and observed total evacuation times from tall office buildings**

In a case study of simultaneous evacuation of an office building Pauls included for an increase to the total evacuation time based on the roughness of the walls and the effect this has on reducing the flow as well as including for a number of occupants wearing coats during the evacuation. However, Pauls also included a reduction in the evacuation time due to the familiarity of building occupants with evacuation drills.

Based a weighted percentage increase or reduction to the total evacuation time a net adjustment of - 8% was calculated for the above factors. Based on this reduction to the total evacuation time, the calculated evacuation time was within 4% of the observed evacuations.

### 3.2.3 Method Based on Approved Document B

Based on a notional evacuation time of two and a half minutes the flow rate in accordance with Approved Document B can be calculated from the values in Table 7 as 1.33 persons/metre/second.

For example an 1800mm wide stair is capable of accommodating 360 persons over a single level (the additional occupancy of a stair serving additional levels is due to the ‘stacking

capacity'). Based on a notional evacuation period of two and a half minutes, the flow rate may be calculated as follows:

- $360 \text{ persons} / 1.8\text{m wide stair} = 200 \text{ persons per metre}$
- $200 \text{ persons per metre} / 150 \text{ seconds} = 1.33 \text{ persons/metre/second}$

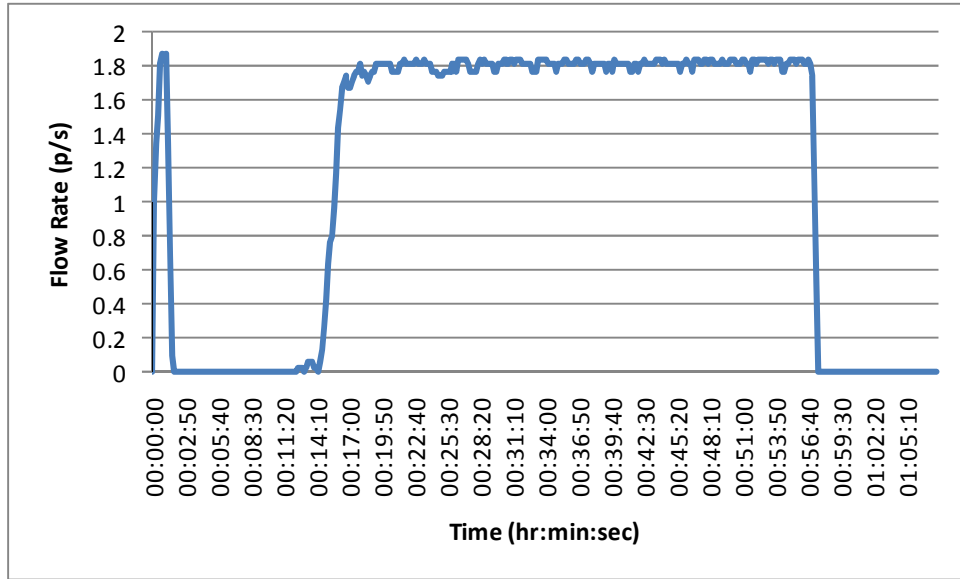
This flow rate is higher than that of Nelson and Mowrer<sup>[3]</sup> as it does not include for a boundary layer. Therefore, based on a stair width of 1400mm the flow rate from the stair is assumed to be equal to 1.862 persons/second. On this basis, the total evacuation time is equal to 1 hour and 7 minutes.

#### 3.2.4 STEPS Assessment of Stair Conditions

Whilst it is noted that the calculation methods above provide a total evacuation time, it is not possible to assess intermediate conditions within the stair during evacuation. Therefore, the simultaneous and phased evacuation of the 50 storey building used as part of the study has been assessed using the STEPS computer evacuation model, as shown below, based on the 1400mm wide stairs required for a code compliant building. Figure 3.2.4 shows the flow rate of the occupants in the stair at the 20<sup>th</sup> floor level during the simultaneous evacuation of the building, which is averaged over a 30 second interval.

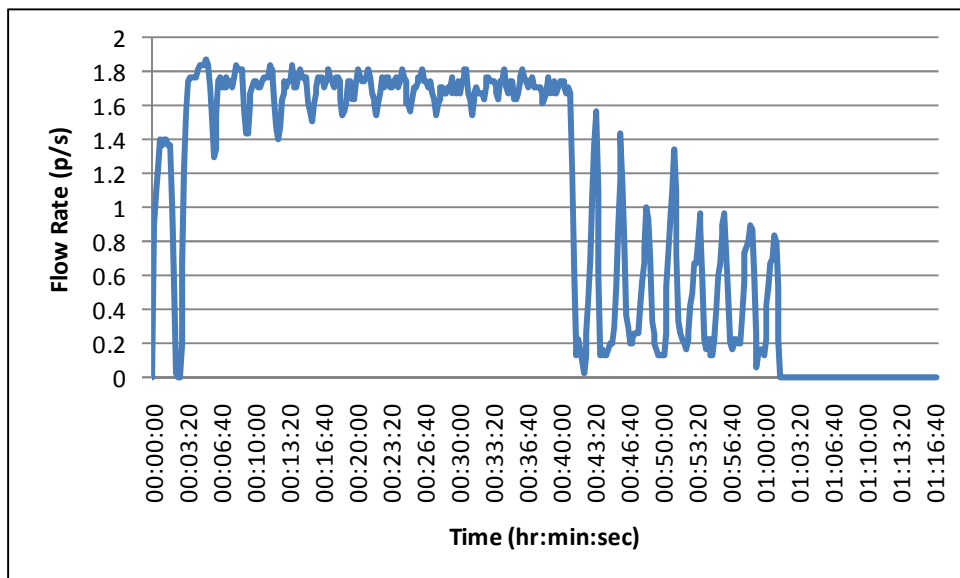
Whilst the flow rate of the final exit is considered to remain constant at 1.862 persons per second, as assumed in the analytical calculation methods detailed above, the flow rate within the upper levels of the stair is severely reduced due to the number of merging flows within the undersized stair enclosure. As can be seen from the graph, the flow rate within the stair reaches the maximum flow rate of 1.862 persons per second approximately one minute after evacuation commences. However, the flow rate within the stair rapidly decreases to zero approximately two minutes after evacuation, suggesting that a large amount of crowding is occurring in the stair, before slowly increasing to the optimum flow rate at sixteen and a half minutes after evacuation commences.

This reduction in the flow rate is considered to significantly increase the overall evacuation time of the occupants within the building, as well as increase anxiety amongst occupants queuing in the stair.



**Figure 3.2.4 – Occupant flow rate during simultaneous evacuation**

Figure 3.2.4 (a) below shows the mass flow rate at the same location within the stair during the phased evacuation of the building. This evacuation method requires the occupants of the floor of fire origin to evacuate first. Then after a two and a half minute interval the floors above the floor of fire origin also evacuate, and so on. Once the floors above the floor of fire origin evacuate the floor levels below commence evacuation. However, this also creates merging flows within the stairs.



**Figure 3.2.4 (a) – Occupant flow rate during phased evacuation**

The benefits of phased evacuation can be seen in the Figure above. Due to the lower numbers of occupants seeking to escape during the initial stages of evacuation the flow rate does not significantly decrease as expected during simultaneous evacuation. The periodical drop in flow rate is considered to be a result of the lag between the assumed floor of fire origin evacuating and those floors immediately above this level evacuating, such that the number of occupants passing the measuring point within the stair at this time is less than the optimum flow rate of the stair.

The reduction in the flow rate at approximately 40 minutes after evacuation commences is due to the location of the fire floor and the order of evacuation of floors above and below the fire floor.

The fire is assumed to be located on the 20<sup>th</sup> floor level. On this basis, the floors above the fire floor evacuate at two and a half minutes intervals. Once the floors above the fire floor evacuate, those floors below commence evacuation. This creates a merging of flows in the stair of occupants from the upper floor levels with those from the lower levels, such that the optimum flow rate is achieved for a portion of the evacuation due to the additional occupants in the stair below this level. However, due to the uneven division of the building, above and below the fire floor, once all the floors from below the fire floor evacuate there is still ten upper storeys which are required to evacuate. Therefore, due to no occupants of the lower floor merging with these occupants, the flow rate is much lower due to the number of occupants passing this point in the stair being less than the optimum flow rate.

### 3.2.5 Occupant Fatigue

The evacuation times calculated above are based on calculation procedures for relatively low rise buildings and do not take into account fatigue as occupants are required to walk down multiple floor levels. It is assumed that this will provide a significant increase in the time required to walk down a large number of stairs and therefore the time to evacuate the building using only stairs.

Later in this thesis, the evacuation simulation software STEPS will be used. In this software, occupants are assumed to travel with a constant speed of 0.95 m/s<sup>[3]</sup>. Whilst this is not unreasonable over a relatively low rise building it is unreasonable to assume that an average person may maintain this speed over many floors.

In a study carried out by Galea et al<sup>[8]</sup> of the evacuation of the World Trade Centre it is acknowledged that the simulation model used in the study didn't include for the fatigue of occupants as they travelled down many flights of stairs. Indeed, Galea et al<sup>[8]</sup> recommend that the results of this simulation could be argued to be between 50 – 100% faster than what would be expected for a lone individual descending some 100 floors.

The total time taken for an occupant to travel down a flight of stairs due to fatigue can be calculated using the following equation<sup>[9]</sup>:

$$t_v(\textit{fatigue}) = t_v + 1.8 \left( \frac{t_v}{100} \right)^2 \quad \text{Equation 3}$$

Where:  $t_v$  is the vertical movement time predicted using evacuation models that do not take fatigue into account

The unit of time for the above equation is not stated. Initial assessments with the units in minutes showed an approximate 2% linear increase in the evacuation time from each floor level. However, based on the use of the time in seconds, the time for evacuation using the fatigue sub-model shows an exponential difference between the fatigue sub-model and the base value, as expected.

The time for evacuation via stairs for each calculation procedure, as well as the time taken using the fatigue sub model, is shown in Figure 3.2.5 below, for comparison.



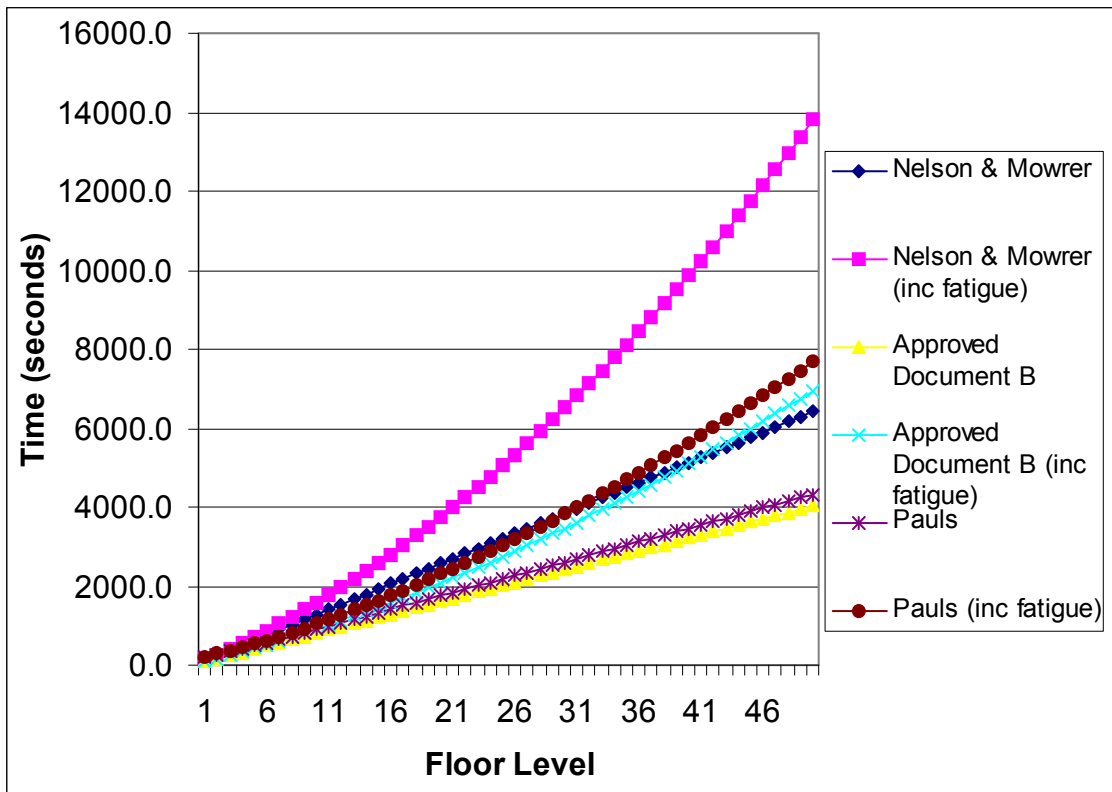


Figure 3.2.5 – Comparison of time for evacuation using fatigue sub-model

As can be seen from the graph, the stair evacuation times are significantly increased when taking into account occupant fatigue. Whilst it is proposed to assess the lift evacuation times with those based on the Approved Document B flow rates, it is noted that this time can be significantly increased when taking into account occupant fatigue. The difference between the calculated stair evacuation time and the ‘fatigued’ stair evacuation time is shown below.

Calculation Method	Stair Evacuation Time	Fatigued Evacuation Time	Factor of Difference
Nelson and Mowrer	6410	13806	2.15
Pauls	4317	7671	1.78
AD-B	4027	6948	1.73

Table 3.2.5 – Summary of fatigued stair evacuation times

### 3.2.6 Summary

Based on the minimal difference between the Approved Document B evacuation times and those calculated using the Pauls method, which have been shown to have a close

correlation to the results of actual evacuation drills, it is proposed to use the Approved Document B method to calculate the stair evacuation times for comparison to the lift evacuation times.

All stair evacuation calculation times are based on the assumption that one of the stairs within the theoretical building is discounted in accordance with Approved Document B, therefore, all of the occupants are assumed to escape via the remaining stair.

Whilst the stair evacuation times will provide a conservative result for comparison to the lift evacuation times, it is noted that in reality these times are likely to be significantly increased when taking into account the fatigue of occupants when descending from the upper storeys of a high rise building. However, it is not proposed to use the 'fatigued' stair evacuation times for comparison due to the limited information and validation available for this calculation method.

### **3.3 Calculation of Evacuation Time Using Lifts**

#### **3.3.1 Introduction**

In normal service the number, the size and speed of passenger lifts in most buildings are designed to be able to move approximately 10% of the total population of the total population of the building from random floors to the level of exit discharge in 5 minutes. This means that any building of any height can be totally evacuated by lift in one hour or less without increasing the number, size, or speed of the lifts normally provided<sup>[39]</sup>.

However, this is based on the assumption that lifts used for evacuation will serve the same floor levels as during ordinary service. In order to allow maximum flexibility in the design of the lift system for evacuation it is considered necessary to assess the building evacuation time for two possible evacuation strategies; evacuation from refuge floors and evacuation from a refuge zone.

### 3.3.2 Calculation Developed By Siikonen

In the work published by Siikonen<sup>[40]</sup>, it is claimed that it is possible to calculate the evacuation time from the lift zone to the discharge floor using one of two calculation methods, depending on the information known.

If the handling capacity of the lifts is known and people are not required to use more than one lift for evacuation (i.e. not required to transfer to lifts at sky lobbies) the egress time may be calculated using the equation below.

$$T_{\text{liftegress}} = 100 \times 5 / 5HC / 1.6 \quad \text{Equation 4}$$

Where: 5HC = Percentage of the building occupants handled by the lift in five minutes

It is possible to use a value for the handling capacity of the lift (5HC) based on information provided in lift design guides.

The value of 1.6 used in the equation is the efficiency factor of the control system, which according to Siikonen<sup>[40]</sup> “can typically be assumed to be 1.6”. This efficiency factor is assumed to take into account the reduction of the lift evacuation time based on the use of the lifts in down-peak mode, on the basis that it is only required to stop at two floors (i.e. the destination and discharge floors). No further guidance is provided by Siikonen with regards to selecting an alternative value. However, it is noted that CIBSE Guide D suggests a value of 1.6 for calculating the down peak travel time.

The value of 100 is considered to be the total percentage of the building occupants, while the value of 5 represents the time period the handling capacity of the lifts are assessed by.

Based on a value of 15% for the handling capacity in five minutes, as recommended in CIBSE Guide D<sup>[27]</sup>, the evacuation time of a lift operating in down-peak mode is approximately equal to 20.8 minutes. However, as discussed in Section 3.3.6, this requires lifts with very high performance values.

On this basis, it is not considered appropriate to apply the above calculation method to buildings which utilise lifts for evacuation that are not used in general evacuation mode.

However, Siikonen also provides an alternative and slightly more detailed calculation procedure for use when the handling capacity percentage of the lift is unknown, which is also discussed in work by Hakonen<sup>[41]</sup>, that may be applied to lifts that are required to accommodate a greater occupancy than designed to accommodate, such as in an evacuation scenario.

The round trip times for each floor can be calculated when we know the distance from the rescue floor to the destination floor  $H_i$  and back, and divide it by the rated speed  $v$ . Additional guidance<sup>[41]</sup> states that  $t_v$  is the time to travel one floor with contract speed and  $H_i$  is the reversal floor index (i.e. the distance between floors).

Based on the procedure detailed by Siikonen it is the authors belief that the value of  $t_v$  is equal to the time to travel 1m at the rated speed of the lift based on the value of  $H_i$  being the distance from the refuge floor to the discharge floor in metres.

In addition to the time to travel the distance between floor levels, the additional times for stops has to be added to the round trip time. Stop times includes, door delays, lift acceleration and deceleration delays ( $t_s$ ) associated with each stop ( $v$ /acceleration), and delays for the  $M$  passengers to transfer in and out from the car ( $t_m$  typically 1 second per person) during down trip  $i$ .

A diagrammatic representation of lift motion for a single trip is provided by Klote<sup>[19]</sup>, and is reproduced in 3.3.5.3.

The sum of all round trip times may be expressed by:

$$RTT = \sum_{i=1}^{N_{RT}} (2H_i t_v + 2t_s + 2M_i t_m) \quad \text{Equation 5}$$

This value for the round trip time is for a single lift car and for a group of  $N$  lifts the time may be calculated by dividing the RTT value by the number of lifts available.

Due to the method of calculation, a constant default value of 10 seconds was used in the calculation for the delay (for a single round trip) due to acceleration and deceleration. This is considered to be reasonable for the lifts at lower speeds, where the difference between

a lift travelling the whole distance at a constant speed and a lift which is required to accelerate and decelerate is approximately equal to this value, when including the additional time to open or close the doors.

However, a more accurate method of calculating the delays associated with acceleration and deceleration has been included in the evacuation calculation spreadsheet, as discussed in Appendix A.

### 3.3.3 Calculation Procedure Developed By Japanese Researchers

A number of Japanese studies have been carried out<sup>[42, 43]</sup> to study the feasibility of using lifts as a method of evacuation.

The first of these methods by Sekizawa et al<sup>[42]</sup> used a very simplified equation to calculate the lift times for the evacuation of a Hiroshima apartment block based on research conducted after a serious fire in the building and is a revised model from the original, developed circa 1998. The study was carried out as a result of the large number of elderly persons in the building used the lifts as a means of escape, even though the lift system was not designed as a means of escape route. The lift system used in the building is a skip-floor type (i.e. the lift stops only on even number floors from the 2<sup>nd</sup> to the 20<sup>th</sup> floors).

The formula developed by Sekizawa et al<sup>[42]</sup> is shown below and requires the transfer time by lift and time for evacuees to enter and exit a lift to be calculated separately and then combined to get an overall evacuation time.

Transfer time by lift

$$T_m = \frac{H_{ij}}{V_{elv}} + \frac{V_{elv}}{\alpha} \quad \text{Equation 6}$$

Where:  $T_m$  is the lift transfer time (s)

$H_{ij}$  is the vertical distance between  $i$ th floor and  $j$ th floor (m)

$V_{elv}$  is the lift velocity (m/s)

$\alpha$  is the lift acceleration ( $m/s^2$ )

Time for evacuees to get on and off a lift

$$T_e = \frac{(P_{fi} - P_{stri})}{(N_{elv} \times W_{elv})} + (T_{op} + T_{cl}) \quad \text{Equation 7}$$

Where:  $T_e$  is the time for evacuees to get on and off a lift (s)

$P_{fi}$  is the number of occupants on the  $i$ th floor

$P_{stri}$  is the number of evacuees by stairs on the  $i$ th floor

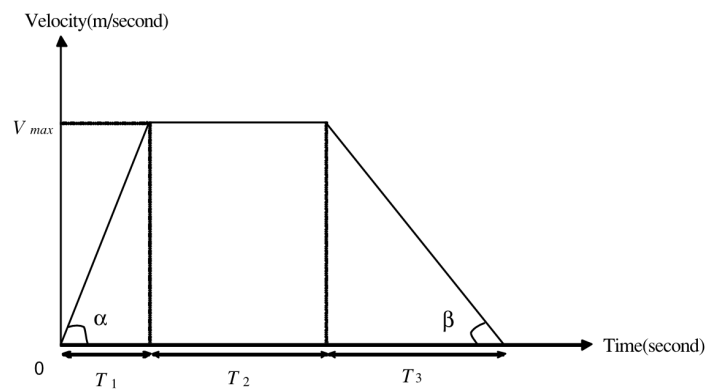
$N_{elv}$  is the flow factor of lift doors (persons/m/s)

$W_{elv}$  is the available lift door width (m)

$T_{op}$  is the opening time of the lift doors (s)

$T_{cl}$  is the closing time of lift doors (s)

An alternative calculation method was later published by Sekizawa et al<sup>[43]</sup>, based on similar time-velocity graphs as those used by Klote<sup>[19, 44]</sup> as shown in 3.3.3.



**Figure 3.3.3 – Graphical representation of single lift trip**

For a lift which has a stage of constant velocity, the vertical distance for the lift movement may be calculated from the following equations:

$$L = \frac{1}{2} \alpha T_1^2 + V_{\max} T_2 + \frac{1}{2} \beta T_3^2 \quad \text{Equation 8}$$

$$V_{\max} = \alpha T_1 = \beta T_3 \quad \text{Equation 9}$$

Where: L is the vertical distance for the lift movement (m)

$\alpha$  is the lift acceleration (m/s<sup>2</sup>)

$\beta$  is the lift deceleration (m/s<sup>2</sup>)

$V_{\max}$  is the maximum lift velocity (m/s)

$T_1$  is the acceleration time (s)

$T_2$  is the constant velocity time (s)

$T_3$  is the deceleration time (s)

From these equations Sekizawa et al derived the following equations:

$$T_1 = \frac{V_{\max}}{\alpha} \quad \text{Equation 10}$$

$$T_2 = \frac{1}{V_{\max} \left( L - \frac{V_{\max}^2}{\alpha} - \frac{V_{\max}^2}{\beta} \right)} \quad \text{Equation 11}$$

$$T_3 = \frac{V_{\max}}{\beta} \quad \text{Equation 12}$$

On this basis, the total time for a single trip can be calculated as follows.

$$T_{total} = T_1 + T_2 + T_3 \quad \text{Equation 13}$$

$$T_{total} = \frac{V_{\max}}{\alpha} + \frac{1}{V_{\max} \left( L - \frac{V_{\max}^2}{\alpha} - \frac{V_{\max}^2}{\beta} \right)} + \frac{V_{\max}}{\beta} \quad \text{Equation 14}$$

Therefore, the round trip time is equal to  $T_{total}$  multiplied by two to include for the lift trip to the discharge floor and back.

However, it is believed that the equation for  $T_2$  has been incorrectly derived from the original equation. This is on the basis that as the distance between floors increases, the denominator decreases, and the resulting evacuation time decreases. However, it is considered reasonable to assume that as the distance between floor levels increases the

time for evacuation should also increase. On this basis, it is believed that the original equation should be derived as follows to determine  $T_2$ :

$$L = \frac{1}{2}\alpha T_1^2 + V_{\max} T_2 + \frac{1}{2}\beta T_3^2 \quad \text{Equation 15}$$

Where

$$T_1 = \frac{V_{\max}}{\alpha} \text{ and } T_3 = \frac{V_{\max}}{\beta} \quad \text{Equation 16}$$

Then

$$V_{\max} T_2 = L - \left( \frac{1}{2} \alpha \left( \frac{V_{\max}}{\alpha} \right)^2 \right) - \left( \frac{1}{2} \beta \left( \frac{V_{\max}}{\beta} \right)^2 \right) \quad \text{Equation 17}$$

$$V_{\max} T_2 = L - \left( \frac{1}{2} \alpha \left( \frac{V_{\max}^2}{\alpha^2} \right) \right) - \left( \frac{1}{2} \beta \left( \frac{V_{\max}^2}{\beta^2} \right) \right) \quad \text{Equation 18}$$

$$T_2 = \frac{L - \left( \frac{1}{2} \frac{V_{\max}^2}{\alpha} \right) - \left( \frac{1}{2} \frac{V_{\max}^2}{\beta} \right)}{V_{\max}} \quad \text{Equation 19}$$

Which can be simplified as follows:

$$T_2 = \frac{L - \frac{V_{\max}^2}{2\alpha} - \frac{V_{\max}^2}{2\beta}}{V_{\max}^2} \quad \text{Equation 20}$$

Based on the initial results achieved using the equation provided by Sekizawa et al it is proposed to assess the lift evacuation time using the modified equation for  $T_2$  stated above.

### 3.3.3.1 Example Calculation

The evacuation of a 53 storey office building was calculated as part of the study by Sekizawa et al<sup>[43]</sup> using stairs as well as the evacuation of the building using only lifts.

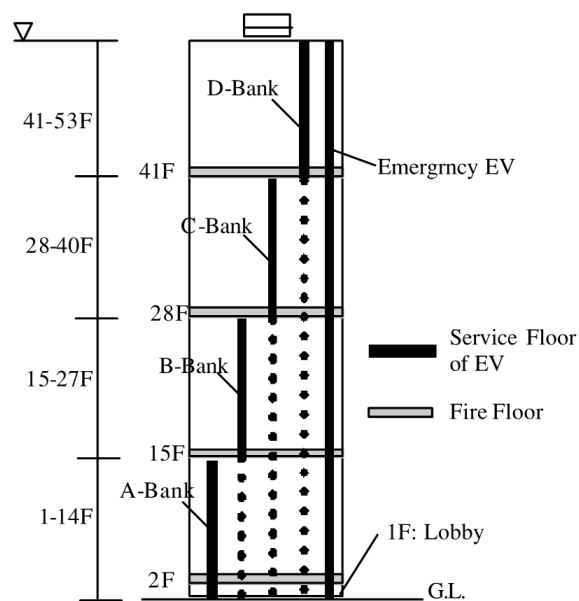


The standard building floor area measured 2629m<sup>2</sup> while the floor to floor height was 3.65m.

The centre core of the building contained four banks of lifts (A to D) which each served a dedicated lift zone as follows:

- A bank - 1<sup>st</sup> to 14<sup>th</sup>
- B bank – 15<sup>th</sup> to 27<sup>th</sup>
- C bank – 28<sup>th</sup> to 40<sup>th</sup>
- D bank - 41<sup>st</sup> to 53<sup>rd</sup>

Each bank contained eight lifts. Therefore, the building was provided with 32 lifts in total. However, as part of the study it was assumed, as the most onerous scenario, that the occupants were unable to use D bank and were instead required to escape via two emergency lifts. A diagrammatic section of the building is shown in the figure below.



**Figure 3.3.3.1 – Section of building used in Sekizawa’s calculations**

The evacuation of the building was then studied using the three remaining banks of lifts contained within the building, plus the two evacuation lifts. The results of which may be seen in Table 3.3.3.1(a).

	Unit	A bank	B bank	C bank	D bank	Emergency lift
Service floor	Floor	1-14	1, 15-27	1, 28-40	1, 41-53	1-53
Number of lifts		8	8	8	8	2
Capacity	Persons	22	22	22	22	22
Constant speed	m/s	4	5	6	7	3
Acceleration	m/s <sup>2</sup>	0.7	0.7	0.7	0.7	0.7
Deceleration	m/s <sup>2</sup>	-0.7	-0.7	-0.7	-0.7	-0.7
Door width	m	1.1	1.1	1.1	1.1	1.1
Occupant load	persons	2520	2520	2520	2520	-

**Table 3.3.3.1 –Lift details**

The evacuation times listed within the paper are shown below as well as the evacuation time for the same building using the modified formula discussed above.

Lift Bank	Stated Time <sup>[43]</sup> (s)	Modified Equation (s)
A	967	314
B	1268	513
C	1483	694
D	6122	2862

**Table 3.3.3.1 (a) – Comparison of Evacuation Times**

***Based on the uncertainty between results, it is not proposed to include the evacuation times by Sekizawa et al in the assessment. Results using the modified equation will be provided for comparison where appropriate.***

#### 3.3.4 STEPS

The STEPS evacuation simulation programme, developed by Mott McDonald, is a commercially available movement/partial behavioural simulation programme, which may be used to simulate the evacuation of a building, and contains controls for describing<sup>[45]</sup>:

- Pre-movement abilities,
- Occupant characteristic,
- Patience factor,
- Family behaviour,

The most detailed information available is presented by Kugligowski<sup>[45]</sup>:

*“The model views the occupants individually and allows the user to give individual traits to each person or groups of people in the simulation. The occupants also have an individual view of the building, because the user can specify each occupants “target” or checkpoint (exit), allowing for the user to aid in the mapping of a defined route for certain groups of people.”*

Also, for each target, each occupant group is assigned an awareness factor between 0 and 1, specifying the fraction of that group which knows about the exit. If a 0 is specified for the occupant group and target, that denotes that no one in the group knows about the target exit, and the label of 1 would specify that everyone in the group knows about the target or exit. The occupants choose the exit that they travel to according to the score assigned to each exit. This score is based on the following four factors:

- 1) The shortest distance to the exit,
- 2) Familiarity with the exit,
- 3) The number of occupants around the exit,
- 4) The number of exit lanes.

Three interconnecting components in the model are considered: the plane and path network, the description of the human characteristics, and the movement of the people within the system. The algorithm for a person to select the travel path is based on a combination of decisions and network-based models. Planes that represent the actual floor space consist of a grid configuration on which people can walk, the spacing of which is dependent on the maximum specified population density. Alternatively, predefined paths or planes are used to represent stairways, upon which deviations of the walking directions are not possible until another path or plane is reached.

As well as the potential to calculate the lift evacuation time, STEPS can also provide additional information on conditions in the building during evacuation, including stair flow rates, lift waiting times and floor space per person on refuge floors.

The programme is provided with a number of pre-programmed values with regards to walking speed, and flow rates. However, these are generally based on NFPA values commonly used in the USA. Nevertheless, the user may input customised values for each variable. To allow a comparison to be made between models, each variable will be specified, rather than using the default values.

The programme is commercially sensitive; therefore, it is not considered possible to access the computer code for the programme to validate the model. However, it is proposed to note the work of others who have been able to validate and verify the accuracy of the programme, as well as conduct sensitivity studies into the accuracy of the model.

#### 3.3.4.1 *Validation*

This model has been validated<sup>[46, 47]</sup> against code compliant evacuation times and has been shown to generally provide an accurate result of the overall evacuation time. Results which do not closely match the code compliant evacuation times are considered to be conservative results which exceed the code compliant evacuation times<sup>[45]</sup>. Details of the validation studies are provided below.

##### *Wall and Waterson*

The accuracy of the software was validated<sup>[46]</sup> by comparing the results for the evacuation of two example train stations detailed in NFPA 130 '*Standard for Fixed Guideway Transit and Passenger Rail Systems*' with the results of the hand calculations detailed in the aforementioned standard.

The STEPS results of both examples give longer and more conservative evacuation times than the figures obtained from NFPA 130 hand calculations (between 0.9% to 11.4%). This is considered to be the result of the assumption within the NFPA calculations that occupants will evenly distribute amongst the available exits. However, based on the STEPS

calculation methodology of calculating an exit 'score', occupants are noted to queue for exits that are in use, whilst others are empty.

Whilst it is noted that the validation has been conducted using the calculation procedure of NFPA 130, Wall and Waterson state that 'by changing the variables for exit flow rates, and passenger travelling speeds, STEPS may be made compatible with other similar standards', such as Approved Document B, BS 7974-6, SFPE Handbook. On this basis, it is acceptable to use this programme with the relevant values from English building codes.

#### *Lord et al*

Additional validation of the STEPS programme was conducted by Lord et al<sup>[47]</sup> by comparing the evacuation times from three buildings calculated with STEPS with those obtained from actual evacuation drills and the simulated times using the EXIT89 programme.

Simulations were conducted of three buildings of varying height and occupancy. Two of the buildings were simulated using the known values for the occupant data, as well as additional simulations with uncertainty analysis data. The third building was assessed using the average value of an uncertainty analysis conducted as part of the study.

A summary of the results for each building is listed below:

#### *London Building*

- STEPS predicted the same evacuation time as the actual evacuation time when the occupant load data for the building was known.
- STEPS over predicted the evacuation by approximately 6% when the average value from the uncertainty analysis was used.

#### *Calgary Building*

- STEPS predicted a value that was approximately 6% less than the actual evacuation time when the occupant load data was known.

- STEPS over predicted the evacuation time by 211% when the average uncertainty analysis data was used.

#### *Ottawa Building*

- STEPS over predicted the evacuation time by 202% when the average uncertainty analysis data was used.

The reason for the large difference between the actual evacuation time and the average uncertainty analysis data for the Ottawa building is noted by Lord et al as ‘relating to the number of people that were actually in the building and the number in the model. The total number of people in the model varied between 1293 and 3738 occupants based on office occupant load factors found in literature and building codes. The low end of this range is more than twice the actual number of people in the office building, which could account for the average evacuation time of the STEPS model being approximately twice the actual evacuation time’.

Nevertheless, based on the results of this assessment, Lord et al<sup>[47]</sup> concluded that “STEPS may over predict the total evacuation time for a building if prior knowledge of the occupant load is not provided”.

STEPS is sensitive to grid-size. Changing the grid from 0.3 metres to 0.6 metres can have a significant impact on the results of the model. Efforts should be taken when using STEPS to use an appropriate grid size and to perform some sensitivity analysis.

### 3.3.5 ELVAC

#### 3.3.5.1 *Introduction*

The ELVAC simulation programme, developed by Klote et al<sup>[19]</sup>, may be used to calculate the evacuation time for one group of lifts. For a building containing more than one group of lifts the programme is required to be used a number of times to calculate the evacuation time for each group. The programme is written in Quick BASIC and will only display the output in numerical form.

There is a limited amount of information available with regards to the results of evacuation studies completed using ELVAC to verify the programme. Limited information on the programme is available based on the example evacuation assessment carried out by Klote et al<sup>[19]</sup>, as shown in Table 3.3.5.4, as well as the description given by Kuligowski<sup>[16, 45]</sup>

### 3.3.5.2 *Model Description*

Kuligowski<sup>[14]</sup> states that “ELVAC is a model dedicated to the simulation of building evacuation by lift only (and) only gives the gross evacuation time of the building, and along with its assumptions, may cause the model to lose accuracy in calculation, especially when compared to a complete simulation model.”

“The ELVAC model works on the two stop evacuation approach meaning that the car travels from the lobby to a specific floor and then back down to the lobby, independent of the number of tenants in the car”[14], similar to the non-stopping on the way down method discussed in Section 2.6.1.3.

Kuligowski<sup>[14]</sup> recommends that changes should be made to the ELVAC model to allow the model to recognise when the lift car is provided with spare capacity and to pick up more occupants on the way down”. However, as discussed in Section 2.6.1.3, this may not decrease the overall evacuation time due to the additional delays associated with the door opening and closing times.

Kuligowski<sup>[14]</sup> states that “in an actual fire evacuation, it is most likely that the cars will move to the fire floor (and floors above and below) to evacuate those occupants first.” However, this is only true for a certain method of evacuation and does not hold true for evacuation between two floors, such as that from a refuge floor.

Based on the same method of operation in the STEPS model, as that in ELVAC, it is considered reasonable to use ELVAC to assess the evacuation time for a lift that serves dedicated refuge floors only as well as lifts that serve evacuation zones containing multiple floor levels.

### 3.3.5.3 Calculation of Evacuation Time

A number of variables within lift evacuation may be calculated using the equations given by Klote<sup>[11, 44]</sup> for use in the computer simulation programme ELVAC. The default values have been used for the input into this simulation programme. On this basis, it is proposed to assess the sensitivity of the results to these values in Section 3.3.5.5.

The calculation procedures detailed by Klote<sup>[19, 44]</sup> are intended to calculate the evacuation time for one group of lifts. The time to evacuate a building can be calculated using the equation below:

$$t_e = t_a + t_o + \frac{(1 + \eta)}{J} \sum_{j=1}^m t_{r,j} \quad \text{Equation 21}$$

Where:  $t_{r,j}$  = time for round trip j

$m$  = is the number of round trips

$j$  = number of lifts

$\eta$  = trip inefficiency

$t_a$  = lift start up time

$t_o$  = the travel time from the lift lobby to the outside or to another safe location

The number of round trips may be calculated by dividing the occupancy by the handling capacity of the lifts (i.e. number of lifts x capacity of lifts).

The value for the trip inefficiency is a default value of 0.1 within the programme and represents trips to empty floors and trips to pick up only a few occupants.

#### *Start Up Time*

“For automatic lift operation during evacuation, a simple approach is to start lift evacuation after all of the lifts have been moved to the discharge floor. For this approach, the start up time ( $t_a$ ) consists of the time for lifts to go to the discharge floor plus the time for the passengers to leave the lifts. This can be expressed as:

$$t_a = t_T + (t_u + t_d)(1 + \mu) \quad \text{Equation 22}$$



Where:  $t_T$  = the travel time for the lift car to go from the furthest floor to the discharge floor

$t_U$  = the time for passengers to leave the lift

$t_d$  = is the time for the doors to open and close once

$\mu$  = is the total transfer inefficiency

The default value within the programme for people to leave the lift is given as 0.6 seconds. A sensitivity study of the time taken for people to transfer out of the lift is provided in Section 3.3.5.5 and demonstrates that this has minimal impact on the total evacuation time.

The time for the doors to open or close is shown in Table 3.3.5.3 below, and may be varied depending on the door width and opening arrangement. The simulations conducted as part of this thesis use a door opening time of 5.33 seconds for an assumed 1200m wide, centre opening door.

The calculation method of the total transfer inefficiency is discussed below for the standing time.

#### *Round Trip Time*

The round trip time starts at the discharge floor and consists of the following sequence:

- Lift doors close
- Car travels to another floor
- Lift doors open
- Passengers enter the lift car
- Doors close
- Lift car travels to discharge floor
- Doors open
- The passengers leave the lift car

The round trip time can be expressed by

$$t_r = 2t_T + t_s$$

Equation 23

Where:  $t_s$  is the standing time

$t_T$  is the travel time for one way of the round trip

This is based on assumption that the lift only stops at one floor to pick up passengers. Therefore, this programme is only considered to be suitable for evacuation simulations of 'non-stopping' on the descent, as discussed in Section 2.6.1. It is not possible to assess different lift operation modes using this programme.

### *Standing Time*

The standing time is the sum of the time to open and close the lift doors twice, the time for people to enter the lift and the time for people to leave the lift. Considering the transfer inefficiencies, the standing time can be expressed as:

$$t_s = (t_i + t_u + 2t_d)(1 + \mu)$$

Equation 24

Where:  $\mu = \alpha + \varepsilon + \gamma$

$\alpha$  = basic transfer inefficiency (generally 0.1)

$\varepsilon$  = door inefficiency

$\gamma$  = other inefficiencies in people transfer into or out of lifts

$t_d$  = time for doors to open and close

$t_i$  = time for people to enter the lift

$t_u$  = the time for passengers to leave the lift

The door inefficiency ( $\varepsilon$ ) is used to adjust for any increase in transfer time over that of a 1200mm wide, centre opening, door. For this simulation a 1200mm wide, centre opening, door has been assumed and, therefore, the value for the door transfer inefficiency is equal to zero. To allow an accurate comparison to be made between models the STEPS simulations also use a door opening time of 5.3 seconds. The value of the door opening times may be adjusted within the model from pre-programmed times, which vary between 4.1 seconds and 9.9 seconds.

The values of  $\epsilon$  are shown in Table 3.3.5.3, which is taken direct from Klote's work.

Door Type	Width mm (in)	Time <sup>1</sup> to Open and Close $t_d$ (s)	Door Transfer Inefficiency $\epsilon$
Single-Slide	900 (36)	6.6	0.10
Two-Speed	900 (36)	5.9	0.10
Center-Opening <sup>2</sup>	900 (36)	4.1	0.08
Single-Slide	1100 (42)	7.0	0.07
Two-Speed	1100 (42)	6.6	0.07
Center-Opening <sup>2</sup>	1100 (42)	4.6	0.05
Two-Speed	1200 (48)	7.7	0.02
Center-Opening <sup>2</sup>	1200 (48)	5.3	0
Two-Speed	1400 (54)	8.8	0.02
Center-Opening <sup>2</sup>	1400 (54)	6.0	0
Two-Speed	1600 (60)	9.9	0.02
Center-Opening <sup>2</sup>	1600 (60)	6.5	0
Two-Speed, Center-Opening <sup>2</sup>	1600 (60)	6.0	0

<sup>1</sup>Time to open and close door includes 0.5 second for car to start.  
<sup>2</sup>When preopening can be used, the time to open and close these door can be reduced by 1 second.

**Table 3.3.5.3 – Door operating time and transfer inefficiency**

The inefficiency ( $\gamma$ ) is used to account for any other inefficiencies as people transfer into or out of lifts, such as increased movement times within a lift car due to an unusual lift car shape or limited physical capabilities. For example, a value of 0.05 is recommended for hospital lifts and 0 in office buildings. However, Klote does not explain how these values have been determined, such that it is not possible to calculate alternative values.

Notwithstanding, it is noted that a value of only 0.05 is applied for lifts in a hospital building, where the transfer inefficiency is assumed to be the highest. On this basis, it is assumed that this factor has a minimal impact on the total evacuation time, when compared to the value for a building with a large number of able bodied occupants. Therefore, it is proposed to apply the default value to all simulations.

As discussed previously, it is not proposed to include for the increased inefficiencies associated with using lifts for the evacuation of wheel chair bound persons.

The time for people to enter the lift depends on the number ( $N$ ) of people entering and on the door operation. The time for ( $N > 2$ ) people to enter the lift can be expressed as:

$$t_i = t_{dw} + t_{io}(N - N_{dw}) \quad \text{Equation 25}$$

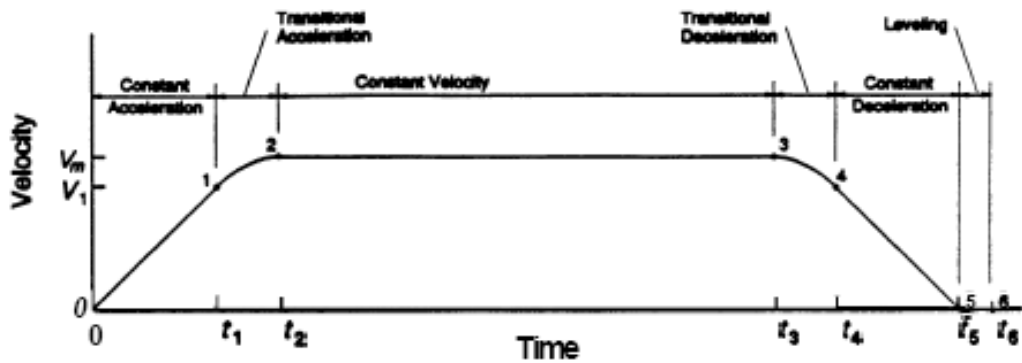
Where:  $N_{dw}$  = the number of people entering the lift during the dwell time

$t_{io}$  = the average time for one person to enter the lift

The default value for a person to enter the lift is equal to 1 second, while the time for a person to exit the lift is 0.6 seconds.

*Travel Time*

Travel time can be represented graphically for motion which reaches normal operating velocity, as shown in Figure 3.3.5.3.



**Figure 3.3.5.3 – Velocity of lift reaching normal operating velocity**

The travel time ( $t_T$ ) is required to calculate the value of the start up time during the sensitivity study. Based on the provision of a lift that reaches normal operating velocity, this may be calculated as follows.

The time to complete constant acceleration motion ( $t_1$ ) is

$$t_1 = \frac{V_1}{a} \quad \text{Equation 26}$$

Where  $V_1$  is the velocity at the end of constant acceleration. This value is dependent on the velocity of the lift and the rate of acceleration.

The distance travelled during constant acceleration is:

$$S_1 = \frac{V_1^2}{2a} \quad \text{Equation 27}$$

The time to reach the end of transitional velocity is approximated by assuming that the product of velocity and acceleration are constant and can be expressed as:

$$t_2 = \frac{V_m^2 - V_1^2}{2V_1 a} + t_1 \quad \text{Equation 28}$$

The distance travelled by the end of transitional acceleration is:

$$S_2 = \frac{1}{3a} \left( \frac{V_m^3}{V_1} - V_1^2 \right) + S_1 \quad \text{Equation 29}$$

Therefore, the one way travel time may be calculated as follows:

$$t_5 = 2t_2 + \frac{S_T - 2S_2}{V_m} \quad \text{Equation 30}$$

Usually lifts do not stop exactly at the desired floor at the end of deceleration, so the lift must be moved slowly up or down to get it nearly level with the floor. The levelling time must be added to the above time to get the total travel time for a one way trip. The default levelling time is 0.5 seconds.

#### 3.3.5.4 Validation

Direct validation of either STEPS or ELVAC is not possible because of the difficulty to obtain experimental data for using lifts in fire evacuation. To give confidence in the use of these two simulation methods, a comparison will be made between the results of these two different simulation methods. For this purpose, a 21 storey exemplar building discussed by Klote<sup>[19]</sup> in the associated ELVAC literature has also been simulated using the STEPS programme.

### *Building Description*

The building used by Klote et al<sup>[19]</sup> in the exemplary calculation has 21 storeys (i.e. Ground plus 20). The upper 11 storeys are required to evacuate via lift while the remaining 10 storeys are required to evacuate via stairs. However, it is assumed that 3% of the occupants of these lower floors were also required to evacuate via lifts due to an inability to travel down the stairs. Each floor is provided with an occupancy of 90 persons. On this basis, the lifts are required to evacuate 3 persons from each of the lower floors.

The evacuation was carried out using a group of six lifts. However, as a safety factor, one of the lifts in the calculation is assumed to be out of operation due to maintenance. Therefore, the evacuation is carried out using five of the lifts. The lift performance is listed below.

- Capacity - 16 persons,
- Door width - 1200mm wide, centre-opening door,
- Door opening time – 5.3 seconds,
- Operating velocity - 3m/s
- Rate of acceleration and deceleration -  $1.2\text{m/s}^2$
- Dwell time - 4 seconds.

### *Results of ELVAC Assessment*

The results of the ELVAC assessment provided by Klote is shown in Table 3.3.5.4 below. The value for the time for evacuation per floor is not equal to the number of round trips multiplied by the round trip time. This is on the basis that, during the final round trip to a floor, the lift is not fully occupied and therefore, the round trip time is less than that of a full lift car. Whilst this is taken into account by the ELVAC programme when calculating the evacuation time per floor, the time for this final trip is not displayed within the outputs.

The number of people on a floor, plus the percentage of those occupants evacuated by lifts, and the time to leave the building are notional values used in the assessment by Klote. The number of round trips is calculated based on the number of lifts and the occupancy capacity per lift required to evacuate those occupants requiring lift evacuation.

The total round trip time is the sum value of all the evacuation times per floor. This value is equal to the sum of the evacuation times per floor on the basis that the lifts are operating in down-peak mode, as discussed in Section 2.6.1, such that the lifts serve the top floor level until it is completely evacuated before moving to the next floor level below. On this basis, the lowest floor level will not be evacuated until the floor levels above are completely evacuated. Therefore, the total round trip time is equal to the sum of the evacuation times per floor. The start up time may be calculated using equation 22. The evacuation time

Floor	Height	One way trip time (s)	Round trip time (s)	People on floor	Percentage evacuated by lift	Number of round trips	Time per floor
20	64	24.4	89.1	90	100	6	524.1
19	60.8	23.4	87.0	90	100	6	511.3
18	57.6	22.3	84.8	90	100	6	498.5
17	54.4	21.2	82.7	90	100	6	485.7
16	51.2	20.2	80.6	90	100	6	472.9
15	48.0	19.1	78.4	90	100	6	460.1
14	44.8	10.2	76.3	90	100	6	447.3
13	41.6	17.0	74.2	90	100	6	434.5
12	38.4	15.9	72.0	90	100	6	421.7
11	35.2	14.2	69.9	90	100	6	408.9
10	32.0	13.8	67.8	90	3	1	396.1
9	28.8	12.7	45.8	90	3	1	45.8
8	25.6	11.6	43.7	90	3	1	43.7
7	22.4	10.6	41.6	90	3	1	41.6
6	19.2	9.5	39.4	90	3	1	39.4
5	16.0	8.4	37.3	90	3	1	37.3
4	12.8	7.4	35.2	90	3	1	35.2
3	9.6	6.3	33.0	90	3	1	33.0
2	6.4	5.2	30.8	90	3	1	30.8
1	3.2	3.8	28.0	90	3	1	28.0
Ground	-	-	-	-	-	-	-
Total round trip time							5395.6
Start up time							41.3
Time to leave building							30.0
Evacuation time							1258.3

**Table 3.3.5.4 – Lift trip and evacuation time calculated by ELVAC computer program**

### *Results of STEPS Assessment*

The STEPS programme provides numerical outputs in Microsoft Excel format, compared to the MS DOS outputs created by ELEVATE. On this basis, the results at the key time steps within the STEPS simulation have been determined from the Excel spreadsheet of outputs and are summarised in the figure below.

The one way trip time and round trip time values have been determined from the values for the lift position during the simulation at two second intervals. On this basis, the round trip time value is considered to be accurate within +/- two seconds. The round trip time for a lift which is not fully occupied has also been included within Table 3.3.5.4 (a) to enable the calculation of the evacuation time per floor.

To ensure that an accurate comparison can be made against the results of the ELVAC assessment it is considered necessary to calculate the evacuation time using the same calculation methodology discussed above. Therefore, the value for the time to outside is also equal to 30 seconds.

The time for people to exit the lift ( $T_u$ ) is not an input within the STEPS model. However, this may be determined from the results of the number of persons in a lift, as discussed below.

The output file of the number of persons within the lift shows the occupancy of a lift at one second intervals during the simulation. On this basis, it is possible to calculate the time for occupants to exit a lift based on the time taken for the lift occupancy to change from full occupancy (16 persons) to empty (displayed as zero persons). Occupants enter and leave the lift in the STEPS programme in four seconds (0.25 seconds per person).

On this basis, the evacuation time using the STEPS programme may be calculated by substituting the relevant values into Table 3.3.5.4, as shown in Table 3.3.5.4 (a) below, which also includes the final round trip time to pick up the last few remaining occupants.



Floor	Height	One way trip time (s)	Round trip time (s)	Shorter Round trip time (s)	People on floor	Percentage evacuated by lift	Time per floor
20	64	26	80	72	90	100	472
19	60.8	24	76	72	90	100	452
18	57.6	22	74	68	90	100	438
17	54.4	22	72	66	90	100	426
16	51.2	20	70	64	90	100	414
15	48.0	20	68	60	90	100	400
14	44.8	20	66	58	90	100	388
13	41.6	18	64	56	90	100	376
12	38.4	18	62	54	90	100	364
11	35.2	18	62	52	90	100	362
10	32.0	14	58	50	90	3	340
9	28.8	14	40	0	90	3	40
8	25.6	12	38	0	90	3	38
7	22.4	12	36	0	90	3	36
6	19.2	10	34	0	90	3	34
5	16.0	8	32	0	90	3	32
4	12.8	8	30	0	90	3	30
3	9.6	6	28	0	90	3	28
2	6.4	6	26	0	90	3	26
1	3.2	6	24	0	90	3	24
Ground	-	-	-	-	-	-	-
Total round trip time							4720
Start up time							42.06
Time to leave building							30
Evacuation time							1110.5

**Table 3.3.5.4 (a) – Summary of lift evacuation times using STEPS programme**

#### *Comparison of Results*

The ELVAC evacuation time is equal to 1258 seconds. However, the evacuation time using the STEPS simulation programme is equal to 1110 seconds. This is 148 seconds less than the value of the ELVAC assessment, which is a reduction of approximately 11.8%. Considering that there are many uncertainties in input values used in these two simulation methods, such a close agreement indicates that both simulation methods have incorporated the essential features of lift evacuation in a consistent way and their simulation results may be considered acceptable.

### 3.3.5.5 Sensitivity Study

The ELVAC simulation programme requires a number of input variable to be provided to determine the value for the evacuation time, other than the default values, discussed in Chapter 5..

Whilst it is noted that a default value for these inputs is provided by Klote<sup>[19, 44]</sup>, it is proposed to conduct a sensitivity study, using the theoretical building detailed in Section 1.4, to assess the sensitivity of the evacuation time, based on varying some of the input values, to determine the sensitivity of the final value to these inputs. The results of this assessment are detailed below.

#### *Trip Inefficiency*

The trip inefficiency accounts for trips to empty floors and trips to pick up a few stragglers. The default value is equal to 0.1.

It is noted as part of this thesis that the difference between evacuation times from a refuge floor and from within an evacuation zone is a result of the additional numbers of inefficient round trips to pick up the few remaining occupants of each floor from within an evacuation zone, compared to just one trip from an evacuation floor.

It is noted that in the example calculation given by Klote<sup>[44]</sup>, that evacuation is provided from each floor level (i.e. an evacuation zone) and that the value of the trip inefficiency is 0.1. Therefore, it is considered reasonable to assume that for a more efficient evacuation system, such as from a refuge floor, the value will be lower.

On this basis, a calculation of the evacuation time for the theoretical building detailed in Section 1.4 has been conducted using the standard default values for speed, acceleration, capacity and number of lifts with the default value for the trip inefficiency factor (i.e. 0.1), as well as a lower value of 0.01 to represent the additional efficiency of evacuation from a refuge floor, for refuge floor and evacuation zone intervals at 10 stories. The results of the assessment are shown in the table below along with the percentage difference.

Refuge Floor Level	Inefficiency – 0.1	Inefficiency – 0.01	Difference
10	30.6	28.1	8.2%
20	37.6	34.6	8.0%
30	44.6	41.0	8.1%
40	51.6	47.5	7.9%

**Table 3.3.5.5 – Impact of variable inefficiency factors from a refuge floor**

Lowest floor in zone	Inefficiency – 0.1	Inefficiency – 0.01	Difference
10	38.3	35.2	8.1%
20	46.4	42.6	8.2%
30	54.4	50.0	8.1%
40	69.1	63.5	8.1%

**Table 3.3.5.5 (a) – Impact of variable inefficiency factors from an evacuation zone**

Based on the results of the assessment above, it is noted that by reducing the value for the trip inefficiency by a factor of ten reduces the total evacuation time by a maximum of 8%. On this basis, it is assumed that the increase in time is approximately linear with the increase in the inefficiency factor.

It is also noted that the same reduction occurs with the results of the evacuation time from an evacuation zone. This is considered to be the result of the calculation assuming a lower number of round trips required for either simulation, such that the reduction in evacuation time is linear, irrespective of the method of evacuation.

#### *People Transfer Time*

It is noted that in ELVAC, a default value of 0.6 seconds is used for the time taken for a person to leave a lift ( $t_u$ ). However, from the STEPS assessment detailed in 3.3.5.4 above, it is noted that it takes approximately half of this time for occupants to exit the lift.

Based on a value of 0.3 seconds for a person to leave the lift, the value of the start up time may be calculated using equation 22, based on a value of  $t_5$  determined using equations 26 to 30, while the value of the standing time may be calculated using equation 24. The result of varying the people transfer time on the start up time, for evacuation from refuge floor levels at 10 storey intervals, is shown in the table below.

Refuge Floor Level	$t_u - 0.6$	$t_u - 0.3$	Difference
10	24.66	24.33	1.33%
20	31.33	31.00	1.05%
30	38.00	37.67	0.87%
40	44.66	44.33	0.74%

**Table 3.3.5.5 (b) – Result of people transfer time on value of start-up time**

Based on the results of Table 3.3.5.5 (b), the value of the people transfer time is considered to have a negligible impact on the total evacuation time, particularly as the overall evacuation time increases as a result of the greater round trip time, and therefore will have minimal impact at the higher floor levels at which lift evacuation will be valid at.

### 3.3.6 ELEVATE

The lift performance specification for the theoretical building used in the study of this thesis has been calculated using the ELEVATE programme, as discussed below. It is noted from this assessment that the required lift specification to meet current design recommendations significantly exceeds that of the default lift performance values used.

On this basis, it is assumed that dedicated lift evacuation systems may be included within buildings without requiring an increase in the lift specification used for general vertical transport.

ELEVATE is a lift industry standard programme that can be used to conduct lift traffic analysis of proposed lift designs within new buildings for specific lift arrangements by specifying lift group, car, passenger loading and building data<sup>[48]</sup>.

The results of an ELEVATE assessment for the theoretical 51 storey high rise office building<sup>[49]</sup>, have shown that, the lift specification required within the building to meet design guidance<sup>[27]</sup> requires the building to be provided with a transfer floor. The specification of the lift serving each zone can be summarised as follows:

#### Upper Lift Zone (Level 35 - 50)

- 6 x 26 person double deck lifts
- 10 m/s
- Hall allocation system

#### Lower Lift Zone (Ground – Level 34)

- 8 x 26 person double deck lifts
- 6m/s
- Hall allocation system

Whilst it is noted that the ELVAC requirements significantly exceed the lift performance values proposed as part of this assessment, this is considered to be reasonable based on the requirement to reduce occupant waiting times for general circulation to significantly lower levels than those necessary for evacuation. Therefore, it is proposed to assess the building based on the lift performance values listed in Chapter 5.

### **3.4 Summary of Methods of Analysis**

Based on the results of the validation assessment for the evacuation calculator created as part of this thesis, as detailed in Appendix A, and the results of the simulation assessments contained in Appendices B to F, it is noted that the lift evacuation times calculated using the Siikonen and modified Siikonen calculation method under predict the lift evacuation times. Therefore, it is not proposed to use either, the original or modified Siikonen equation for comparison to the stair evacuation times.

Based on the validation work of independent researchers<sup>[45, 46]</sup> and availability of the calculation process for the ELVAC simulation programme, it is proposed to use this method for calculating the lift evacuation times for comparison with the stair evacuation times.

This is considered to be reasonable based on the conservative values of the ELVAC lift evacuation times for both methods of evacuation, using different refuge floor and evacuation zone sizes and ratio of occupants escaping via the lifts, as shown in Appendix B to F.

It is noted that some of the methods listed above are capable of providing limited information with regards to the building evacuation. This can be summarised as follows:

Calculation Method	Calculation of delays	Assumptions	Limitations	Validation	Application	Accuracy
Siikonen	Delays in the round trip time due to acceleration and deceleration delays and occupants entering and exiting lift	Occupants arrive at lift immediately. No delays included for lift returning to dispatch floor	Calculates the round trip time only		May be used in a spread sheet to calculate the lift evacuation time for comparison to the stair evacuation time as this method does not include delays in the arrival of occupants	Slight variance between these results and ELVAC values considered to be the result of a standard acceleration delay
Sekizawa	Delays in the round trip time due to acceleration and deceleration delays and occupants entering and exiting lift	Occupants arrive at lift immediately. No delays included for lift returning to dispatch floor	Calculates the round trip time only		May be used in a spread sheet to calculate the lift evacuation time for comparison to the stair evacuation time as this method does not include delays in the arrival of occupants	Large difference in evacuation times for each variable.
STEPS	Calculates multiple delays including lift waiting times	Lift operation assumes that lifts are dispatched from ground floor level as occupants enter the refuge floor, rather than as a group as ELVAC is considered to do.	Can be used to calculate lift travel times between two floors only without additional operating license.	Kugligowski <sup>[45]</sup> Wall & Waterson <sup>[46]</sup>	Can be used to calculate conditions within the stairs and refuge floors as a result of the variation in refuge floor separation and lift specification	Compared to code complaint flow rates and evacuation times and other evacuation simulations. No information available with regards to the validation of lift movement
ELVAC	Calculates delays due to lift returning to Ground floor before commencing evacuation only, occupants entering lift and delays due to acceleration and deceleration	No assumptions are considered to be included within the calculation process. Each value within the calculation is entered by the user.	Provides values with regards to the round trip time only.  Difficult to obtain different input data for a lot of terms	Klote <sup>[19]</sup>	Can be used to accurately calculate the round trip time based on varying each of the values listed in Chapter 5	

**Table 3.4 – Summary of Calculation Methods**

## CHAPTER 4 - PREVIOUS SIMULATIONS

Since the 1970's there has been a large amount of research carried out on the use of lifts for the evacuation of occupants in tall buildings.

Although a number of simulations have been carried out since those of Bazjanac<sup>[18]</sup> and Pauls<sup>[12]</sup> in 1977, namely Klote<sup>[19]</sup>, Siikonen<sup>[40]</sup> and Wong<sup>[50]</sup>, these simulations have a limited amount of quantitative data available which can be used when designing the lifts to be used for evacuation. A brief summary of each study is provided below.

### 4.1 Bazjanac V. (1977)

#### 4.1.1 Summary of Study

In 1977 Bazjanac<sup>[18]</sup> attempted to simulate lift evacuation, based on the methodology described by George Strakosch<sup>[51]</sup> for a lift in 'down peak mode', to assess its effectiveness for partial or total evacuation.

Down peak mode describes the operation of a lift which is sent to the highest floor on the first trip, and in the subsequent trips only responds to calls from the second highest floor once no more calls are received from the previous highest floor, and so on.

The main focus of this study was on using lifts to evacuate occupants of a three floor fire zone (i.e. floor of fire origin plus a single floor above and below), known as the evacuation zone, out of immediate danger, such that those occupants may then use the stairs or different lifts at the lower floor level to evacuate to Ground floor level. Occupants outside of the fire zone were not assumed to evacuate.

Multiple simulations were undertaken for a number of three floor zones to determine which zone took the longest amount of time to evacuate completely. Based on this strategy, the obvious conclusion was made that the zone that required the longest period of time to be evacuated was the highest zone. This is considered to be a result of the greater distance the lift is required to travel for each round trip, compared to the lower zones, when evacuation is provided via lifts that are not designed for evacuation (i.e. are not provided with the handling capacity required during simultaneous evacuation).

The study also assessed the impacts of the lifts discharging at Ground floor level, rather than the floor immediately below the evacuation zone to reduce the travel distance, and found that this had a minimal impact on the overall evacuation time. Bazjanac does not state the reason for the small reduction in the evacuation time within the paper. However, this is considered to be the result of a minimum number of round trips required to evacuate the zone, such that the lift evacuation factor is more dependent on other variables such as door opening and closing times or rate of acceleration.

The study also reviews the total evacuation of building occupants from their floor of origin only, but does not assess evacuation from a refuge floor. However, this total building assessment is of a 22 storey office building, which is quoted as being evacuated in approximately nine minutes. Based on limited information available with regards to this assessment, this evacuation time is considered to be of limited use to this study.

The conclusion of the report simply notes that for a building with lift provisions for normal up and down peak travel, evacuation may be achieved in approximately 30 minutes. It is noted that this may be reduced to 10 minutes if the building is provided with an 'efficient' lift system.

#### 4.1.2 Summary

Very little information regarding the simulation programme or variables used to calculate the evacuation times are provided within the reference. On this basis, the study by Bazjanac is considered to provide a minimal amount of useful information to this study. The findings and recommendations of Bazjanac's paper can be summarised as follows:

- The study identified the problems caused by using lifts as a method of evacuation, such as the congestion of the lift system and the difficulty faced by emergency personnel to reach the floor of danger.
- It also recognised the potential of lifts to get people away from the area most at risk from a fire, considered as the evacuation zone.



- It noted the variance between real life evacuation times and the simulation times are a result of the difference in the extent of control exercised in the evacuation procedure. However, based on the research conducted into human behaviour, it is assumed that minimal control will be required for efficient evacuation to occur.
- The report concluded that it is considered necessary to assess the control of the lift calls during the evacuation and how these are handled.
- The worst case assumption was noted as being 100% of the buildings occupants within the affected zone would use the lifts to evacuate as a worst case scenario.
- A building with normal up and down peak lifts may be simultaneously evacuated in less than 30 minutes.

The main focus of this work is primarily on the evacuation of the three storey 'evacuation zone' of a relatively low density office building. Whilst this is not considered to apply to this study, it is worth noting the conclusion that the whole building may be simultaneously evacuated by lifts operating under normal conditions in less than 30 minutes based on down peak travel, which is also noted by Siikonen et al<sup>[40]</sup>.

## **4.2 Pauls (1977)**

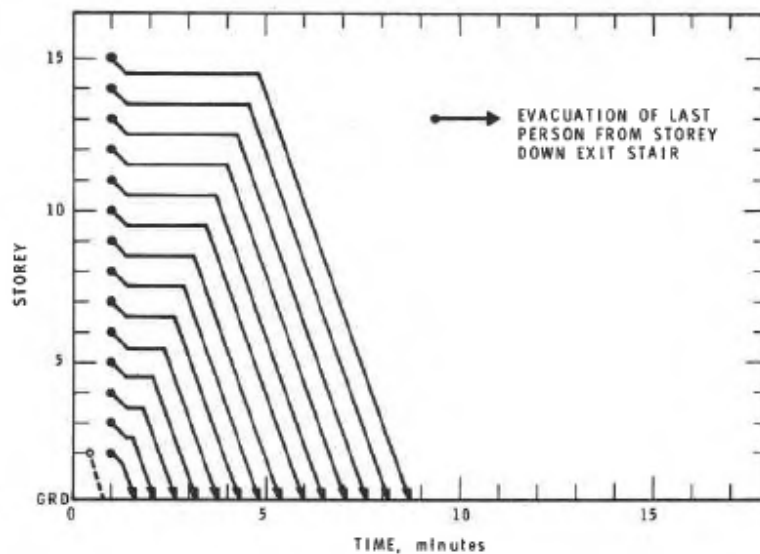
This work reviewed three possible methods of evacuation from a high-rise building including:

- Simultaneous evacuation via stairs (referred to as 'total evacuation' in the text)
- Phased evacuation via stairs,
- Lift evacuation.

Pauls proposed the use of refuge floors for the simultaneous evacuation of the whole building via lifts. However, this required occupants to walk down stairs to the nearest refuge floor below their floor of origin, which is a contrast to the work of Bazjanac, who recommended that occupants are evacuated from their floor of origin.

A trace of the occupant's movements for the simultaneous evacuation of a 15 storey building using only stairs is shown in Figure 4.2. The gradient of the line indicates speed of

movement. On this basis, Pauls demonstrates that the higher an occupant is located in a building, the greater the time to evacuate. This can be compared to the occupant trace for a high rise office building provided with lifts, as shown in Figure 4.2.2 below.



**Figure 4.2 – Trace of occupant movement for a 15 storey building**

#### 4.2.1 Summary of study

Pauls<sup>[12]</sup> compares the three evacuation methods and comments on the suitability of each using a theoretical building of 40 storeys, which is provided with two stairs and a total building occupancy of 4,500 persons (~113 persons per floor level).

When assessing simultaneous evacuation, Pauls notes that the time for completion of evacuation via the two stairs requires approximately 40 minutes. Pauls also calculated that the last occupant to leave the upper floor is required to queue on their floor of origin for approximately 27 minutes before beginning the descent, as shown by the dashed line in Figure 4.2.2.

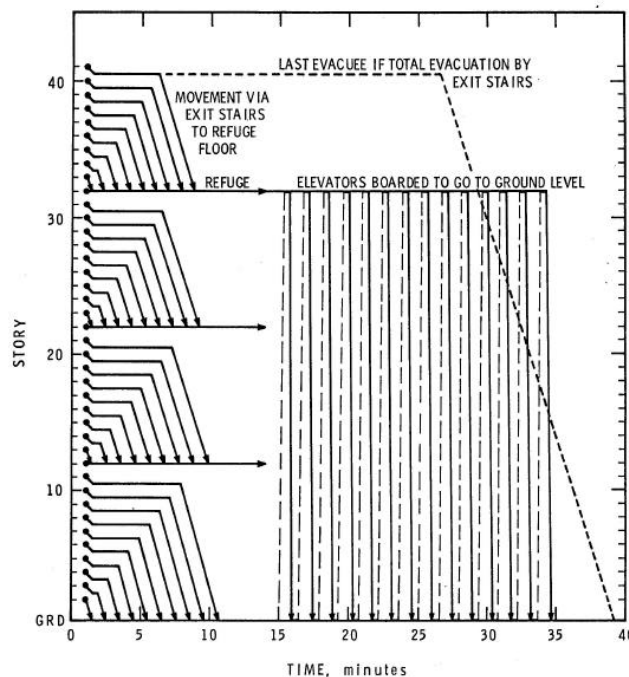
On this basis, Pauls<sup>[12]</sup> recommends that the most suitable method of providing lift evacuation is to have the occupants of a certain number of floors escape to a refuge floor where they can wait for a lift to take them direct to ground floor.

As a measure of safety, Pauls<sup>[12]</sup> recommends that for a period of up to approximately 15 minutes after the alarm has been raised and evacuation has commenced, the lifts would be returned to the ground floor and 'checked' by the Fire Service before being used for

evacuation. This is considered to significantly increase the total lift evacuation time, such that the majority of occupants are likely to seek to escape via the stairs. However, based on the requirement for lifts to return to ground floor level in the event of a fire, this time may be reduced by having an automated message play inside the lift car, in addition to the sounding of the alarm, to ensure that occupants leave the lift. On this basis, the most effective lift start up time may be considered to be approximately equal to that assumed in the ELVAC programme<sup>[19]</sup>, which is based on the time for lifts to go to the discharge floor from the most onerous floor level plus the time for any passengers within the lift to exit.

#### 4.2.2 Results of Simulation

An approximate calculation of the time taken to evacuate a building using lifts is presented by Pauls<sup>[12]</sup> for the exemplary 40 storey building, discussed above, using the calculation procedures given by Strakosch<sup>[51]</sup> for down peak mode, which is also used by Bazjanac. It is claimed that the four lifts in the group serving the highest refuge floor (32<sup>nd</sup> floor) would be required to make 14 trips, which would require 20 minutes to evacuate 1000 persons, as shown in Figure 4.2.2 below.



**Figure 4.2.2 – Occupant trace for lift evacuation of 40 storey office building**

The lift evacuation time shown within the figure includes a 15 minute period for checking of the lifts. On this basis lift evacuation from the top zone is approximately 7% to 8% faster than stair evacuation zone. However, when excluding the time to check the lifts, this

increases to approximately 47%. This is a significant reduction in the building evacuation time.

In this paper Pauls<sup>[12]</sup> also makes note of the possibility of reducing the evacuation time from 20 minutes to 14 minutes by having approximately one third of the occupants of the refuge floor evacuate via stairs. The reduction in evacuation time is commensurate with the evacuation times shown in Appendix B and Appendix C, when approximately 25% of the building occupants evacuate via stairs. This corresponds to an approximate reduction of the stair only evacuation time of approximately 63%. On this basis, it has been demonstrated that lifts designed specifically for evacuation may provide an efficient means of escape from the upper floor levels of high buildings, particularly when supplemented with stair evacuation.

Based on the above, it is noted that the total evacuation time of the building is less than 30 minutes, when excluding the time period occupants are required to wait while the lifts are 'checked' by the Fire Service. This provides a significant reduction in the evacuation time compared to the use of stairs only.

#### 4.2.3 Summary

The lift evacuation times stated by Pauls as part of the theoretical evacuation from the building are also based on the lift performance data published by Strakosch<sup>[51]</sup>. Therefore, it is considered reasonable to compare the relative lift evacuation times of Pauls with other lift evacuation studies which assume the lifts operate in down peak mode.

The studies were conducted on a theoretical 40 storey building served by four groups of four lifts with a variety of speeds from 4m/s to 6.1m/s. The building occupancy is equal to 4500 persons (113 persons per floor level). This is less than the 150 person per floor level occupancy of the theoretical building occupancy used in this study (~25%).

On this basis, the times quoted by Pauls are expected to be less than those calculated for the default values used in this study. However, this information is considered useful to highlight the impact of a reduced occupancy on the building evacuation times.

The evacuation times quoted by Pauls from the individual refuge floors, is considered to be the result of using lifts which are designed for general circulation (i.e. evacuation time is not assessed as a result of the handling capacity of the lift). On this basis, the evacuation times are considered to be shorter from the lower refuge floor levels than those from the upper refuge floor. This assumption is commensurate with the results of this study based on lift specifications which are independent of the general circulation requirements, as discussed in section 3.3.6.

### **4.3 Siikonen (2003)**

Two papers were published by Marja-Liisa Siikonen et al in 2003<sup>[33, 40]</sup>, which studied lift evacuation.

The first paper by Siikonen, Barlund and Kontturi<sup>[40]</sup>, titled *Transportation Design for Building Evacuation*, attempts to derive a simple formula for calculating the round trip time for a single lift, as detailed below, which gives an approximate value for the evacuation time for a lift operating in the more efficient down peak mode of travel used in the previous simulations by Bazjanac and Pauls.

The second paper by Siikonen and Hakonen<sup>[33]</sup>, titled '*Efficient evacuation methods in tall buildings*', provides a brief summary of the findings of the first paper as well as reviewing the impact of the number of occupants per floor and the total number of floors served by the lift, when operating in down peak mode, as utilised for the evacuation simulations used in this thesis.

#### **4.3.1 Summary of Comparative Assessment**

A brief comparative assessment of evacuation from an 88 storey building, with a total population of 10,700 persons is contained in *Transportation Design for Building Evacuation*<sup>[40]</sup>. A summary of each assessment is provided below:

##### **4.3.1.1 *Simulation 1***

It is stated by Siikonen et al that in the first simulation of the building "people use only lifts when going down". However, this does not clearly state that the lifts are used to serve a

full lift zone or a refuge floor. However, as the second simulation is clearly indicated as having occupants depart from refuge floors it is assumed that this simulation is of evacuation from an evacuation zone.

#### 4.3.1.2 *Simulation 2*

The second simulation assumes that occupants travel to a refuge floor where they are taken to ground floor level by express lifts. This method is stated by Siikonen et al to take approximately 1.5 – 2 times longer than the first evacuation simulation. However, this conclusion is not in accordance with the findings of this study in which evacuation from refuge floors provides lower evacuation times than those from an evacuation zone.

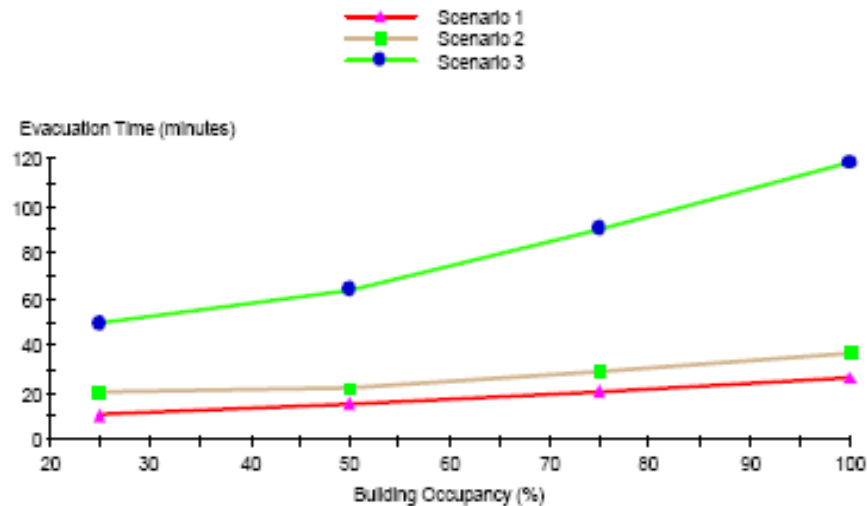
However, further work carried out by Siikonen and Hakonen in *Efficient evacuation methods in tall buildings*<sup>[33]</sup> on a simulated 20 storey building, with 60 persons per floor, showed very little difference in the time taken to evacuate the building using methods very similar to those discussed in Simulation 1 and 2 above as well as an additional method where occupants were required to evacuate the building from every third floor within the building. On this basis, Siikonen et al<sup>[33]</sup> note that “in office buildings the egress time by the stairs is shorter for a building with 50 floors or less, and fewer than 50 persons per floor. For 100 persons per floor, the evacuation time by lifts is faster for 25 floors or more”. This conclusion is considered to be consummate with the findings of this study.

#### 4.3.1.3 *Simulation 3*

The third evacuation simulation of the building was carried out to assess the time taken for the occupants to escape using only the stairs. It is stated by Siikonen et al that ‘people have to wait at upper floors for a long time before they can enter the shaft’, which is consummate with the conclusion by Pauls<sup>[12]</sup>.

In accordance with Approved Document B<sup>[1]</sup> of the Building Regulations 2000, the occupants of the upper floors should have escaped from their floor of origin within the two and a half minute notional evacuation time. This queuing on the upper floor levels is considered to be the result of insufficient escape capacity within the stair for simultaneous evacuation.

Nevertheless, it is quoted that this method of evacuation takes approximately five times more than that of the two previous methods. The theoretical time taken for the evacuation of the mega-high rise building using the three methods discussed above is shown in Figure 4.3.1.3, which is taken from the work of Siikonen et al<sup>[40]</sup>.



**Figure 4.3.1.3 – Evacuation time for scenarios 1, 2 and 3**

#### 4.3.2 Summary of Studies

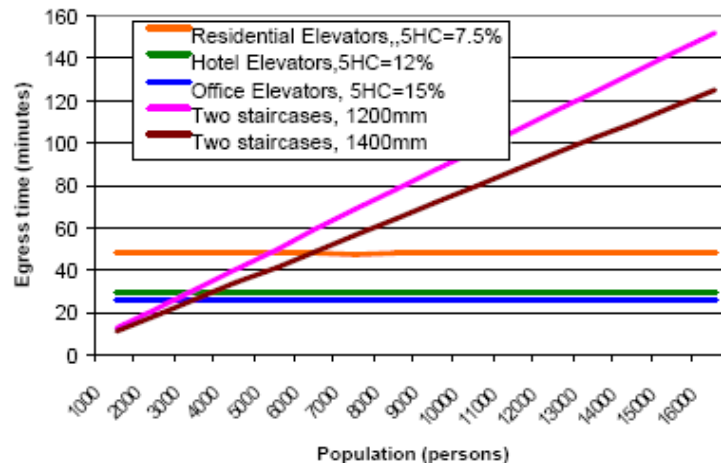
It is claimed by Siikonen et al<sup>[40]</sup> that the fastest way to evacuate a building if the population is below 2500 – 3000 persons is by using at least two stairs. However, it is claimed that if the building contains a population of more than 3500 – 4000 people two staircases do not fulfil the requirements. This is considered to be the result of the occupancy exceeding the stacking capacity available in the available stairs and is therefore also highly dependent on the number of storeys in the building.

It is claimed that in these situations, in high-rise office buildings with well planned lifts, that the entire population may be evacuated in 20-30 minutes. This is commensurate with the conclusion of Bazjanac, based on the provision of lifts operating throughout the whole building in down peak mode. However, Bukowski<sup>[39]</sup> states that this will require 60 minutes or less based on a 5 minutes handling capacity of 10% of the building population. While this value is lower than the design standard used in the U.K, this validates the conclusions of Bazjanac, Pauls and Siikonen.

Both papers<sup>[33, 40]</sup> state that the evacuation time of a building may be reduced by approximately half if the occupants escape using both stairs and lifts, which is commensurate with the findings of this assessment and those by Pauls.

In the simulations carried out using a 30 storey building with 100 persons per floor<sup>[33]</sup> the evacuation time is 22 minutes using just lifts, 26 minute using only stairs and approximately 13 minutes using a combination of stairs and lifts for evacuation, where approximately 50% of the building occupants escape via the stairs and the remaining 50% escape via the lifts. The evacuation using a combination of stairs and lifts is approximately 50% less than the evacuation time using stairs only, when the occupancy is reduced by the same percentage, and approximately 40% less than the evacuation time using lifts only.

Figure 4.3.2 is taken from the work by Siikonen et al<sup>[40]</sup> and shows the time taken to evacuate a given population using a number of methods. The varying values of the handling capacity in five minutes (5HC) are dependent on the use of the building, with the different values shown on the graph. However, this graph does not take into account the time taken for occupants to arrive at the lifts and is therefore considered applicable to evacuation from a dedicated evacuation zone only. Nevertheless, this may be adjusted based on a calculation of the time taken for the first occupants to arrive at the lift.



**Figure 4.3.2 – Egress times with stairs and lifts**

The egress times for the lifts in this graph are constant as these are assumed to be designed to ensure that the required handling capacity is provided for a certain percentage of the population. Therefore, as the population increases so will the handling capacity of



the lifts, allowing the same percentage of the buildings occupants to be evacuated in the same time.

The evacuation time by stairs increases linearly with the occupancy as the stair is based on a set flow rate, which does not increase with the building occupancy compared to the lift performance values, which increase with the building population, such that the handling capacity requirement is achieved and the evacuation time remains constant.

Siikonen et al<sup>[33]</sup> conclude that 'lifts can transport about 1.5 times more passengers in down-peak than in up peak. Therefore, as an example, if a group of lifts is designed to transport 15% of the population in up peak, the same lifts can transport 22.5% of the population in five minutes in down peak on the basis that the lifts will have fewer calls in down peak.'

#### 4.3.3 Summary

The results for lift evacuation times<sup>[33, 40]</sup> stated in the work by Siikonen are produced using the computer simulation programme Building Traffic Simulator (BTS), which is produced by Kone lift designers and manufacturers. On this basis, the results shown in the papers can not be directly compared with those results by Bazjanac, Pauls, Wong or those contained within the appendices, on the basis that the calculation method is unknown.

Brief comparative assessments between evacuation from a refuge floor and from an evacuation zone were conducted in both papers. The conclusion of the paper assessing the taller 88 storey building<sup>[40]</sup> stated that evacuation from a refuge floor is between 1.5 – 2 times longer than from an evacuation zone. This could be the result of a number of factors including the occupancy per floor level, lift capacity and refuge floor locations. However, the conclusion of the assessment of the smaller building<sup>[33]</sup> states that the egress times of the three different scenarios are very similar. Therefore, it is proposed to determine the difference between both evacuation methods as part of this study, based on the whole building evacuation time.

#### 4.4 Wong et al (2005)

The evacuation of a theoretical high-rise office building from dedicated refuge floors using shuttle lifts has also been studied by Kelvin Wong et al<sup>[50]</sup>.

The assessment was conducted using the STEPS simulation programme for evacuation from refuge floors only. Whilst it is not stated within the STEPS supporting documentation, it is not believed that the lift movement within the programme is in accordance with the calculation procedure of Strakosch. On this basis, it is not considered possible to directly compare the results from the assessment by Wong et al with those by Pauls and Bazjanac.

##### 4.4.1 Summary of Study

The assessment carried out by Wong et al<sup>[50]</sup> is of a 100 storey building with a top finished floor level of 500m. This is 2.5 times the height of the theoretical building used as part of this study. The total occupancy of the building was 21,000 people, which is equal to 210 persons per floor level when assuming that the occupants are evenly distributed on each floor level, which is very similar to the occupancy of the World Trade Centre at full capacity. This exceeds the 150 person occupancy assumed for each floor level of the theoretical building used as part of this study.

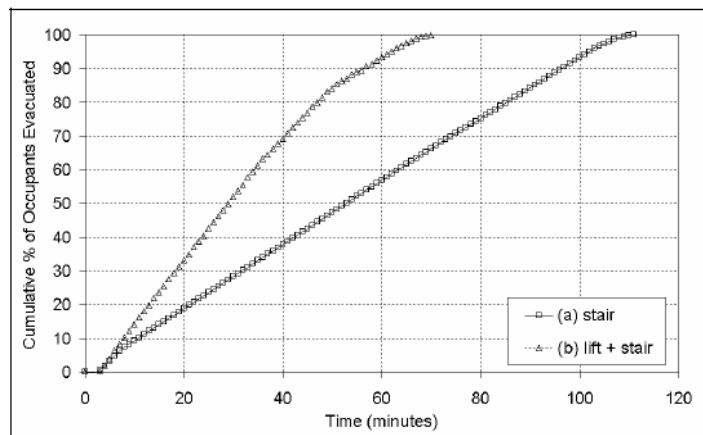
The maximum separation distance between refuge floor levels is equal to 24 storeys (i.e. 25 storeys including the refuge floor), which is equal to the maximum separation distance used in this study between refuge floor levels, based on the guidance used in Hong Kong<sup>[6]</sup>. Whilst the lift evacuation times quoted by Wong et al are generally assumed to be higher than those from the theoretical building described in Section 1.4, this information is considered to be useful with regards to the validation of the refuge floor separation distances.

##### 4.4.2 Results of Simulations

Wong notes that “the main advantage of using shuttle lifts (compared to evacuation from the floor of origin in an evacuation zone) is that they can eliminate the requirement for complicated control and management required to pick up occupants on different levels”.

Wong et al also recommends that a combination of lifts and stairs are used as part of the overall evacuation strategy, rather than using only lifts for evacuation.

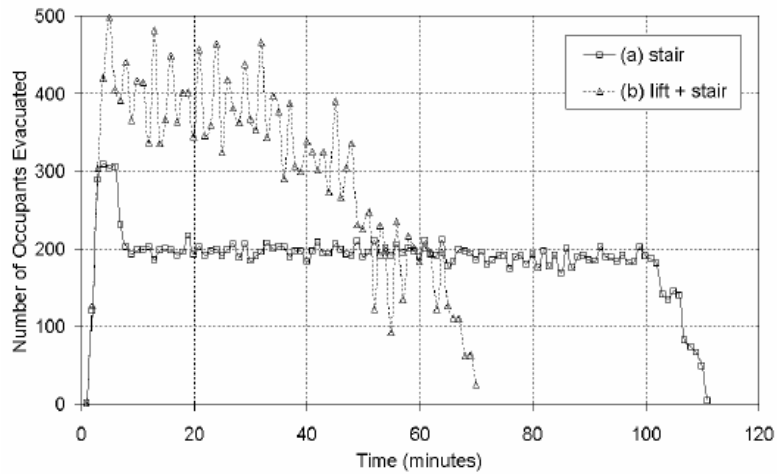
Figure 4.4.2 below shows the cumulative percentage of occupants evacuated against time, for a mixture of stair and lifts as well as stairs only. It is noted from the graph that a combination of lifts and stairs provides a significantly greater rate of evacuation.



**Figure 4.4.2 – Cumulative percentage of occupants evacuated**

The time to complete the evacuation took 70 minutes using a mixture of lifts and stairs, while the evacuation took approximately 110 minutes using just stairs. This is an increase of approximately 36% compared to the time when using a mixture of stairs and lifts for evacuation. The difference between methods is approximately equal to that noted by Siikonen et al<sup>[33]</sup> and Pauls<sup>[12]</sup> for a combination of stairs and lifts. The difference between references is considered to be the difference in the percentage of occupants assumed to escape via the stairs.

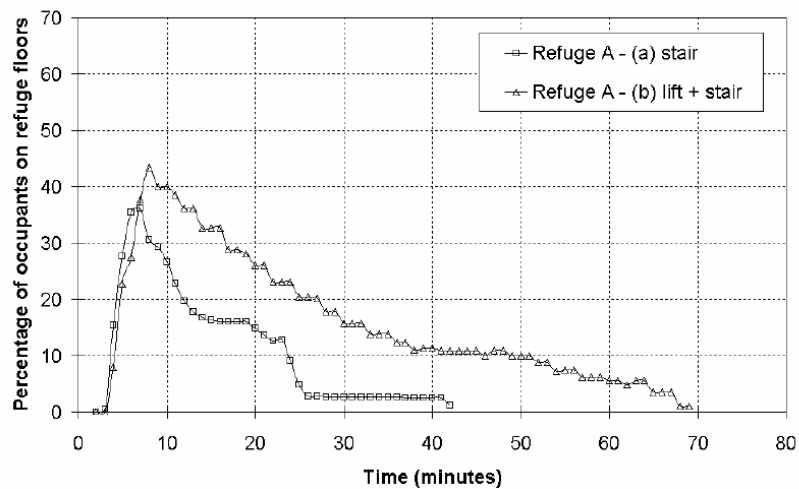
Figure 4.4.2 (a), also taken from work by Wong et al<sup>[50]</sup>, shows the number of occupants evacuated at each minute of the building evacuation.



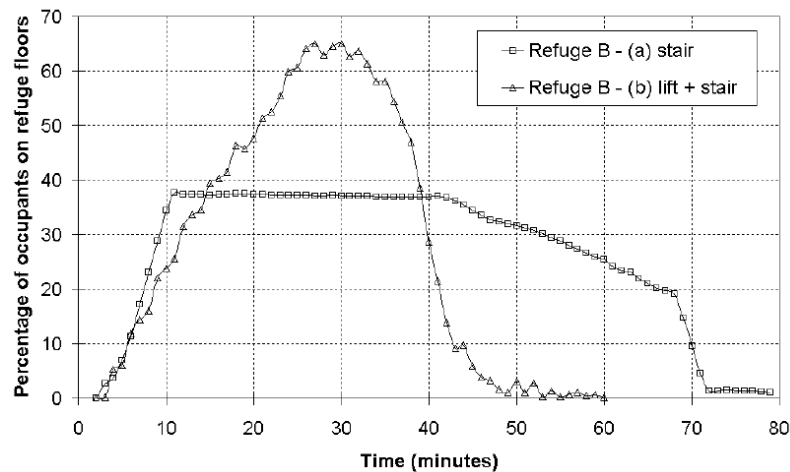
**Figure 4.4.2 (a) – Number of occupants evacuated**

The observed change of gradient at around 50 minutes for the lift and stair evacuation indicates that not all evacuation lifts are fully utilised at that time. This is considered to be a result of lower refuge floors being completely evacuated, therefore, decreasing the occupant flow rate from the building. On this basis, it is assumed that the simulations by Wong et al were not specifically designed to simultaneously evacuate the building in accordance with general design guidance.

Wong et al<sup>[50]</sup> also studied the percentage of occupants on the refuge floor at any instant, compared to the total number of occupants that are required to evacuate via the specific refuge floor. The results of which can be seen in Figure 4.4.2 (b) for the high level refuge floor and Figure 4.4.2 (c) for the mid level refuge floor.



**Figure 4.4.2 (b) – Percentage of occupants contained on refuge floor at high level**



**Figure 4.4.2 (c) – Percentage of occupants contained on refuge floor at mid level**

As noted by Wong et al<sup>[50]</sup> the plateau of the curves which represent scenario a) on both graphs indicate that the staircases below the refuge floors are fully occupied, occupants on the refuge floors need to wait until occupants on the lower floors are discharged and the space inside the staircases is freed up. This observation is commensurate with those in the theoretical building used as part of this study.

#### 4.4.3 Summary

The results of this assessment demonstrate that most of the occupants are required to wait for a section of the evacuation phase on the refuge floors, irrespective of their method of evacuation. However, it is noted that there are more occupants required to wait on the refuge floors when evacuation is provided by a mixture of lifts and stairs (maximum 65% of occupants).

This is considered to be a result of the number of occupants waiting for the lift to evacuate, rather than pausing to rest during descent. This is not considered to be the result of an ineffective evacuation system, which is supported by the time for the lift and stair evacuation to be completed compared to the stair only evacuation.

The results of the simulations have shown that the total evacuation time of a building, twice the height of the theoretical building used as part of this study, with an increased occupancy of 28.5% may be achieved in 110 minutes when using only the stairs. However, the total evacuation time may be reduced by approximately 36% when occupants also use the lifts to evacuate. Whilst the percentage of occupants assumed to escape via the stairs is

noted stated within the paper<sup>[50]</sup> for the combined evacuation, it is assumed from the results of the simulations conducted as part of this thesis, and previous studies, that the reduction in occupancy is approximately equal to the reduction in the evacuation time.

The results of the stair evacuation times quoted by Wong et al, for a building twice the height of that used as part of this study, are not double that calculated for the theoretical building. This is a result of the assessment by Wong et al being conducted based on the provision of three 1200mm wide stairs (total stair flow rate of 4.788 p/s), compared to the single 1400mm wide stair assumed to be available as part of this study (total stair flow rate of 1.862 p/s). On this basis, it is not considered possible to directly compare studies.

## 4.5 BRE Research

### 4.5.1 Introduction

In October 2007, the BRE held a conference titled '*Use of lifts and escalators for evacuation from buildings*'. This included a number of presentations by members of the BRE and guest speakers on the issue of lift and escalator evacuation, and provided the background information to BD 2466 '*Guidance on the use of lifts or escalators for evacuation and fire and rescue service operations*.'<sup>[9]</sup>

The most relevant of the presentation to this study was that given by Fraser-Mitchell<sup>[52]</sup>, based on the studies carried out by the BRE on the use of lifts for evacuation, using the CRISP simulation software, which studied the evacuation of a number of different building types including:

- High rise office (16 storeys in height)
- Medium rise office (8 storeys in height)
- Hotel (16 storeys in height)
- Shopping Centre
- Underground station

The evacuation of the office building was studied using the following scenarios:

- Baseline – phased evacuation using stairs and lifts (base)

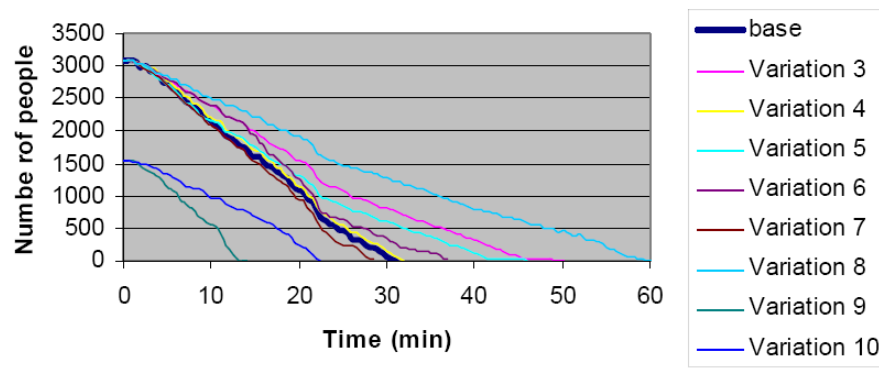
- Baseline without lifts available (variation 3)
- Baseline but lift does not call at fire floor (variation 4)
- Baseline but only disabled people may use lift (variation 5)
- Baseline but lift does not go to fire floor or above (variation 6)
- Baseline but lift may stop on other floors until full (variation 7)
- 50% of lifts available (variation 8)
- 8 floors, fire on floor 4 (variation 9)
- 50% population (variation 10)

Based on the results of the simulations within the presentation, it is considered reasonable to assume that the BRE research assessed the lift evacuation times using only the evacuation zone method.

#### 4.5.2 Summary of Study

The majority of the assessments for the high-rise office building assumed a fire on the 8<sup>th</sup> floor of the building (i.e. half way up the building). The base case, which the results are assessed against, is based on 3007 occupants evacuating via the six lifts and two stairs in the central core. As a sensitivity study, the building was reduced to 8 storeys in height and was assumed to have a fire on the 4<sup>th</sup> floor.

The results from the study were presented in graphical form. Figure 4.5.2 shows the number of people inside the building against time.



**Figure 4.5.2 – People inside building at set time**

The most notable feature of this graph is the lack of plateaus in the occupant traces. It is assumed that this is a result of occupants being able to use the stairs and therefore a relatively constant discharge rate is achieved. This idea is supported by small increases in the discharge rate when a lift discharges occupants in addition to the stairs.

Whilst this is considered to show good conditions during evacuation, this graph does not show the flow rate in the upper levels of the stair where occupants are considered likely to be queuing. However, the exact time of each floor to evacuate is shown in Table 4.5.2. This highlights the impractical nature of the assessment as occupants of Level 1 are assumed to be waiting for 31.1 minutes for a lift to arrive even though they are 4m above discharge level, which is significantly greater than the time required using stairs.

Zone	Initial population	Time cleared (min)	Zone	Initial population	Time cleared (min)
1	193	31.1	9	193	21.8
2	193	30.7	10	193	20.4
3	193	29.4	11	193	20.2
4	193	28.4	12	193	18.3
5	193	26.9	13	193	17.8
6	193	25.2	14	193	13.7
7	193	24.2	15	193	16.1
8	193	23.6	16	193	13.9

**Table 4.5.2 – Clearance time for each storey**

Whilst it is noted that a number of alternative variations were studied, the simulations included within this study are considered to only calculate the evacuation times using the evacuation zone method (i.e. occupants are evacuated from their floor of origin). Therefore, it is not considered possible to compare the evacuation times from the building using both methods of evacuation. This is considered to be the result of the relatively low height of the building used in the study, which contains 16 storeys and is therefore, not suitable for evacuation from a refuge floor, due to the relatively small number of floors served by a refuge floor.

However, it is considered worth noting the difference in evacuation times of the studies conducted using the evacuation zone method, which are compared against the baseline study of phased evacuation using stairs and lifts. Whilst it is unclear which line represents the scenarios listed above, it is noted that there is minimal difference between evacuation



times, with the exception of two case's which have a lower time and are believed to be those with 50% of the base case population, and that with eight storeys, and one which significantly exceeds the base case evacuation time, which is assumed to be the simulation in which half of the lifts are available compared to the base case scenario.

#### **4.6 Summary**

The work of Bazjanac on lift evacuation is considered to be of limited use to this thesis on the basis that the main lift evacuation strategy studied is based on the fire affected floor floor, plus one floor above and below this floor, evacuating via the lifts. Therefore, this study provides a minimal amount of useful information with regards to lift evacuation. However, based on Bazjanac's summary of the time difference between a discharge floor immediately below the fire affected zone and at Ground floor level, it is proposed that the evacuation simulations used in this thesis will be based on all evacuation lifts discharging at ground floor level.

The above papers generally only consider one method of lift evacuation (i.e. refuge floors or evacuation zone). Therefore, whilst it is noted that the evacuation of a building is generally considered to be faster from a refuge floor, the difference in total evacuation times between these methods is currently unknown.

Whilst the recommendations of the above papers vary on recommended lift evacuation strategies, a number of papers recognise the benefit of supplementing lift evacuation with stair evacuation. Therefore, it is also proposed to assess the impact on the lift evacuation times when a certain percentage of the buildings occupants escape via stairs.

There is limited information available in the papers discussed above with regards to the lift evacuation times when compared to the evacuation times via a code compliant protected escape stair. On this basis, this research will focus on the comparison of overall evacuation times from a theoretical building using the two different lift evacuation strategies discussed in Section 1.2 and compare these to the evacuation times using stairs.

## CHAPTER 5 - CALCULATION VARIABLES

### 5.1 Introduction

It is proposed to use the ELVAC simulation programme to generate lift evacuation times for each of the lift evacuation methods discussed in Section 1.2 for different refuge floor and evacuation zone separation distances as well as different ratios of occupants escaping via the lifts.

It is also proposed to use the STEPS simulation programme to assess the conditions within the building during a code compliant evacuation and for a number of different lift evacuation scenarios. To ensure that the outputs of these simulation programmes are accurate, it is necessary to consider the value of the inputs used in each of these programmes and the impact this might have on the final value.

### 5.2 Lift Specification

The purpose of this study is to compare the lift evacuation times of a theoretical 50 storey office building using two different lift evacuation strategies, and lift performance values. The values used in the assessment are discussed below.

#### 5.2.1 Lift Speed

Based on the recommended maximum lift speed for lifts serving floors more than 120m<sup>[27]</sup> the default lift speed is 6 m/s. However, sensitivity studies have been carried out using rated speeds of 5m/s and 7m/s, based on Fortune's<sup>[31]</sup> recommendation for the maximum speed on a non-pressurised lift, as well as 16m/s based on the approximate lift speed used in Taipei 101.

Whilst it is noted that a number of floors in the study will be less than 120m in height, the use of this value is considered to be reasonable on the basis that the lift will be continuously accelerating until it reaches its target floor, therefore ensuring that the evacuation time from the lower floor levels is as low as possible.

### 5.2.2 Lift Acceleration

Based on the recommendations of CIBSE Guide D<sup>[27]</sup> for a lift serving a floor level more than 120m in height, a default acceleration, and therefore deceleration, value of  $1.2\text{m/s}^2$  has been used. However, an additional sensitivity study has been carried out based on the work of Fortune<sup>[31]</sup> using a lift acceleration value of  $1.5\text{m/s}^2$ .

### 5.2.3 Door Opening and Closing Time

The lift doors have been assumed as 1200mm wide centre opening doors. Based on the default value in the ELVAC programme, the time to opening is considered to be 5.3 seconds. This provides a conservative evacuation time as CIBSE Guide D<sup>[27]</sup> requires a combined opening and closing time of 4.5 seconds for an 1100mm wide centre opening door.

Based on the use of this conservative value in each calculation, no additional validity assessments have been carried out on the impact of different door opening and closing times.

### 5.2.4 Lift Car Capacity

A lift car capacity of 10, 12 and 16 persons has been used based on the values taken from Strakosch's work<sup>[51]</sup>. Based on these values, an additional validity study have been carried out using a lift capacities of 21 persons (similar to the capacity of the lifts used in Taipai 101)<sup>[30]</sup>. This value is also provided to allow a comparison with an increased number of lift shafts.

## 5.3 **ELVAC Inefficiencies**

The ELVAC programme includes for a number of inefficiencies which are not directly included within the values listed in Chapter 5. The values used in the ELVAC simulations, and the source of these values is discussed below.

The ELAVC programme assumes a dwell time of 4 seconds. The basis for the use of this figure is unknown, based on the associated literature provided with the programme<sup>[19]</sup>. It is not possible to amend this value in the programme.

The Standing Time and Start Up Time include a value for transfer inefficiencies ( $\mu$ ), which consists of three variables, as follows:

*Basic transfer inefficiency ( $\alpha$ )* - allows for rounding off of probable stops, door operating time, door starting and stopping time, and the unpredictability of people. Typically a value of 0.10 is used for the basic transfer inefficiency for commonly accepted arrangements of elevator groups. This value can be manually entered within ELVAC programme, however, the reference does not include recommendations for the basis of this value and how to calculate alternative values.

*Door inefficiency ( $\epsilon$ )* - is used to adjust for any increase in transfer time over that of a 1200 mm wide centre opening door. Values are provided within a table in the reference document<sup>[19]</sup>, as reproduced in Table 3.3.5.3. However, it is not possible to calculate this value for lift door arrangements that are not included in this table.

*Inefficiency ( $\gamma$ )* - is used to account for any other inefficiencies in people transfer into or out of the lift, such as increased movement times within a lift due to an unusual elevator car shape or limited physical capability of passengers. This value is often chosen to be 0.05 for hospital elevators and 0 for office buildings. The ELVAC assessment is based on a value of 0 and includes for able bodied and non-able bodied occupants. The use of the 0.05 value is considered to represent significant inefficiencies such as occupants in beds etc, therefore, it is not proposed to apply this value to include for any disabled occupants in an office building, based on the speed at which these may enter the a lift when supervised during an evacuation.

#### **5.4 STEPS Variables**

The STEPS programmes requires additional input variables to be provided to those listed in Section 5.2 and Section 5.3.

#### 5.4.1 Dwell Time

As discussed above, the dwell time is provided as a fixed value of 4 seconds in the ELVAC programme. However, it is considered necessary to input this value in the STEPS programme.

The model used to compare the evacuation times of the theoretical building described by Klote<sup>[19]</sup>, as discussed in Section 3.3.5.4, also uses a value of 4 seconds for this factor, so that a direct comparison can be made between the two methods.

All other STEPS models use a value of 2 seconds for the lift dwell time. This is considered to be reasonable when including the motor delay time, which is also not included in the ELVAC assessment, such that a notional delay is provided between the methods. This is considered to provide a minimal variance between the evacuation times.

#### 5.4.2 Motor Delay

The Motor Delay value is required in the STEPS simulations to include for how long it takes for the lift motor to start. This delay is not included in the ELVAC assessment, therefore, this value has not been included in the STEP programme used to compare the values of the notional building discussed by Klote<sup>[19]</sup>, as discussed in Section 3.3.5.4.

However, a notional value of 1 second has been used for all other STEPS assessments, such that the total delay for lift motion to commence is equal to 3 seconds, compared to 4 seconds in the ELVAC simulations. This is considered to provide a minimal variance between the evacuation times.

#### 5.4.3 Summary

Whilst it is considered that these delays will have minimal impact of the values of the STEPS output used in the study of this assessment, it is noted that these delays will increase the total evacuation time for the evacuation zones, particularly with the larger evacuation zones. However, this is assumed to be reasonable on the basis that this will increase the lift evacuation time, creating a more conservative evacuation result for comparison to the stair evacuation times.

## 5.5 Refuge Floor Location

There is little guidance available with regards to the maximum separation distance between refuge floors. The evacuation of the Petronas Twin Towers requires the occupants of the highest floor to travel 44 storeys by stairs before reaching express lifts to discharge level<sup>[16]</sup>. However, this is considered to be an excessive travel distance that will require a prolonged period of time for occupants to reach the refuge floor.

Work by Lay<sup>[26]</sup> recommends a refuge floor interval of approximately 35 storeys to be reasonable. However, the Hong Kong Building Code<sup>[6]</sup> recommends that any non-industrial building, exceeding 25 storeys in height should be provided with protected lobbies at a maximum spacing of 25 storeys between refuge floors or the ground floor to allow a space for escape occupants to rest if required to do so.

So et al<sup>[53]</sup> suggest a more conservative figure of providing refuge floors every fifteen to twenty floors in modern high rise buildings.

Nevertheless, whilst it is appreciated that lifts may be able to evacuate the occupants of a zone, which contains more than 25 storeys, the limiting factor in the location of the refuge floors in the simulation will be the time taken for the occupants to reach the refuge floor and the associated effort.

Therefore, the results of this assessment will be conducted for a maximum spacing between refuge floors of no more than 25 storeys, while the minimum spacing will be 10 storeys, which is based on the findings of previous simulations where 100% of the building occupants use the lifts to evacuate.

## 5.6 Stair/Lift Evacuation Ratio

To reduce the lift evacuation time it is proposed to simulate evacuation via stairs and lifts. Therefore, each simulation will assume a certain percentage of occupants will escape via the stairs from each zone.

Charters and Fraser-Mitchell<sup>[9]</sup> note that a limited number of evacuation drills and experiments indicate that in tall office buildings approximately 50% (+/- 10%) of building

occupants choose to use the lifts for vertical evacuation. This is supported by Siikonen and Hakonen<sup>[33]</sup> who found that the evacuation time of a building when using lifts and stairs is approximately 40% that using lifts only when half of the building population escape using the lifts.

Previous work carried out by Klote et al<sup>[19]</sup> suggests that, for buildings of a larger height, the optimum percentage of occupants evacuating by lifts is approximately 65%.

Due to the lack of guidance on lift evacuation it is not known what percentage of occupants will evacuate via lifts or stairs. On this basis, it is proposed to assess the evacuation times for the building based on a more onerous lift occupancy of 75% of the building occupancy, as well as the least onerous value of 50% of the building occupancy.

## **5.7 Occupancies**

The occupancy of each floor level is equal to 150 persons. Whilst it is noted that this creates a total building occupancy of 7500 persons, when including fire sterile refuge floors, this is considered to provide a comparable value for comparison against other lift evacuation studies and stair evacuation times, which can be summarised for comparison as follows:

- Wong – 21,000 persons over 100 storeys. Approximately equal to 210 persons per floor level when not discounting any floors reserved as refuge floors.
- Siikonen et al<sup>[33]</sup> – Assess the impact of varying the occupancy between 50 persons to 200 persons per floor level.
- Klote – 90 persons per floor level.
- Pauls – Between 70 and 120 persons per floor level.

Galea et al<sup>[54]</sup> reviewed the occupancy of the World Trade Centre Tower 1 at the time of impact during the 2001 terrorist attacks and note that the occupancy level per floor was approximately 127 persons. Based on an occupancy similar to the theoretical building used

as part of this study, it is assumed that conditions within the limited area of the escape stairs will be similar to those within the World Trade Centre during an evacuation.

Nevertheless, Galea et al<sup>[54]</sup> also noted that the building was not occupied to full capacity (25,500 persons), which would produce an occupancy of approximately 274 persons per occupied floor level. This significantly exceeds the number of occupants provided within the simulations used as part of this study and would significantly increase the evacuation time.

## 5.8 Summary

Each of the calculation methods discussed in Chapter 3 are based on the input values listed in Table 5.8 below. Whilst it is noted that the majority of the inputs are the same for each method, the STEPS programme requires additional inputs to be provided for the dwell time and the motor delay time.

Variable	Values used	Reference
Refuge floor separation	10, 15, 20, 25 storeys	[6], [23]
Floor to floor height	4m	-
Lift speeds	5, 6, 7, 16 m/s	[27], [31]
Lift acceleration	1.2, 1.5 m/s <sup>2</sup>	[27], [31]
Door opening and closing times	5.3 seconds	[19]
Lift capacity	10, 12, 16, 21 persons	[30], [51]
Time to exit the building	10 sec (ELVAC)	-
Trip inefficiency	0.1 (ELVAC)	[19]
Dwell time	4 seconds	[19]
Motor delay	1 second (STEPS)	-
Delay due to acceleration/deceleration	10 seconds (Siikonen)	-
People transfer time	0.6 sec(ELVAC), 0.3 sec (STEPS), 1 sec (Siikonen)	[19]

**Table 5.8 – List of input values**

The Siikonen calculation method uses a default value of 10 seconds for the delay associated with acceleration and deceleration, however, the impact of this is discussed in Section 3.3.2.

The default values used in ELVAC, as discussed previously are not listed below, unless these are variable when inputting the values in the calculation.



The use of a 10 second delay for occupants to exit the building in the ELVAC programme is considered to have a negligible impact on the total evacuation time. Whilst it is noted that the analytical methods do not include this delay, the additional time is only considered to have an impact on the final round trip of the lift, therefore, based on the total building evacuation time at the time of the last round trip, the provision of an additional 10 seconds (0.16 minute) to the total evacuation time is considered to have a negligible impact on the overall value of the building evacuation time.

It is not possible to specify a value for the time for occupants to leave the building in the STEPS model. This is a result of the distance to the nearest exit and the walking speed. However, the use of a 10 second delay in the ELVAC model is considered to provide a reasonable approximation with the STEPS model.

## CHAPTER 6 - STEPS MODELLING

### 6.1 Introduction

Before presenting the STEPS simulation results to identify the optimum method of evacuation using lifts, this chapter will present the results of a preliminary study to further elaborate on the input parameters used in STEPS simulations and also to examine some of the detailed output results from STEPS to further assess the correctness of this simulation package.

### 6.2 Sensitivity Study

The STEPS programme may be used to calculate the lift and stair evacuation times as well as conditions within the escape routes during the evacuation. Whilst the results of the STEPS assessment have been verified against those produced from the ELVAC programme, it is also considered necessary to conduct a sensitivity study to assess the impact of the variables on the outcome of the simulations.

Lord et al<sup>[47]</sup> states:

*“A sensitivity analysis of a model is a study of how changes in model parameters affect the results generated by the model. Model predictions may be sensitive to uncertainties in input data, to the level of rigor employed in the modelling of occupant movement, and to the accuracy of numerical treatments. The purpose of conducting a sensitivity analysis is to assess the extent to which uncertainty in model inputs is manifested to become uncertainty in the results of interest from the model. This information can be used to:*

- *Determine the dominant variables in the models,*
- *Quantify the sensitivity of output variables to variations in input data, and*
- *Inform and caution any potential users about the degree and level of care to be taken in selecting input and running the model.”*

Even deterministic models rely on inputs often based on experimental measurements, empirical correlations, or estimates made by engineering judgment. Uncertainties in the model inputs can lead to corresponding uncertainties in the model outputs. Sensitivity

analysis is used to quantify these uncertainties in the model outputs based upon known or estimated uncertainties in model inputs. Sensitivity studies can be grouped into three categories:

- Scenario Specific Data – Such as the geometry of the building or space, occupant flow rate through exits or other building components, and if the model is grid-based, the grid size chosen to model the scenario.
- Occupancy Specific Data – Such as the total number of occupants, the demographics of the population, size of occupants, walking speeds (stair walking speed), pre-movement times, occupant patience factors, and other similar variables.
- Model Specific Data – Which can include various coefficients and other factors specific to the model being studied, such as the patience factor.

On this basis, a sensitivity study will be undertaken to assess the impact of the grid size, occupant walking speed and occupant patience factor on the results of the STEPS assessment, as discussed below.

### 6.2.1 Cell Grid Size

Lord et al notes that: “STEPS is generally sensitive to grid-size. Changing the grid from 0.3 metres to 0.6 metres can have a significant impact on the results of the model. Efforts should be taken when using STEPS to use an appropriate grid size and to perform some sensitivity analysis.”

Therefore, a sensitivity analysis has been undertaken to determine the impact of the grid size on the results of a simulation. The grid sizes used in the sensitivity study were as follows:

- 0.3m<sup>2</sup>
- 0.5m<sup>2</sup>
- 0.6m<sup>2</sup>

Figure 6.2.1 shows the average stair flow rates in the stair on the 20th floor of the theoretical building during the simultaneous evacuation of the building by stairs only. As can be seen from the chart, the grid size used has a large impact on the output provided by the model.

There is a quantitative difference between using the  $0.3\text{m}^2$  grid size and the  $0.5\text{m}^2$  and  $0.6\text{m}^2$  grid sizes. For the  $0.3\text{m}^2$  grid size, the flow rate initially increases slightly and the high flow rate is maintained. But for the  $0.5\text{m}^2$  and  $0.6\text{m}^2$  grid sizes, the flow rate drops drastically after a short period of time.

After consultation with the creators of the STEPS programme<sup>[55]</sup> it was confirmed that a grid size of the  $0.3\text{m}^2$  is not a very realistic grid cell size to use, on the basis that there are more cells available in the staircase, which means that you can fit more people in the staircase than with a wider grid. On this basis, the upper floors can be evacuated in a lower time than with the larger grid cell size.

The reason the flow rate decreases with a wider grid size is because people entering the stairs in the floors below the 20th floor (level flow rate is measured at) reduce the walking speed of the people in the stairs on the floors above, which causes the stair flow rate to decrease on those upper floors. The reason that the flow rate initially increases is due to the fact that, at the start of the simulation, the stairs are empty, and therefore, people are free to walk at their maximum speed, before it is reduced when merging with occupants on the lower floor level.

Once the occupants of the upper floors have entered the stair, the exit flow rate (i.e.  $1.33\text{ p/s/m}$  multiplied by a stair width of  $1.4\text{m}$  equals  $1.8\text{p/s}$ ) controls the flow rate of the staircase, rather than the rate at which people enter the stair. In the case of a larger grid size, there are fewer cells available, therefore the staircase capacity is lower and as a result it takes longer to evacuate the floors.

The difference between the flow rate in the  $0.5\text{m}^2$  grid cell model and the  $0.6\text{m}^2$  grid size model is a result of the number of occupants able to queue at the exit, such that the flow rate of the exit exceeds the number of occupants able to move towards the exit.

Despite the different grid sizes, the initial peak flow rate ties well with the value of 1.33 person/second/metre which is the flow rate currently used in Approved Document B.

STEPS assumes that all people are the same size as the grid cell that they occupy. The STEPS model uses a default grid size of  $0.5\text{m}^2$ , which is approximately commensurate with the unit exit width principle detailed within the Post War Building Studies<sup>[37]</sup>. Based on the results of the sensitivity study, each STEPS simulation programme has been conducted using the default grid cell size of  $0.5\text{m}^2$ .

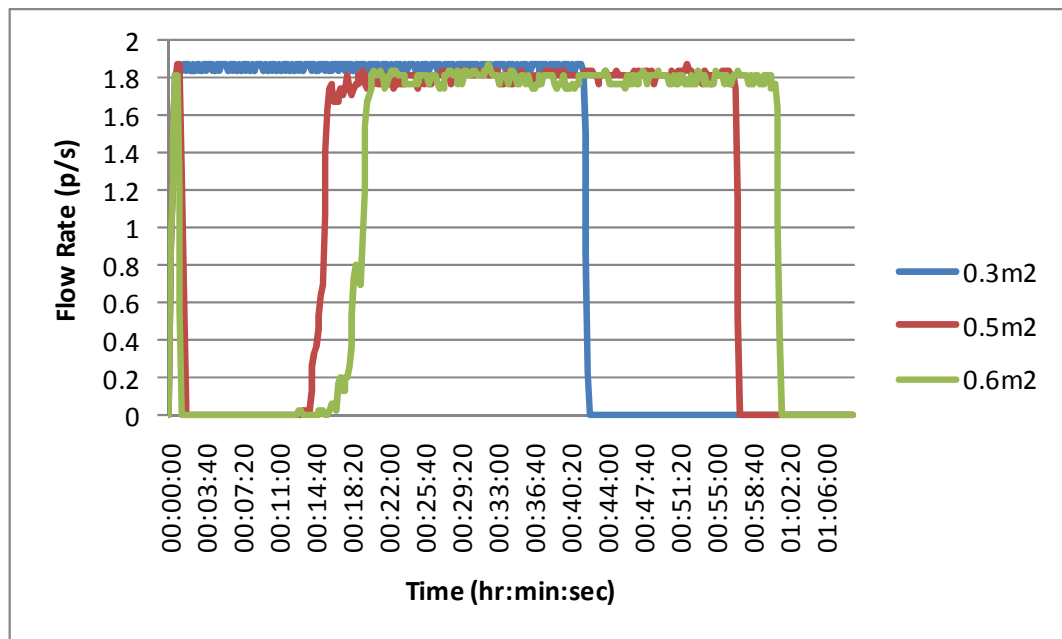


Figure 6.2.1 – STEPS stair flow rates based on different grid sizes

### 6.2.2 Walking Speed

The lift walking speed has been varied based on the guidance of Nelson and Mowrer<sup>[3]</sup> for travel down the diagonal of a stair. The values used in the assessment are:

- 0.85m/s
- 0.95m/s
- 1.05m/s

The values of ‘the number of persons that left’ the simulation are shown in the graph below. As can be seen from the graph, the difference in the number of persons that leave the model is not dependent on the walking speed in the model. Due to the congestion

within the stair this factor is considered to be a result of the queuing of people in the stair, which reduces walking speed to approximately zero. Therefore, the occupant walking speed is not considered to be a controlling factor in this simulation.

On this basis, it is considered reasonable to use the value of 0.95m/s, based on the riser and going dimensions<sup>[3]</sup>, and the resulting stair angle.

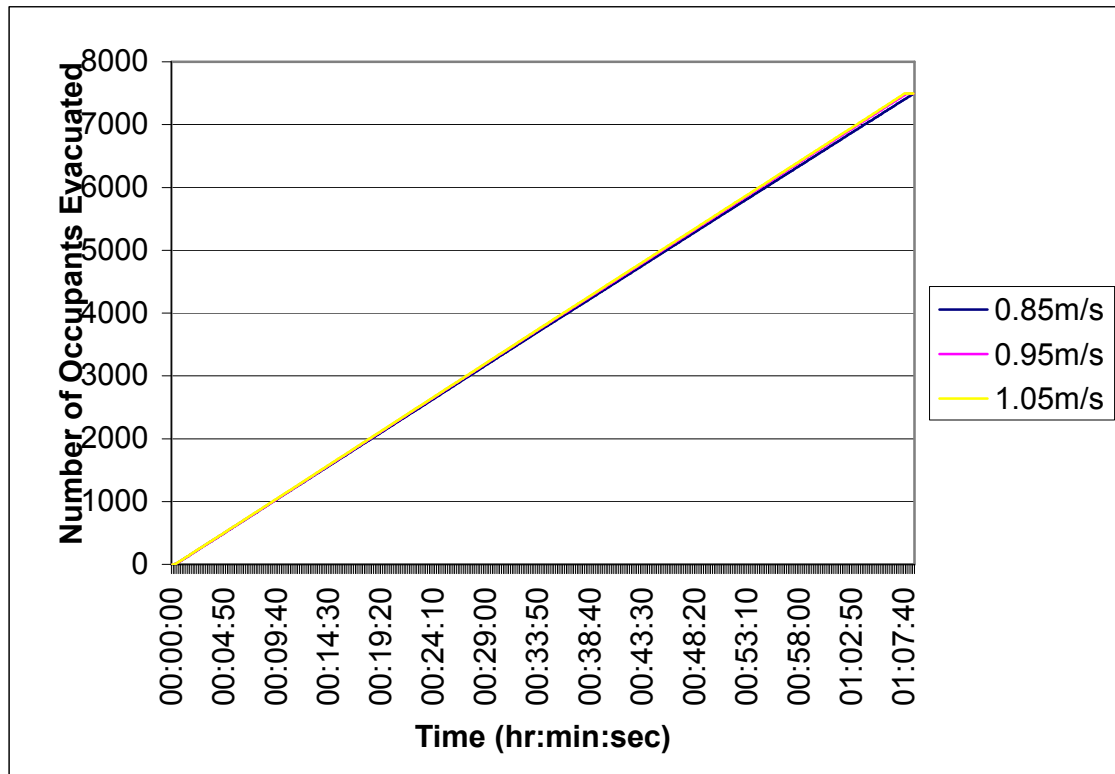


Figure 6.2.2 – Evacuation times based on walking speeds

### 6.2.3 Patience

In a queuing situation, some people are more patient than others. The less patient people will seek alternative routes and the more patient people will stay in place. In STEPS, an adjustment factor is used to change the queuing time based on the occupants' patience level. This adjustment factor is calculated using the following equation:

$$C_{adjustqueue} = 1 + \frac{(C_{patience} \times (0.5 - Patience))}{0.5} \quad \text{Equation 31}$$

Where: Patience is the value being varied (between 0 (impatient) and 1 (patient))

$C_{patience}$  is a co-efficient entered in the Edit Decision Process dialog box

The value of  $C_{patience}$  is maintained as 1 for each assessment.

The patience factor is considered to be a model specific variable. A sensitivity study has been undertaken to determine the impact of the patience factor on the results of the model. The following patience factor values have been used in the assessment:

- Patient (0.9)
- Mid-point Value (0.5)
- Impatient (0.1)

In this application of STEPS simulation, the alternative to queuing is to access an alternative exit via the refuge floor. Using lifts is not allowed. The results of the sensitivity study are shown below based on the theoretical building detailed in Section 1.4, which contains 50 storeys above Ground and assumes occupants escape via one of the two available stairs, due to a single stair being discounted in accordance with Approved Document B<sup>[2]</sup>.

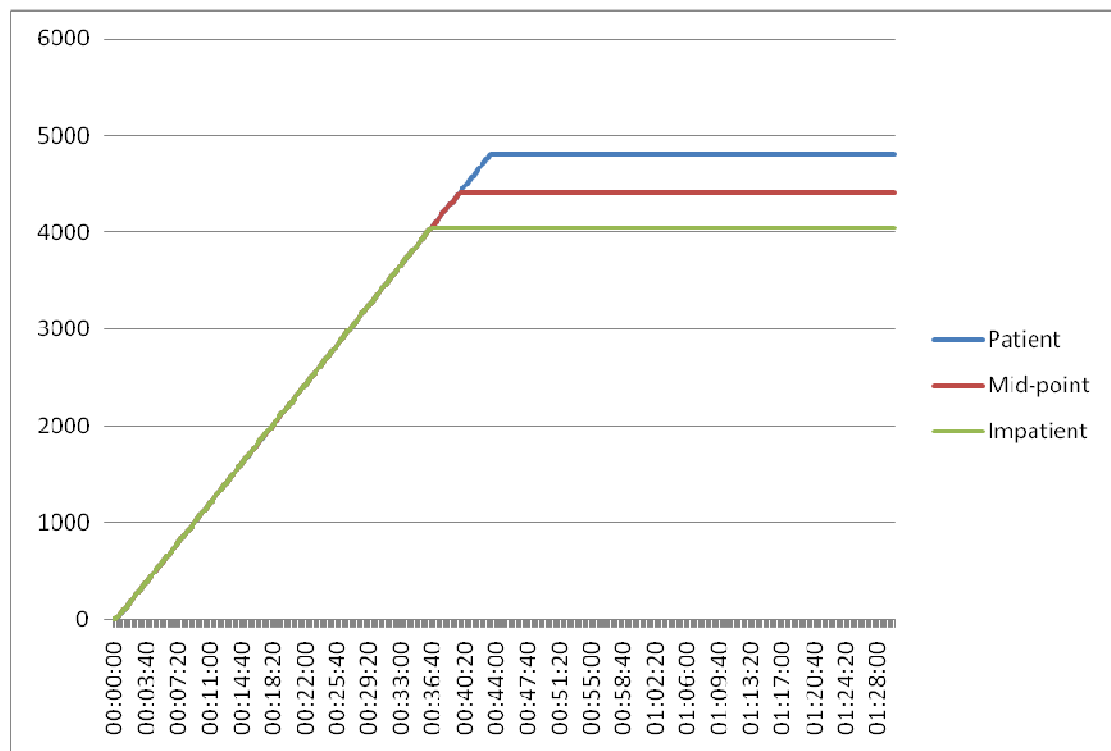


Figure 6.2.3 – Number of occupants evacuated via Stair 1

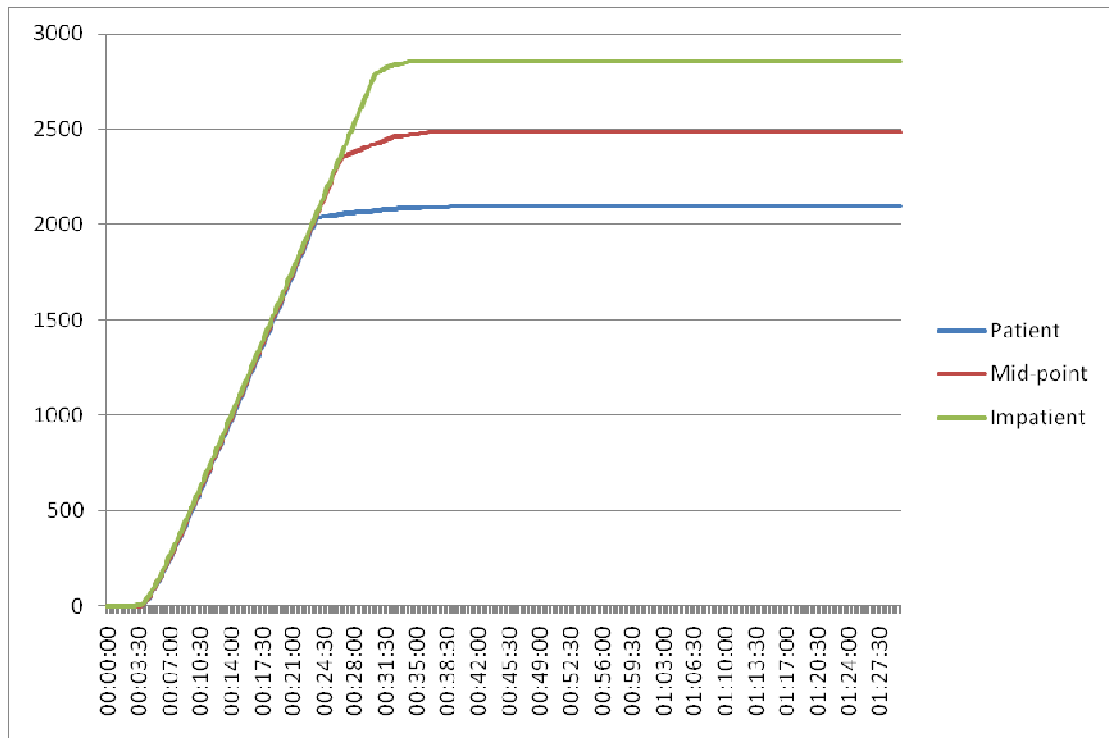


Figure 6.2.3 (a) – Number of occupants evacuated via Stair 2

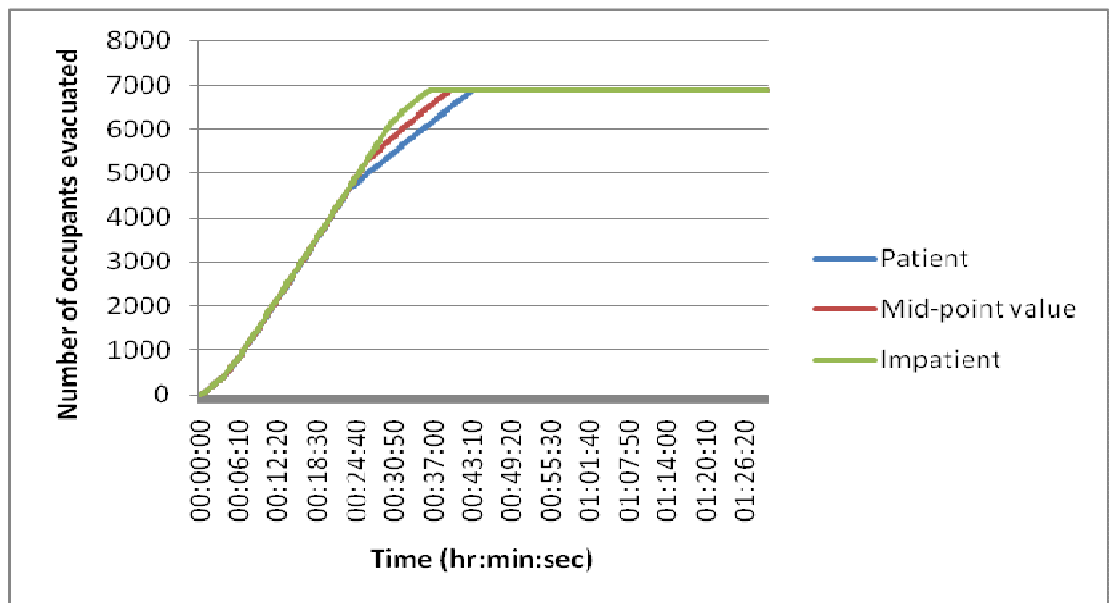


Figure 6.2.3 (b) – Time for evacuation based on patience level

As can be seen from Figure 6.2.3 and 6.2.3 (a) above, the occupants with the lower value of patience factor (impatient) are more likely to seek to escape via the alternative means of escape (i.e. Stair 2 as shown in Figure 1.4). This is demonstrated by the number of occupants of the 'impatient' model escaping via the alternative exit.



Whilst this increases the time for occupants to escape via the alternative means of escape (i.e. Stair 2), the reduction in the number of persons escaping via the more congested Stair 1 reduces the overall evacuation time. The difference in the overall evacuation time between the patient and impatient occupants is 6 minutes and 50 seconds (Figure 6.2.3). Therefore, the evacuation time of the impatient occupants is approximately 15% less.

On this basis, the patience factor is considered to be an important variable where alternative means of escape are available. Since the purpose of this simulation is merely to demonstrate behaviour of the simulation results, the mid-point value, which is considered to represent the different levels of patience within a large group, will be used in further studies.

#### 6.2.4 Summary

Whilst the results of the sensitivity study cannot be directly applied to the lift evacuation studies used for comparison with the code compliant stair evacuation times, this assessment provides confidence to the user that the results provided by the STEPS programme are accurate.

The results of each of the three assessments in Section 6.2 provide the expected results and have minimum deviation from the expected trend.

### 6.3 **Results**

The STEPS computer simulation programme was used as part of the study to provide additional details about the occupant conditions within the building during the evacuation. These generally included the time required for occupants to leave the building, number of persons located on a refuge floor and space per person on the refuge floors.

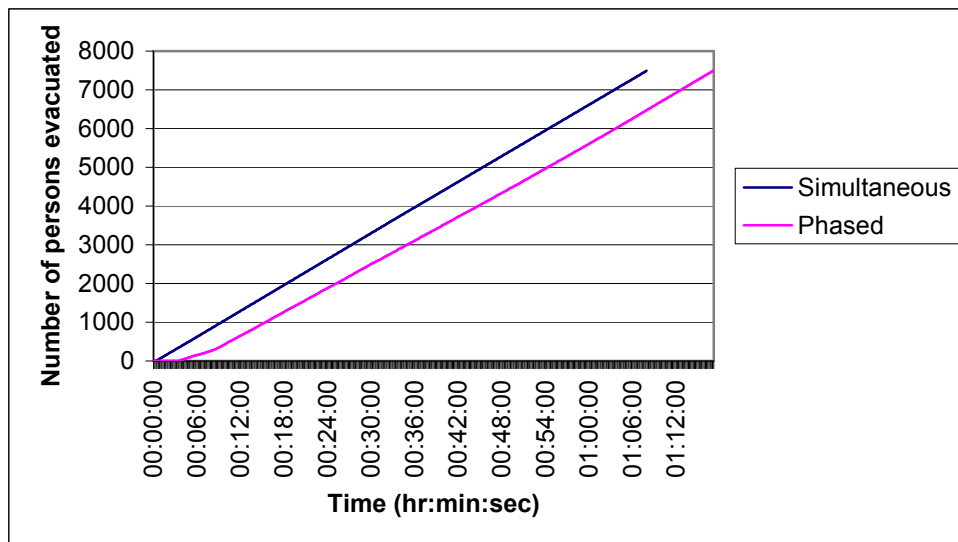
This allowed the author to assess the conditions of the evacuation system in more detail compared to those results provided by the ELVAC programme or the analytical calculation methods provided by Siikonen<sup>[40]</sup> and Sekizawa<sup>[42]</sup>, such that suitable conclusions can be made with regards to the appropriate evacuation strategy and comparison with stair evacuation.

### 6.3.1 Comparison of Phased and Simultaneous Evacuation

Current guidance in the UK would recommend that a high rise building be provided with phased evacuation. Phased evacuation generally requires the floor of fire origin to evacuate upon detection, then after a set time delay, usually of two and a half minutes, the next two floors above will evacuate and so on.

Phasing the evacuation of a high-rise building allows only a handful of storeys to evacuate at anyone time. Therefore, the means of escape routes, such as stairs and doorways, can be designed based on the relatively low number of occupants from a few floors, rather than the more onerous occupancy during simultaneous evacuation.

However, in the event that the whole building is required to evacuate, occupants will be required to escape via a staircase which has not been designed to accommodate the large number of occupants required to use it. This will result in crowding on the stairs, which will reduce and possibly stop the flow of occupants in the upper levels of the stairs.



**Figure 6.3.1 – Comparison of simultaneous and phased evacuation**

It is noted from Figure 6.3.1 above the number of occupants who have left the building during the simultaneous evacuation, exceeds that during phased evacuation. The difference between the evacuation times is considered to be based on the time taken for the first occupants of the phased evacuation simulation to reach the final exit of the stair compared to simultaneous evacuation. During simultaneous evacuation, the first occupants

arrive at the final exit within a short period of time due to the short travel distance from the floor nearest to the final exit, compared to that during phased evacuation, which may be much higher within the building.

Whilst simultaneous evacuation does provide quicker evacuation times, it is noted from the stair flow rate results in Section 6.2.1, that the flow rate within the stair during simultaneous evacuation is very low, and therefore it is assumed that occupants of floors immediately affected by the fire may not be able to enter the stair due to overcrowding. Therefore, based on the higher flow rate within the stair, throughout the whole of the phased evacuation period, the provision of a phased evacuation strategy allows people to evacuate the fire floor quicker.

### 6.3.2 Space per Person

Whilst the main purpose of providing a building with lift evacuation is to reduce the total evacuation time to less than that when providing code compliant stairs, designed to accommodate phased evacuation, it is also to provide improved conditions within the escape route. Accounts of evacuation of the World Trade Centre's noted that the stairs were blocked due to the merging flows of many floor levels into a stair of limited width and the counter flow of fire fighters attempting to access the upper floor levels.

However, it is noted that based on the provision of a refuge floor serving 25 storeys, approximately 3600 people will access the lifts via the refuge floor. Whilst these occupants will not simultaneously occupy the refuge floor, due to the delay in occupants from the upper floor levels reaching the refuge floor, it is noted that the flow rate onto the refuge floor may exceed that of the lift evacuation system, such that occupants queue on the refuge floor. On this basis, an assessment of the space per person provides an overview of the conditions on the refuge floor, which may be compared with those in the stair.

Based on the provision of lift evacuation from an evacuation zone, it is not considered necessary to assess the space available per occupant. This is on the basis that occupants do not move between floors to board a lift. Therefore the floor space factor is considered to be no worse than during normal occupancy. On this basis, it is only considered necessary to assess the floor space factor per person for evacuation from refuge floors.

Each refuge floor is approximately 1850m<sup>2</sup>. Based on a 10 storey interval between refuge floors, the most onerous floor space factor value is equal to 1.73m<sup>2</sup>/person, at the 40<sup>th</sup> refuge floor level. The most onerous value at the 10<sup>th</sup> refuge floor level is equal to 2.83m<sup>2</sup>/person. The lower value at the 40<sup>th</sup> floor is considered to be the result of the increased distance between the refuge floor and the discharge floor which increases the lift round trip time such that the net flow rate of occupants on to the refuge floor between round trips is greater than the floor levels below.

As expected, the space per person increases within a shorter time of evacuation commencing from the lower floor levels, than that of the upper floor levels. This is considered to be the result of the lower lift evacuation time from this floor level.

The space per person reduces to a minimum value of 0.77 m<sup>2</sup>/person based on a 25 storey interval between floor levels.

Whilst it is noted that this space per person is in excess of the lowest values discussed in Section 2.5.3 for each scenario, the results of the simulation demonstrated that occupants are provided with a low area per person (<1m<sup>2</sup>/person) for approximately 27 minutes during the most onerous scenario. These conditions are considered to be similar to the crowded conditions within the stair during a code compliant evacuation, which lift evacuation attempts to overcome. Therefore, it is considered necessary to reduce the lift waiting time if refuge floors are provided at the maximum recommended spacing or ensure the refuge floors serve floor levels with low numbers of occupants (i.e. < 150 persons). However, this will require an increase in the lift performance values.

### 6.3.3 Number of Occupants Evacuated

Based on the number of occupants who exit the STEPS simulation from the lift discharge floor it is considered possible to calculate a lift 'flow rate' for the following three scenarios:

- Evacuation from refuge floors at 10 storey intervals
- Evacuation from refuge floors at 15 storey intervals
- Evacuation from refuge floors at 25 storey intervals

Each graph follows the same trend such that the number of persons that exit the model increases at a steady rate. However, the gradient of the graph then decreases once the occupants of the lower floor levels have exited the building via the stairs (i.e. flow rate is equal to that of the lift discharge rate only).

A comparison of the number of occupants evacuated is shown in Figure 6.3.3, for evacuation from a refuge floor.

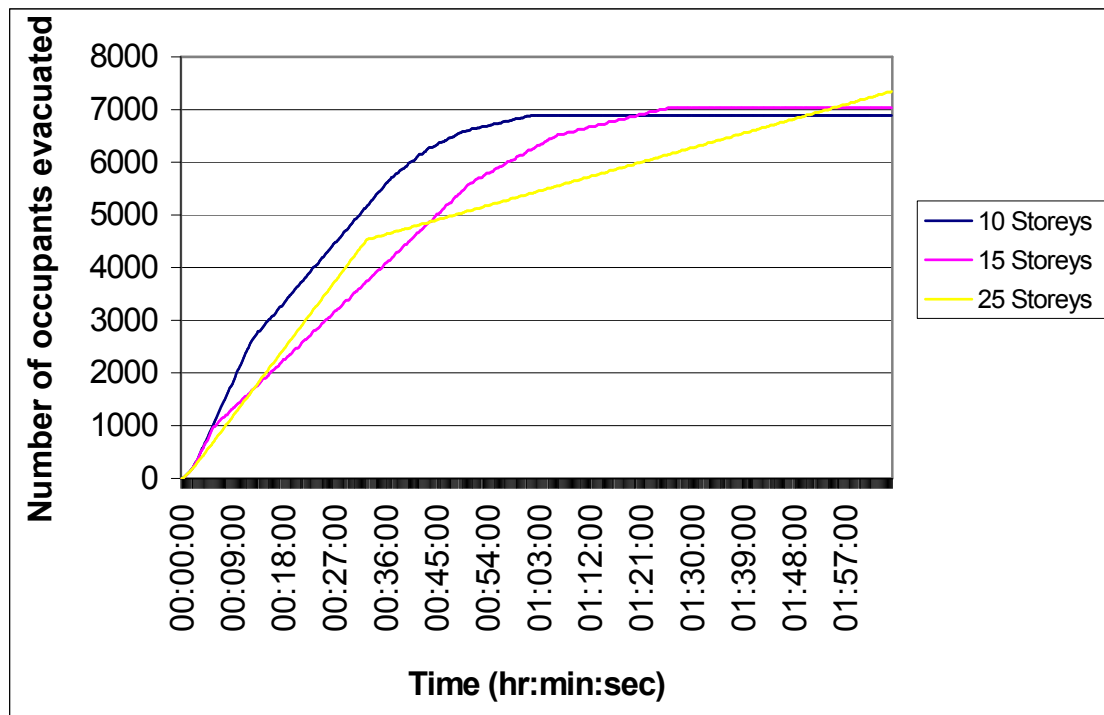


Figure 6.3.3 – Evacuation time lines

As can be seen from the graph the most efficient lift evacuation strategy is based on the provision of refuge floors at 10 storey intervals. The results of the graph show that at any given time, the flow rate from a building provided with refuge floors at 10 storey intervals exceeds that evacuated by refuge floors at greater intervals.

It is noted from the Figure above that the gradient of the line for the 25 storey interval simulation is greater than that of the 15 storey simulation until approximately 30 minutes after evacuation commences. The rate at which occupants exit the building in the 25 storey simulation then reduces significantly, such that the rate at which occupants exit the building is much higher for the 15 storey model. This is considered to be the result that up to approximately 30 minutes after evacuation commences, more occupants of the 25 storey model are evacuating via the higher flow rate stairs (25 storeys), compared to those

in the 15 storey simulation (5 storeys evacuate via stairs). The reduction in the number of occupants exiting in the 25 storey simulation after approximately 30 minutes is considered to be the result of the remaining occupants of the 25 storey model being forced to evacuate via the lifts, which have a lower flow rate of occupants than the stairs. The rate people exit the 15 storey model remains relatively high based on the provision of multiple groups of lifts, serving smaller zones, such that the flow rate of the lift system is maintained at a higher level in the 15 storey model than the 25 storey model.

It is noted from Figure 6.3.3 that the number of occupants evacuated is different for each of the three scenarios above. This is a result of the number of refuge floors provided in each model. Based on the assumption that each refuge floor is a non-occupied, fire sterile floor, the occupancy of the models with more refuge floors will be less than those with fewer floors.

Based on a 10 storey interval between floors the average flow rate from the building (i.e. the flow rate over the full evacuation period) using lifts is equal to 1.85 persons/second. This decreases to 1.36 persons/second for a 15 storey interval between floor levels and 0.97 persons/second for a 25 storey interval between refuge floor levels.

However, based on the provision of lifts with a rated speed of 16m/s serving refuge floors at 10 storey intervals the flow rate increases to 2.18 persons/second (15.1% increase). Likewise, based on the provision of 8 lifts serving refuge floors at 15 storey intervals, the flow rate increases to approximately 2.64 persons/second (48.5% increase).

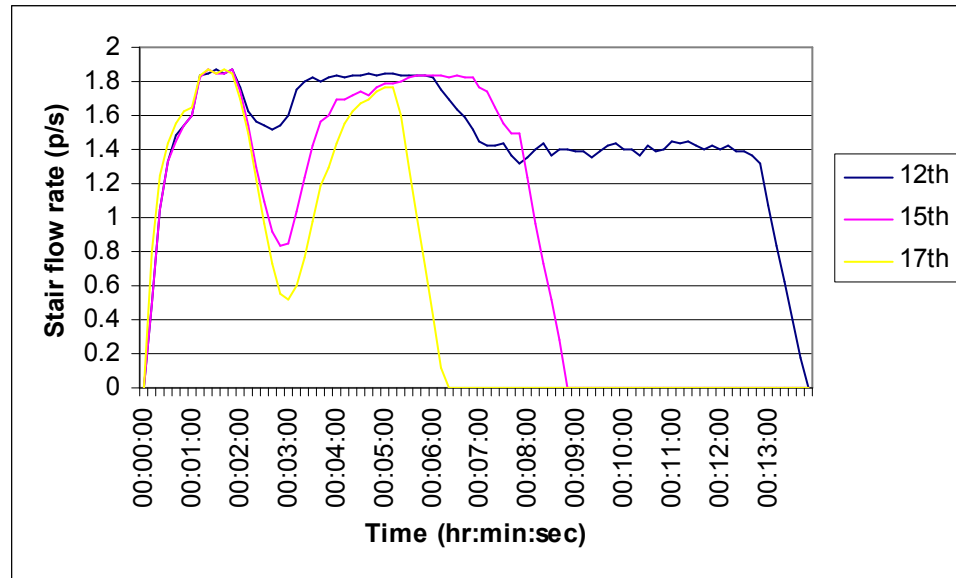
#### 6.3.4 Stair Flow Rate

The use of evacuation via lifts increases the flow rate within the stairs as a result of the lower number of persons required to use the stairs.

This may be demonstrated based on the provision of refuge floors at 10 storey intervals, where the stair width required for occupants to reach their refuge floor is less than that for the simultaneous evacuation of the building.

Whilst the stair size required remains in excess of that required for the phased evacuation for the smallest refuge floor evacuation distance, it is noted that the flow rate in the stair is

increased as a result of the reduction in the number of occupants attempting to access the stair. The flow rates in the stair serving the 10<sup>th</sup> refuge floor are shown for three locations within the stair in the graph below (approximately 1/3<sup>rd</sup> intervals). The stair flow rate for the upper refuge floor levels generally follows the same trends.



**Figure 6.3.4 – Stair flow rate serving 10<sup>th</sup> floor level**

In each scenario studied the largest decrease in the flow rate is always for the higher floor levels. This is considered to be the result of a queue forming within the stair as the occupants from the lower floor levels merge with those occupants descending the stair causing the occupants of the upper floor levels to reduce their walking speed and therefore the stair flow rate. However, the reduced stair flow rate is approximately double that of the flow rate during the simultaneous evacuation of the whole building, as shown in Figure 3.2.4.

The flow rate at the lower floor level is not considered to reduce as significantly as the higher floor level as a result of occupants from a smaller number of floor levels below attempting to access the stair, therefore, allowing the optimum flow rate to be achieved for the duration of the evacuation.

As a result of the increase in the number of floor levels serving each refuge floor, due to an increase in the separation distance between refuge floors, the reduction of the flow rate within the stair is greater, such that, based on a 15 storey separation distance between refuge floor levels, the flow rate approaches that of a stair used for the simultaneous evacuation of the whole building.

### 6.3.5 Lift Waiting Times

As expected the lowest lift waiting times are those for a 10 storey interval between refuge floors. On this basis, the maximum lift waiting time is equal to 267 seconds (approximately four and a half minutes), which is significantly lower than the eight minutes recommended by Lane<sup>[5]</sup>.

The STEPS assessment has shown that the maximum lift waiting time for the default values is for a 25 storey interval between floor levels, which is equal to 600 seconds (~10 minutes).

Whilst it is noted that this waiting time exceeds the recommended eight minutes<sup>[5]</sup>, this is considered to be reasonable on the basis that this recommended time is based on a notional evacuation time based on evacuation from sports stadia, plus the additional time is less than the 30 minutes occupants have been observed to wait for a lift to arrive<sup>[9]</sup>.

### 6.3.6 Effects of Reduced Occupancy

The use of the lifts for evacuation by half of the buildings occupants increases the space per person on each refuge floor to approximately twice that when the whole building occupancy escapes via lifts. In addition, the stair evacuation time is less than that during the simultaneous evacuation of the building.

As the graph below shows, the flow rate in the stair decreases such that occupants are required to stand and wait in the stair for approximately 90 seconds in the upper floor levels of a stair serving a refuge floor. However, a similar effect is noted for every refuge floor separation distance studied with a reduced occupancy. The rapid increase in the stair flow rate is considered to be the result of a reduction in the number of occupants escaping via the stair such that the flow rate reaches the optimum flow rate throughout the stair value within a relatively short time period of evacuation commencing.



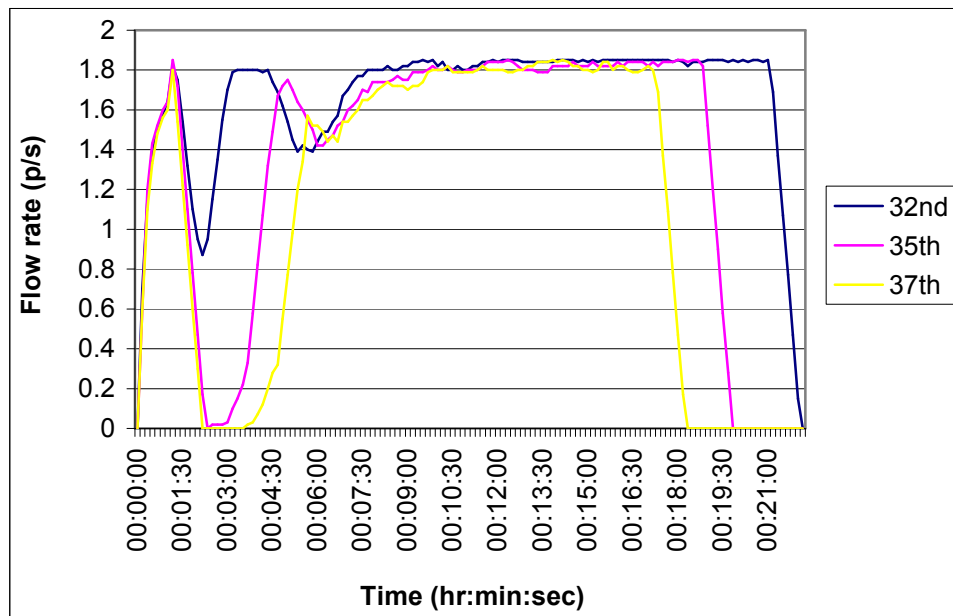


Figure 6.3.6 – Flow rate in stair serving 30<sup>th</sup> refuge floor

The flow rate within the stairs also follows the same trend based on a greater refuge floor separation distance, such that the flow rate in the upper levels of a stair reaches its optimum flow rate after those floor levels below. The flow rate at the upper floor levels ends prior to those floor levels below based on all of the occupants of the zone having passed that measurement point prior to the end of the simulation.

### 6.3.7 Summary

The results of the STEPS assessment have provided additional information other than the total evacuation time, which will allow designers to provide optimum lift evacuation procedures to be implemented as well as investigate the conditions within a building once a lift evacuation strategy is agreed.

For example, it is simple to note from the STEPS assessment that the space per person on a refuge floor remains above the recommended floor space factor when refuge floors are provided at the greater interval, and that the flow rate throughout the stair is maintained at a higher level than a code compliant solution.

Whilst this information is not essential when trying to determine the quickest lift evacuation strategy, it will provide designers with additional information that will allow them to provide the optimum lift evacuation strategy which is unique to the specific building being studied, rather than using predetermined values.

## CHAPTER 7 - ANALYSIS OF RESULTS

The results of the time required to evacuate the theoretical building using the calculation procedures detailed by Siikonen<sup>[40]</sup> and Sekizawa<sup>[43]</sup> as well as those obtained using the ELVAC computer programme have been compared with the stair evacuation time from an equivalent floor level, which has been calculated using the Approved Document B flow rates, to determine the most efficient evacuation method.

The results of the assessment are contained in the appendices, while a discussion of the results is provided below, which includes the following information:

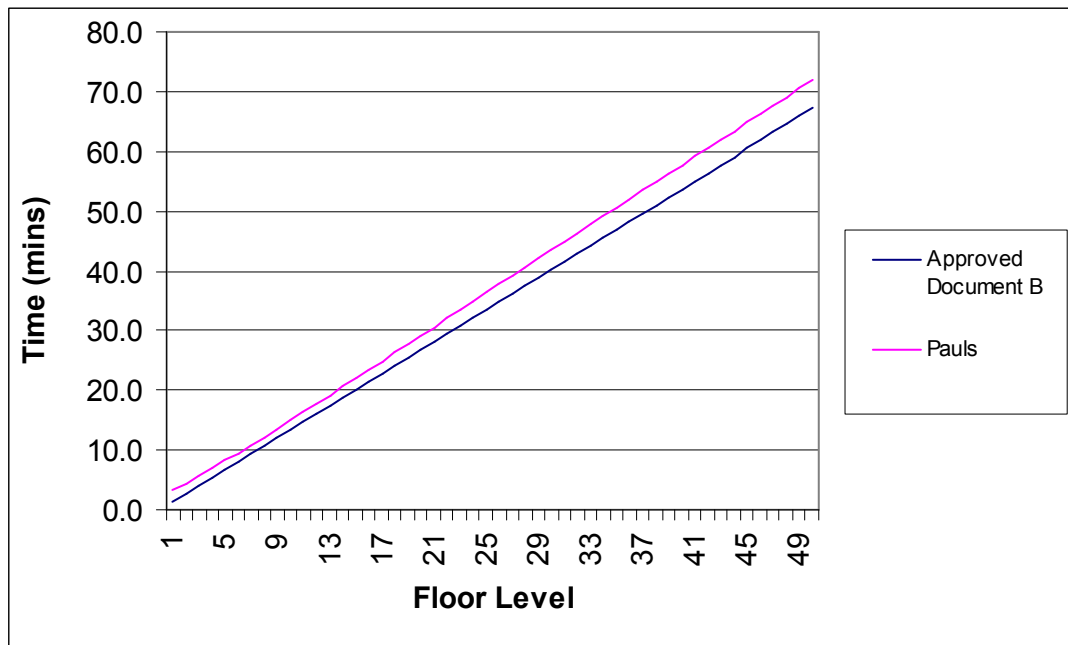
- a) A comparison of the lift evacuation times using different lift performance values with the code compliant stair evacuation time.
- b) A comparison of the lift evacuation times using different lift performance values with the associated stair evacuation times when provided with a combination of lift and stair evacuation.
- c) A comparison of the lift and stair results in point b) with the code compliant evacuation times.

The results of this comparative assessment will demonstrate the most efficient evacuation strategy, which may be used to support the results of the evacuation calculator contained in Appendix A. It will also verify the lift performance values listed in Chapter 5 are suitable for use with lift evacuation, and therefore, demonstrate that lifts provided for general circulation use within tall buildings (i.e. not designed for evacuation of zones or refuge floors only) may be used to evacuate buildings in less time than a code compliant method of evacuation (i.e. stairs sized for phased evacuation).

### 7.1 Code Compliant Evacuation

The evacuation time using stairs has been calculated using the method detailed by Pauls<sup>[10]</sup>, as discussed in Section 3.2.3 and the Approved Document B flow rates<sup>[2]</sup>, as discussed in Section 3.2.2. The results of this assessment are shown in Figure 7.1 below.

It is not proposed to use the calculation method of Nelson and Mowrer due to the variation between the results calculated using this method and those of Approved Document B, which have been shown to have a close correlation with the results of evacuation drills conducted by Pauls<sup>[10]</sup>.



**Figure 7.1 – Time for evacuation using stairs only**

The time taken for each floor level to evacuate is based on the assumption that the occupants of the floor levels below are also evacuating. Therefore, the stair is full to capacity.

As can be seen from the graph above, the difference between the method described by Pauls, and the evacuation time based on the AD-B flow rate is small (approximately 6.7% difference). This gives confidence in the assumptions of AD-B for calculating the code compliant stair evacuation time for comparison to the lift evacuation times. It is not proposed to compare the stair evacuation times, using the method detailed by Pauls, with the lift evacuation times. On this basis, it is proposed to compare the lift evacuation times with the stair evacuation times calculated using the AD-B flow rates only, based on the use of this document in England and Wales.

Based on the simultaneous evacuation of the building, the total evacuation time is equal to 66 minutes, based on the flow rates used in Approved Document B. Therefore, all lift

evacuation times which are greater than 66 minutes are considered to be more onerous than a code compliant design.

## 7.2 Evacuation via Lifts Only

An assessment of the time to evacuate the full building occupancy using only lifts has been made for each of the proposed lift evacuation strategies. The results of the assessment are contained in the Appendices.

### 7.2.1 Refuge Floor

#### 7.2.1.1 *Stair evacuation calculations*

The time for evacuation from each refuge floor using stairs has been calculated for comparison against the lift evacuation times, as shown in Table 7.2.1.1 below.

Refuge Floor Level	Time (mins)
5	5.6
10	12.3
20	25.8
25	32.5
30	39.2
35	45.9
40	52.6

**Table 7.2.1.1 – Time for evacuation by stairs from refuge floor based on AD-B flow rates**

However, these stair evacuation times have been calculated from the same level as the refuge floor and therefore cannot be directly compared to the code compliant stair evacuation times or the evacuation zone times. Therefore, to allow a comparison of the code compliant stair evacuation time with the lift evacuation time from a refuge floor, it is also necessary to compare the lift evacuation times with the code compliant stair evacuation time, which takes into account the additional occupants of the floor levels above the refuge floor.

On this basis, it is also proposed to assess the lift evacuation times with the stair evacuation times listed in Section 7.2.2.1 below, which takes into account the evacuation time for the whole building.

### 7.2.1.2 Results of calculations

Based on a 10 storey interval between refuge floors the whole building evacuation time (i.e. evacuation time from highest refuge floor) is approximately equal to the time taken using stairs only (lift evacuation is 60 seconds faster), when using the default lift values. The impact of the variable lift performance values is discussed below.

- Based on a lift velocity of 16m/s the whole building evacuation is approximately 10 minutes faster than the time required using stairs. The time for evacuation from the 30<sup>th</sup> refuge floor level using lifts is equal to the time required using stairs from the same level (39.2 minutes). The time for evacuation from the lower refuge floor levels using stairs is less than that required using lifts.
- An increase in the lift acceleration is considered to have a negligible impact on the whole building evacuation time when applied to a lift with the default values.
- The whole building evacuation time is generally less than the stair evacuation time when the lifts are provided with an increased capacity compared to the default value. The exception to the above is considered to be the evacuation time from the 10<sup>th</sup> and 20<sup>th</sup> refuge floor levels, which is faster by stairs when the lift capacity is equal to 16 persons or less. The evacuation time from the 20<sup>th</sup> floor level is approximately equal to the time required using stairs, when the lift capacity is equal to 21 persons (lifts are 12 seconds faster).
- Based on the use of the default lift performance values, the lift evacuation time is faster from the 20<sup>th</sup> (lift evacuation is 1% less) to the 40<sup>th</sup> refuge floor levels (lift evacuation is 28% less), when compared to the code compliant stair evacuation time. Evacuation is faster from every refuge floor level based on the provision of 21 person capacity lifts, or more than 6 lifts serving each refuge floor level. A summary of the lift evacuation times compared with the code compliant stair evacuation times is shown in Figure 7.2.1.2 (a) below.

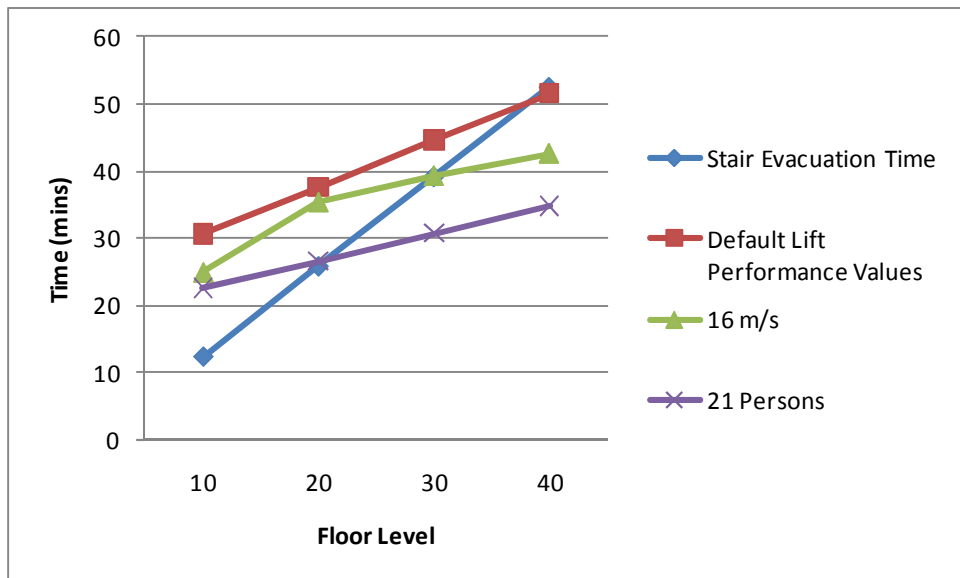


Figure 7.2.1.2 – Summary of lift and stair evacuation times from a refuge floor

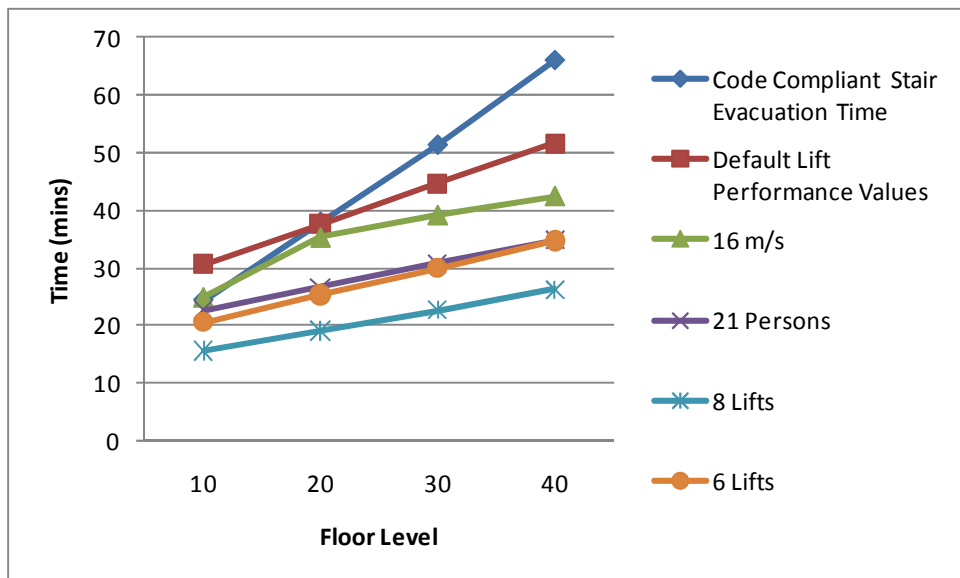
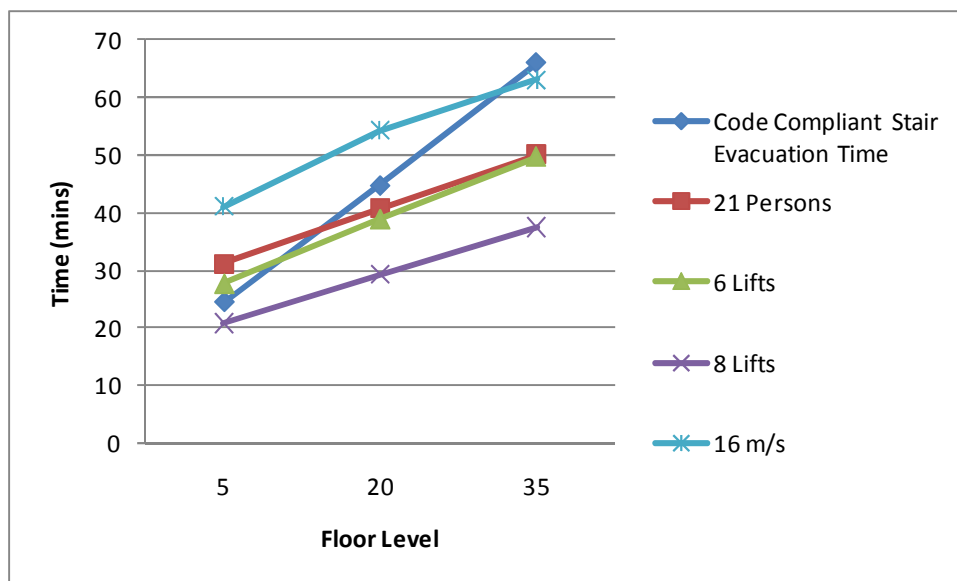


Figure 7.2.1.2 (a) – Evacuation from refuge floors at 10 storey intervals compared to code compliant evacuation time

Once the refuge floor interval is increased to 15 storeys the lift evacuation times increase significantly, such that stair evacuation is generally quicker for the whole building evacuation from the same floor level. This is due to an increase in the occupants required to evacuate from each floor level without an increase in the lift performance values used for the evacuation from refuge floors at 10 storey intervals to accommodate these additional occupants. With the exception of the following:

- The whole building evacuation requires less time than stair evacuation for a 15 storey interval between refuge floors when 8 lifts are provided to serve each floor level. However, the evacuation time from the lower refuge floor levels (5<sup>th</sup> and 20<sup>th</sup>) using stairs is less than that required using lift evacuation.
- The whole building lift evacuation is faster than the code compliant stair evacuation time when lifts are provided with a rated speed of 16m/s. However, evacuation from the 5<sup>th</sup> and 20<sup>th</sup> refuge floor levels is faster by stairs. Nevertheless, evacuation is faster from the 20<sup>th</sup> floor level by lifts with a 21 person capacity, or 6 lifts serving each refuge floor. Evacuation is faster by lifts from each floor level based on the provision of 8 lifts serving each floor level (lift evacuation is 14.8% faster from the lowest refuge floor). A summary of the lift evacuation times compared with the code compliant stair evacuation times is shown in Figure 7.2.1.2 (b) below.

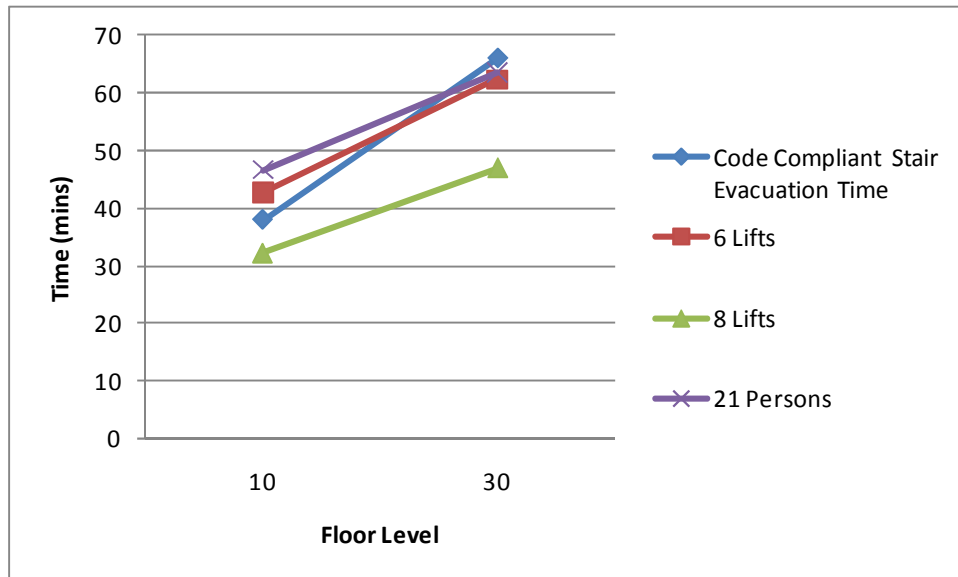


**Figure 7.2.1.2 (b) – Evacuation from refuge floors at 15 storey intervals compared to code compliant evacuation time**

Once the interval between refuge floors exceeds 15 storeys the whole building evacuation time using lifts significantly exceeds that required using stairs from the same floor level. Whilst evacuation via lifts is slower than stairs from an equivalent floor at a separation distance of more than 15 storeys, lift evacuation remains faster than the code compliant stair evacuation times based on increased lift performance values up to a 20 storey separation distance between refuge floors. However, evacuation from the lower refuge

floor is generally faster via code compliant stairs, with the exception of 8 lifts serving each refuge floor.

A comparison of the lift evacuation times, compared to the code compliant stair evacuation time is shown in the figure below.



**Figure 7.2.1.2 (c) – Evacuation from refuge floors at 20 storey intervals compared to code compliant evacuation time**

***Once the separation distance between refuge floors increases to 25 storeys the code compliant stair evacuation time is also faster than the stair evacuation time.***

## 7.2.2 Evacuation Zone

### 7.2.2.1 *Stair evacuation calculations*

The time to evacuate using stairs for each evacuation zone (i.e. a zone of floors served by a group of lifts, rather than a single refuge floor) has also been calculated for comparison to the lift evacuation times. The time for evacuation from an evacuation zone, includes for occupants of an evacuation zone (i.e. occupants of a certain floor level within the zone, plus those on floor levels below the evacuation zone), as discussed above. On this basis, the stair evacuation time used for comparison to the lift evacuation times in an evacuation zone is equal to the code compliant stair evacuation times. Therefore, it is not proposed to compare these evacuation times separately. An indicative diagram of the stair evacuation



calculation method is provided in Figure 7.2.2.1 below, while the stair evacuation times are provided in Tables 7.2.2.1 (a) to 7.2.2.1 (d).

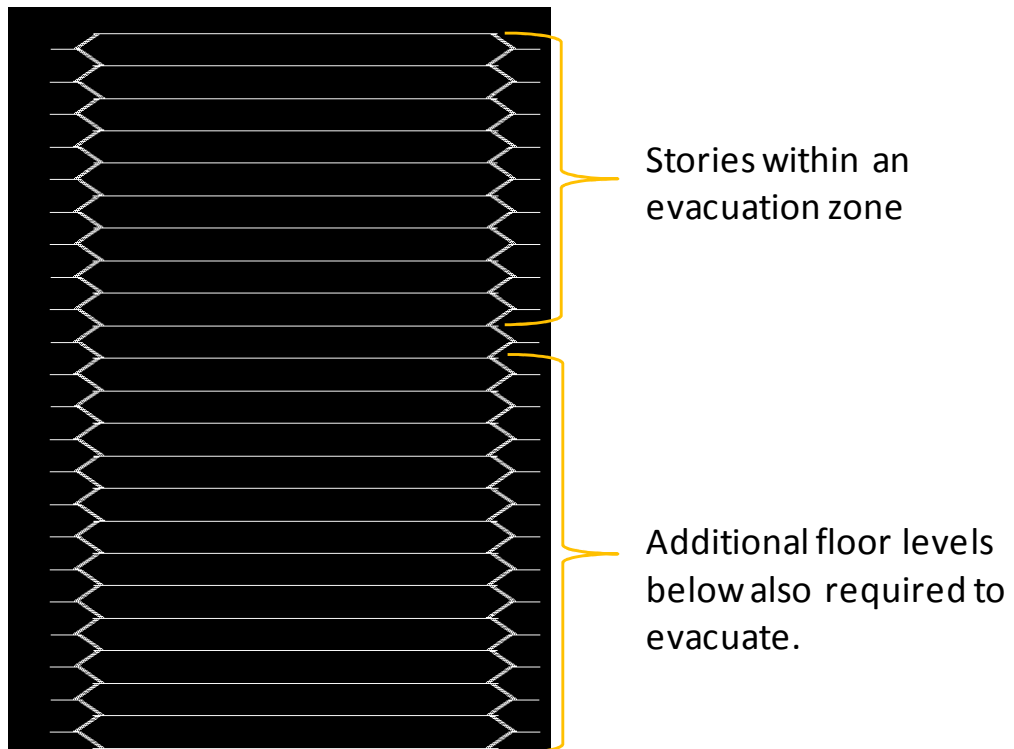


Figure 7.2.2.1 – Indicative diagram of stair evacuation times for comparison to evacuation zone lift times

Lowest floor in zone	Time (mins)
10	25.8
20	39.2
30	52.6
40	66

Table 7.2.2.1 (a) - Time for evacuation by stairs from 10 storey evacuation zone

Lowest floor in zone	Time (mins)
5	25.8
20	45.9
35	66

Table 7.2.2.1 (b) - Time for evacuation by stairs from 15 storey evacuation zone

Lowest floor in zone	Time (mins)
10	39.2
30	66

**Table 7.2.2.1 (c) - Time for evacuation by stairs from 20 storey evacuation zone**

Lowest floor in zone	Time (mins)
25	66

**Table 7.2.2.1(d) - Time for evacuation by stairs from 25 storey evacuation zone**

It is noted that the stair evacuation times are not consistent for each evacuation zone, depending on the size of the evacuation zone. This is based on the method of calculation of the stair evacuation time.

For example, the stair evacuation time from the refuge zone from 10<sup>th</sup> to 20<sup>th</sup> floor level of a building provided with 10 storey evacuation zones has been calculated based on the assumption that 150 persons from each of the nine floor levels in the refuge zone, as well as the occupants of the 10 floors below are seeking to simultaneously escape via the remaining protected stair. However, the stair evacuation from the same floor level in a building provided with 20 storey evacuation zones includes the occupants of the 19 floor levels above this floor level (evacuation zone is labelled by lowest floor in the zone), plus the occupants of the 10 storeys below this zone.

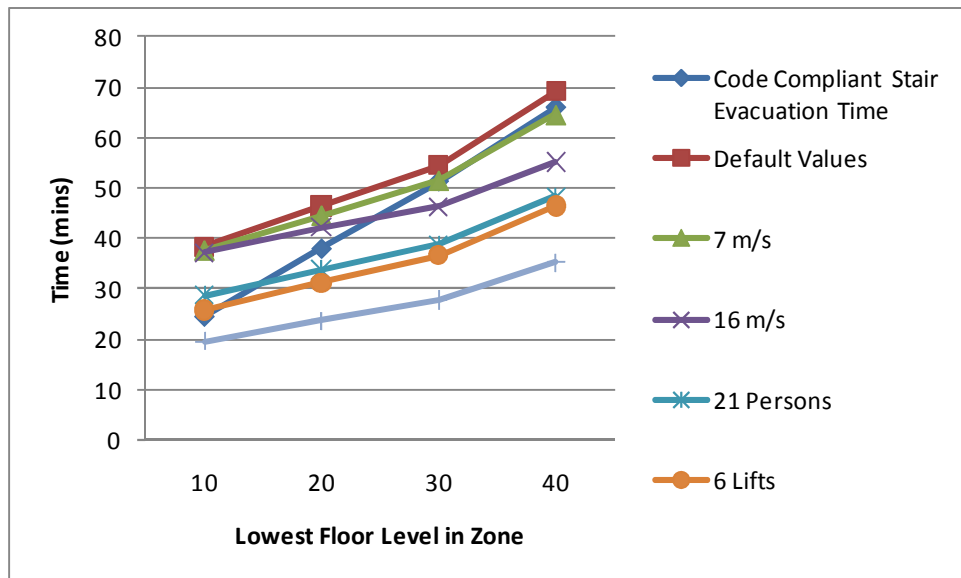
Due to the numbering of evacuation zones it is not possible to directly compare the stair evacuation times for difference sized evacuation zones. However, this is not considered to affect the accuracy of these results. For example, whilst the evacuation time from the 10<sup>th</sup> storey evacuation zone is equal to 25.8 minutes for a building provided with 10 storey evacuation zones, it is noted that the evacuation time from the 5<sup>th</sup> refuge floor in a building provided with a 15 storey evacuation zone (both zones which end at the 19<sup>th</sup> storey) is equal to 25.8 minutes.

#### 7.2.2.2 *Results of calculations*

Based on a 10 storey evacuation zone, the evacuation time using lifts only is slightly in excess of the evacuation time for stairs when using the default values. However, based on

an increase in the default lift performance values, the whole building evacuation time using lifts is less than the time using stairs only. The results of this lift evacuation assessment are contained in Appendix C. However, an overview of the results is provided below:

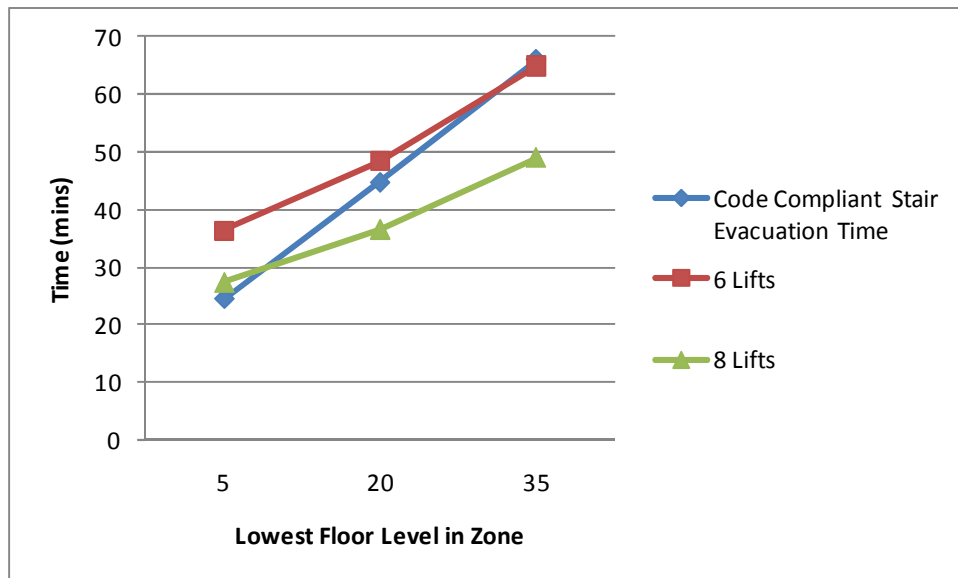
- The whole building evacuation time is approximately equal to the evacuation time when using stairs only, based on a lift velocity of 7m/s (lifts are 2.3% faster). However, the occupants on the three lower refuge zones are provided with a lower evacuation time based on evacuation via stairs only.
- Evacuation time from the upper two refuge zones is less than the evacuation time via stairs only based on a lift velocity of 16m/s or more.
- The whole building evacuation time using lifts is approximately equal to the stair evacuation time using an acceleration of 1.5m/s<sup>2</sup> (stairs are 2.5% faster).
- Based on the provision of a 16 or 21 person lift capacity, the whole building evacuation time is less than the stair evacuation time. The lift evacuation time from each refuge zone is less than the time required using stairs, based on a 21 person lift, with the exception of the lowest zone, where lift evacuation requires an additional 4.3 minutes (15%).
- The whole building evacuation is less than the stair evacuation time by approximately 19.6 minutes (30%), based on the provision of 6 lifts serving the evacuation zone. The evacuation time via stairs from the lowest evacuation zone is approximately 84 seconds less (5.4%) than the evacuation time using lifts only. Based on the provision of 8 lifts the evacuation time from each zone is less than the stair evacuation time.



**Figure 7.2.2.2 – Summary of evacuation from evacuation zones at 10 storey intervals**

Based on the provision of 15 storey evacuation zones the lift evacuation time from the building is significantly in excess of the stair evacuation time for most variables, with the following exceptions.

- The whole building evacuation time is approximately equal for stair and lift evacuation based on the provision of 6 lifts (lifts are 1.7% faster). The stair evacuation times from the lower evacuation zones is less than the evacuation time required for lifts.
- The lift evacuation time for the whole building is significantly less (17.1 minutes) than the stair evacuation times based on the provision of 8 lifts serving each evacuation zone. The evacuation times from the mid refuge zone are also less than the stair evacuation time. However, the stair evacuation time from the lowest evacuation zone is approximately 3 minutes less than the lift evacuation time (11% difference).



**Figure 7.2.2.2 (a) – Summary of evacuation from evacuation zones at 15 storey intervals**

Once the interval between refuge floors exceeds 15 storeys the whole building evacuation time using lifts generally exceeds that required using stairs only, with the exception of the following:

- Based on the provision of a 20 storey evacuation zone, the lift evacuation time is approximately 6% less than the code compliant stair evacuation time.

***Once the evacuation zone is increased to 25 storeys, the lift evacuation time significantly exceeds the stair evacuation time.***

### 7.2.2.3 Comparison of results

It is noted that the evacuation time from an evacuation zone does not require occupants to travel via stairs to reach the lift departure level, as required by evacuation from a refuge floor, which increases the evacuation time. Nevertheless, this travel time is considered to provide a nominal increase in the evacuation time, as occupants of the floor level closest to a refuge floor are considered to commence evacuation as soon as they enter the refuge floor. Therefore, the time difference between each method, as a result of the stair travel time, is only equal to the time taken for occupants of the floor level immediately above the refuge floor to descend a single flight of stairs to the refuge floor. Based on the calculation method described by Nelson and Mowrer<sup>[3]</sup>, this may be calculated as approximately 17 seconds.

Based on the comparison of results for the two strategies, using the default values discussed in Chapter 5, the whole building evacuation time for the evacuation zone strategy (i.e. lifts serve multiple floors within a zone) requires an additional 17.5 minutes (approximately 25% difference), based on a 10 storey evacuation zone.

The time difference between the two strategies increases by an additional 5.2 minutes (approximately 23.4% difference) for the whole building evacuation time, when the evacuation zone increases to 15 storeys.

The percentage difference between the default values increases to 24.1% and 26.2% when the evacuation zone increases to 20 storeys and 25 storeys respectively.

#### 7.2.2.4 *Summary*

The whole building evacuation time is considered to be less than the stair evacuation time for the default lift performance values for evacuation from refuge floors at 10 storey intervals. However, the lift evacuation time from the lower floor levels exceeds the stair evacuation time.

The lift evacuation time slightly exceeds the stair evacuation times for evacuation from a refuge zone at the default values.

For the lowest floor levels to have approximately equal to, or better than, the stair evacuation time, it is necessary to provide a minimum of 8 lifts.

Once the interval between refuge floors exceeds 20 storeys, the whole building evacuation time using lifts exceeds that required using stairs only.

### **7.3 Evacuation via Stairs and Lifts (75% Lift Usage)**

#### 7.3.1 Introduction

The combined use of stairs and lifts to evacuate a building is considered to provide a more efficient evacuation time. However, the overall evacuation time of the building is determined by the slowest of either method, which in this case is considered to be the lift

evacuation time. On this basis, the resulting stair evacuation time will always be significantly lower than the associated lift evacuation time, as noted from the Graphs in the Appendices.

### 7.3.2 Refuge Floor

#### 7.3.2.1 *Stair evacuation calculations*

The stair evacuation times have been calculated based on the percentage of the building occupants assumed to escape via the stairs.

The time for occupants to reach the refuge floor is identical irrespective of the final method of evacuation. Therefore, the stair evacuation times used in the refuge floor level assessment have been calculated from the refuge floor level only. The stair evacuation time only includes for occupants in the stair below the refuge floor level, based on the flow rate contained in Approved Document B.

<b>Refuge Floor Level</b>	<b>Time (mins)</b>
5	1.6
10	3.3
20	6.6
25	8.3
30	10.0
35	11.7
40	13.3

**Table 7.3.2.1 – Time for evacuation by stairs from refuge floor in accordance with AD-B**

Based on approximately 25% of the building occupancy using the stairs to evacuate, the stair evacuation times will be approximately 25% of those calculated in Section 7.2.1.1. However, the lifts are required to accommodate the remaining 75% of the building occupancy. As noted from the graphs contained within the Appendices, the lift evacuation times always exceed the associated stair evacuation time. On this basis, the limiting factor on the total evacuation time will be the lift evacuation time. Therefore, it is proposed to compare the lift evacuation times (as the most onerous evacuation time) with the code

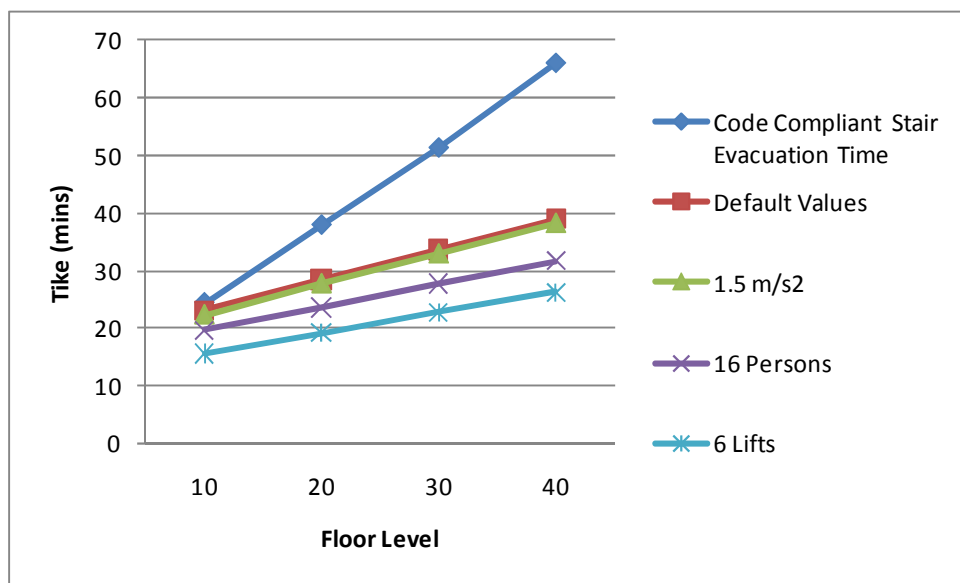
compliant stair evacuation times (i.e. 100% of the occupancy uses the stairs to evacuate) only.

The code compliant stair evacuation times are the same as those listed in Table 7.2.2.1 (a) to 7.2.2.1 (d).

### 7.3.2.2 Results of calculations

Based on a 10 storey interval between refuge floors the whole building evacuation time (i.e. evacuation time from highest refuge floor), plus those from the 20<sup>th</sup> and 30<sup>th</sup> floor levels is less than the time taken using stairs only, when using the default lift values. The impact of the variable lift performance values is discussed below.

- Evacuation is also faster by lift from the 10<sup>th</sup> refuge floor level based on a lift acceleration of 1.5m/s<sup>2</sup>, 16 and 21 person lift capacity, as well as 6 and 8 lifts.



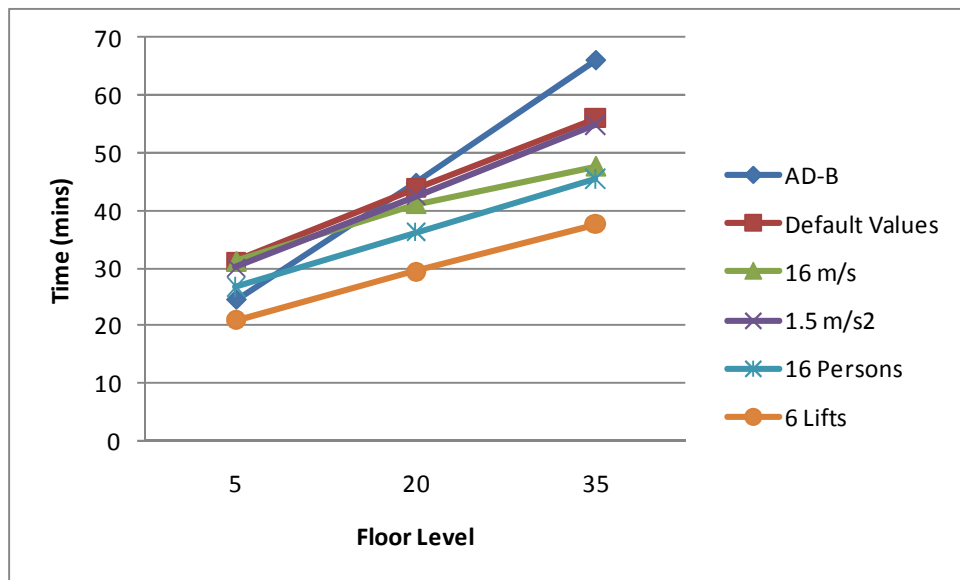
**Figure 7.3.2.2 – Evacuation from refuge floors at 10 storey intervals compared to code compliant evacuation time**

Due to the lower number of occupants escaping via the lifts, the whole building evacuation time is less than the code compliant stair evacuation time when assessing the default value for a 15 storey evacuation zone. However, the lift evacuation time from the 5<sup>th</sup> and 20<sup>th</sup> refuge floor levels is in excess of the stair evacuation time, with the exception of the following:



- Lift velocity of 16m/s,
- Acceleration of 1.5m/s<sup>2</sup>
- Lift capacity of 16 and 21 persons.

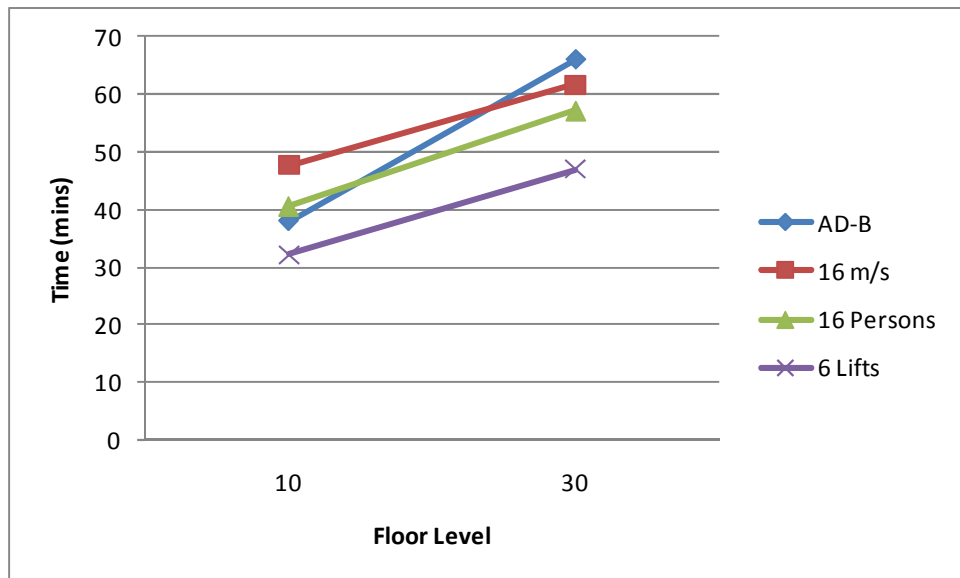
However, evacuation is faster from every refuge floor level by lifts based on the provision of 6 or 8 lifts serving each refuge floor



**Figure 7.3.2.2 (a) – Evacuation from refuge floors at 15 storey intervals compared to code compliant evacuation time**

Based on an increase in the separation distance between refuge floors to 20 storeys, the lift evacuation time is approximately equal to the stair evacuation time for the whole building, based on the default lift performance values (lift evacuation times are approximately 6% longer). However, the whole building lift evacuation time is faster than the code compliant stair evacuation time based on the following lift performance values:

- a lift velocity of 16m/s or a minimum lift capacity of 16 persons. However, the lift evacuation time remains slower than the stair evacuation time from the lower refuge floor level.
- Nevertheless, the lift evacuation time from both refuge floors is faster than the stair evacuation time based on the provision of 6 or 8 lifts.



**Figure 7.3.2.2 (b) – Evacuation from refuge floors at 20 storey intervals compared to code compliant evacuation time**

Based on a further increase in the refuge floor separation distance to 25 storeys, the whole building evacuation time is greater than the code compliant stair evacuation time when using the default values. However, lift evacuation provides a reduction in the code compliant evacuation time based on the following lift performance values:

- The evacuation time is equal to the code compliant stair evacuation time when 16 person lifts are provided.
- The lift evacuation time (and therefore, whole building evacuation time) is faster than the stair evacuation time based on the provision of 21 person lifts or a minimum of 6 lifts.

### 7.3.3 Evacuation Zone

#### 7.3.3.1 *Stair evacuation calculations*

The time for evacuation from an evacuation zone is based on the occupants of that zone seeking to simultaneously seeking to escape via the escape stairs as well as any occupants of the refuge zones below. Therefore, the time for evacuation from each refuge zone varies depending on the number of occupants in the refuge zone as well as the number of

occupants on the floor levels below the evacuation zone. The time for evacuation of 25% of the theoretical buildings occupants is shown in Table 7.3.3.1 (a) to 7.3.3.1 (d), below.

Lowest floor in zone	Time (mins)
10	6.3
20	9.7
30	13
40	16.7

**Table 7.3.3.1 (a) - Time for evacuation by stairs from 10 storey evacuation zone**

Lowest floor in zone	Time (mins)
5	6.3
20	11.3
35	16.7

**Table 7.3.3.1 (b) - Time for evacuation by stairs from 15 storey evacuation zone**

Lowest floor in zone	Time (mins)
10	9.7
30	16.7

**Table 7.3.3.1 (c) - Time for evacuation by stairs from 20 storey evacuation zone**

Lowest floor in zone	Time (mins)
25	16.7

**Table 7.3.3.1 (d) - Time for evacuation by stairs from 25 storey evacuation zone**

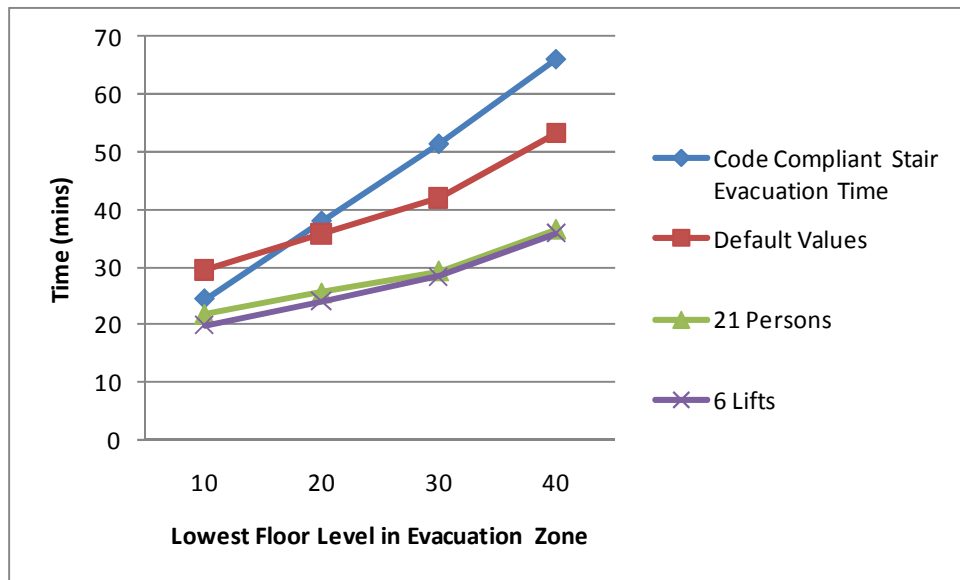
The lift evacuation times have also been compared with the code compliant stair evacuation times, as listed in Tables 7.2.2.1 (a) to 7.2.2.1 (d).

### 7.3.3.2 Results of calculations

Based on the assumption that approximately 75% of the buildings occupants escape via lifts the whole building evacuation time is considered to be faster than the code compliant

evacuation time when using the default values for a 10 storey evacuation zone. However, evacuation is generally faster from the lowest refuge floor levels by stairs, with the following exceptions:

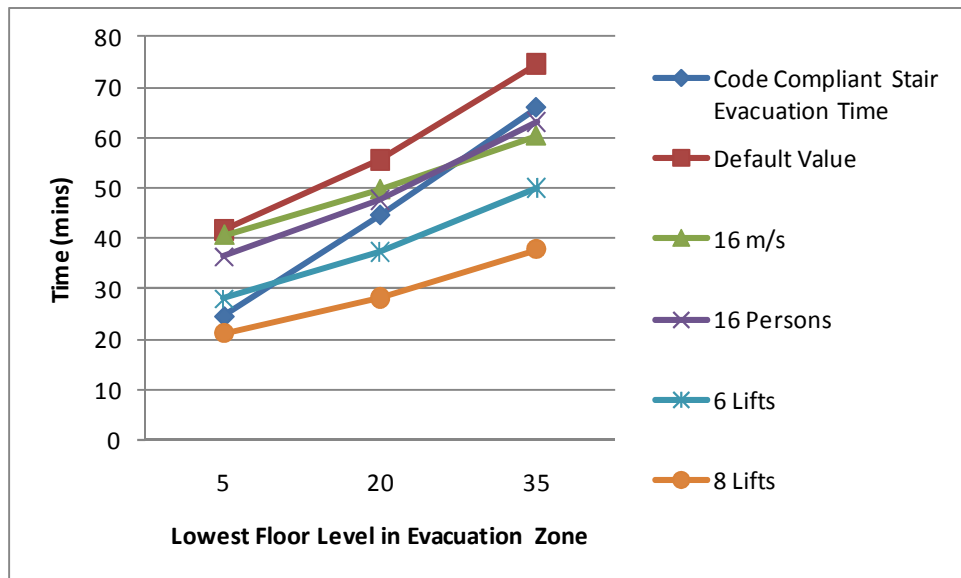
- Lift capacity of 21 persons or a minimum of 6 lifts.



**Figure 7.3.3.2 – Comparison of code compliant stair evacuation time with lift evacuation from 10 storey evacuation zones**

Based on an increase in the evacuation zone to 15 storeys, the whole building evacuation time by stairs is faster than that using lifts, when approximately 75% of the building occupancy escape via lifts, with the following exceptions.

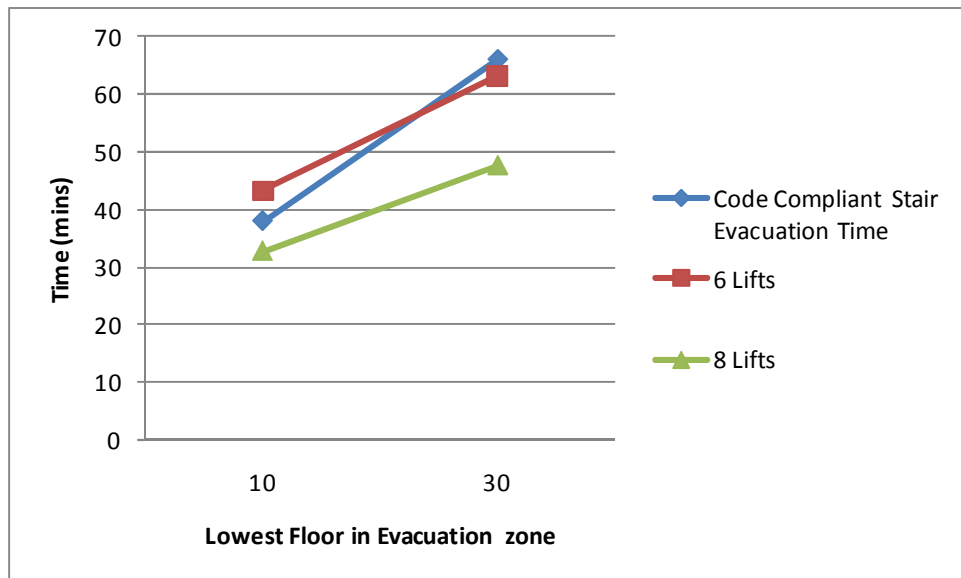
- The whole building evacuation time using lifts is less than that using stairs based on a lift velocity of 16m/s, a lift capacity of 16 persons, or the provision of 6 lifts. However, the evacuation time from the lower evacuation zones is faster by stairs.
- Nevertheless, evacuation from each evacuation zone is faster than stair evacuation based on the provision of 8 lifts (12 person capacity) serving each zone.



**Figure 7.3.3.2 (a) – Comparison of code compliant stair evacuation time with lift evacuation from 15 storey evacuation zones**

Based on a 20 storey evacuation zone the whole building evacuation is less based on the use of code compliant stairs. However, lift evacuation provides a reduction in this time based on the following performance values.

- The whole building evacuation time using lifts is less (lifts evacuation time 4.2% less) than the stair evacuation time, based on the provision of 6 lifts. However, the evacuation time from the lower refuge floor is less based on the use of stairs for evacuation.
- The lift evacuation time from both zones is less than the stair evacuation time based on the provision of eight lifts.



**Figure 7.3.3.2 (b) – Comparison of code compliant stair evacuation time with lift evacuation from 20 storey evacuation zones**

***Once the evacuation zone increases to 25 storeys, the whole building evacuation time is less using code compliant escape stairs, with the exception of the lift evacuation times when 8 lifts are provided.***

### 7.3.3.3 Comparison of results

Based on the evacuation of 75% of the building occupants via lifts, the lift evacuation time is considerably in excess of the associated stair evacuation time (which is required to evacuate only 25% of the buildings occupants).

Whilst it is noted that this will cause some occupants waiting for the lift to arrive to suffer from anxiety if they know other persons have commenced evacuating the building by using the stairs, it is considered that this ratio may be a suitable method if large numbers of persons are unable to descend the stairs due to physical health.

Whilst this difference between the evacuation times for this ratio are noted, it is considered worth noting the reduction in the overall evacuation time when compared to the code complaint evacuation time (i.e. 100% of the occupants escapes via lift). On this basis, lift evacuation from evacuation zones containing up to 25 storeys may be provided based on 8 lifts serving each zone.

Based on a comparison of results for the two strategies, using the default values discussed in Chapter 5, the whole building evacuation time for the evacuation zone strategy (i.e. lifts serve multiple floors within a zone) requires between 24.8% and 27.9% longer than via a refuge floor.

As previously discussed the evacuation time from an evacuation zone does not require occupants to travel via stairs to reach the lift departure level, as required by evacuation from a refuge floor, which increases the evacuation time. However, this additional travel time is considered to provide a nominal increase in the evacuation time, as occupants of the floor level closest to a refuge floor are considered to commence evacuation as soon as they enter the refuge floor. Therefore, the time difference between each method is only equal to the time taken for occupants of the floor level immediately above the refuge floor to descend a single flight of stairs to the refuge floor.

#### 7.3.3.4 *Summary*

Based on a 25% reduction in the number of building occupants seeking to escape via lifts the lift evacuation time also reduces by approximately 25%. However, the time to evacuate using lifts is significantly in excess of the evacuation time of the remaining occupants via stairs.

Nevertheless, based on the slowest evacuation time (i.e. lift evacuation time), the whole building evacuation is generally less than the time required for the whole building evacuation via stairs only, for the small evacuation zone/refuge floor separation distance. Nevertheless, this assessment has shown that based on a reduction in the number of occupants using the lifts by a quarter, allows for evacuation zones and refuge floors to be incorporated at a maximum of 25 storey intervals, without the requirement for unfeasible numbers of lifts shafts or lift car capacities.

### **7.4 Evacuation via Stairs and Lifts (50% Lift Usage)**

Based on an equal distribution of the buildings occupants between lift and stair evacuation it is noted that the difference in evacuation times between the two methods is significantly less than those discussed in Section 7.3 above.

However, whilst it is proposed to compared the evacuation times achieved for both methods based on a reduced occupancy, as detailed within the appendix, it is also proposed to assess the most onerous of these evacuation times with the code compliant stair evacuation time (taken as the stair evacuation time for 100% occupancy).

#### 7.4.1 Refuge Floor

##### 7.4.1.1 *Stair evacuation times*

The stair evacuation times have been calculated based on the percentage of the building occupants assumed to escape via the stairs only. Due to the even distribution of occupants between the lifts and stairs, such that the differences between evacuation times will be significantly less than those discussed in Section 7.3, it is proposed to assess the lift evacuation times with the stair evacuation times when utilised by 50% of the building occupancy **and** with the code compliant stair evacuation times.

The stair evacuation times used in the refuge floor level assessment have been calculated to compare the time taken once occupants of a certain floor level have reached their designated refuge floor level. Therefore, the stair evacuation times have been calculated based on the assumption that the stair is full to capacity below the refuge floor level only, and does not include for any occupants above this floor level. The equivalent lift evacuation time includes the occupants served by the relevant refuge floor only.

The most onerous of the evacuation times (i.e. lift or stair evacuation time) for each scenario have also been compared to the code complaint stair evacuation times as listed in Section 9.2.1.1.

Refuge Floor Level	Time (mins)
5	2.9
10	6.3
20	13.0
25	16.4
30	19.7
35	23.0
40	26.4

**Table 7.4.1.1 – Stair evacuation time for 50% of building occupancy based on AD-B**



It is also proposed to assess the lift evacuation times with the code compliant stair evacuation times listed in Section 7.2.2.1, which takes into account the evacuation time for the whole building.

#### 7.4.1.2 *Results of calculations*

Based on a 10 storey separation distance between refuge floors, the lift evacuation time is slightly in excess of the stair evacuation time when using the default values (stairs are 0.4% faster). Based on an increase in these values, the whole building evacuation time using lifts is generally less than the time using stairs only. The impact of the variable lift performance values on the evacuation times is discussed below:

- Based on a lift velocity of 16m/s the whole building evacuation time is less than the associated stair evacuation time. However, the evacuation time from the lower refuge floor levels exceeds the stair evacuation time.
- The whole building evacuation time is less than the associated stair evacuation time when the lifts are provided with an increased capacity in relation to the default value. However, the evacuation time from the 10<sup>th</sup> and 20<sup>th</sup> refuge floor levels remains less by stairs.
- Based on the provision of 6 lifts to each group, the whole building evacuation is approximately 8.4 minutes (31.8%) faster than the associated stair evacuation time. The lift evacuation time is less than the stair evacuation time from the 20<sup>th</sup> - 40<sup>th</sup> refuge floor levels. Based on the provision of 8 lifts in each group, the evacuation time using lifts is considered to be less than that using stairs from the 20<sup>th</sup> to 40<sup>th</sup> floor levels. Stair evacuation from the 10<sup>th</sup> floor level is approximately 108 seconds (22%) faster.
- Based on the use of the default values, the combined evacuation time (i.e. via stair and lifts) is faster than the code compliant stair evacuation time from each refuge floor level, as shown in Figure 7.4.1.2 (a) below.

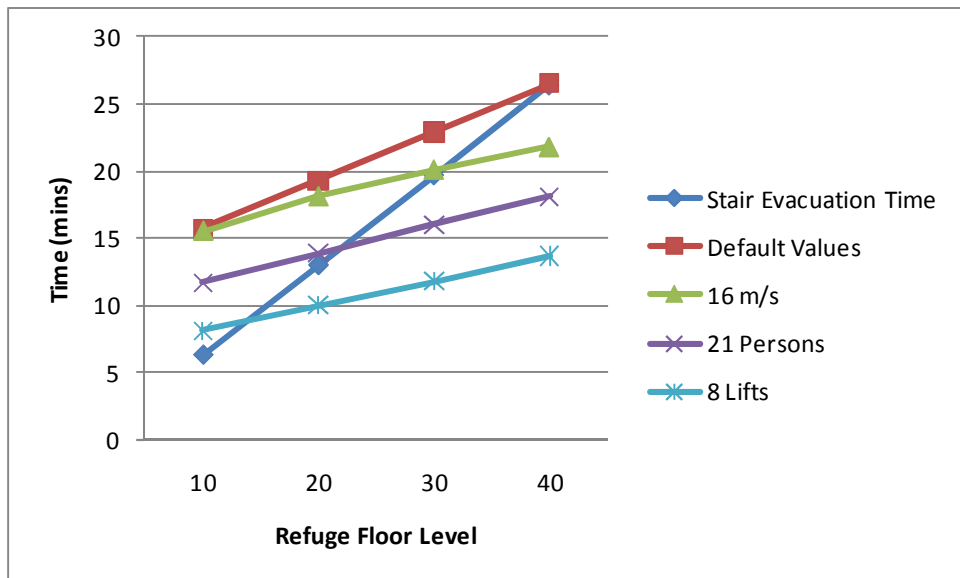


Figure 7.4.1.2 – Comparison of lift evacuation time with stair evacuation times

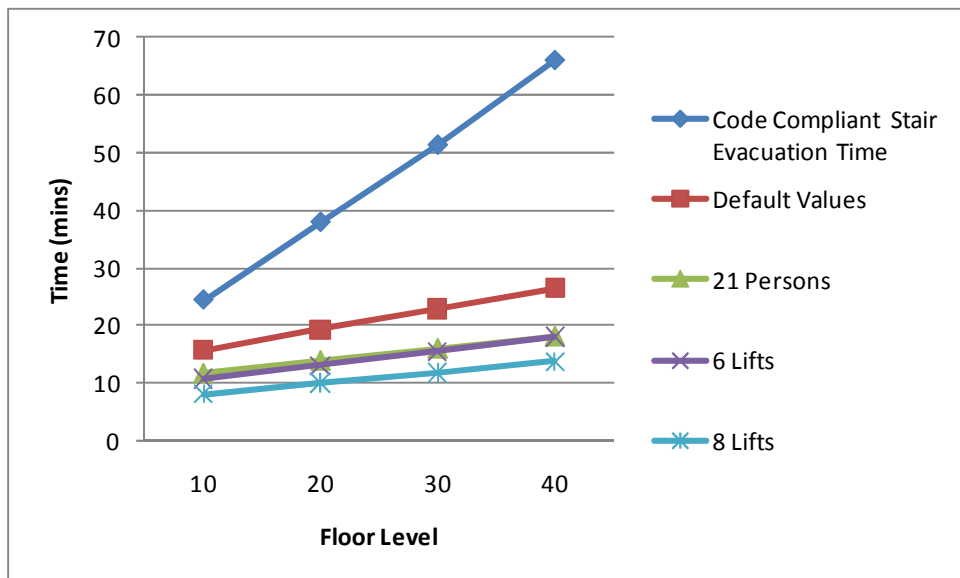


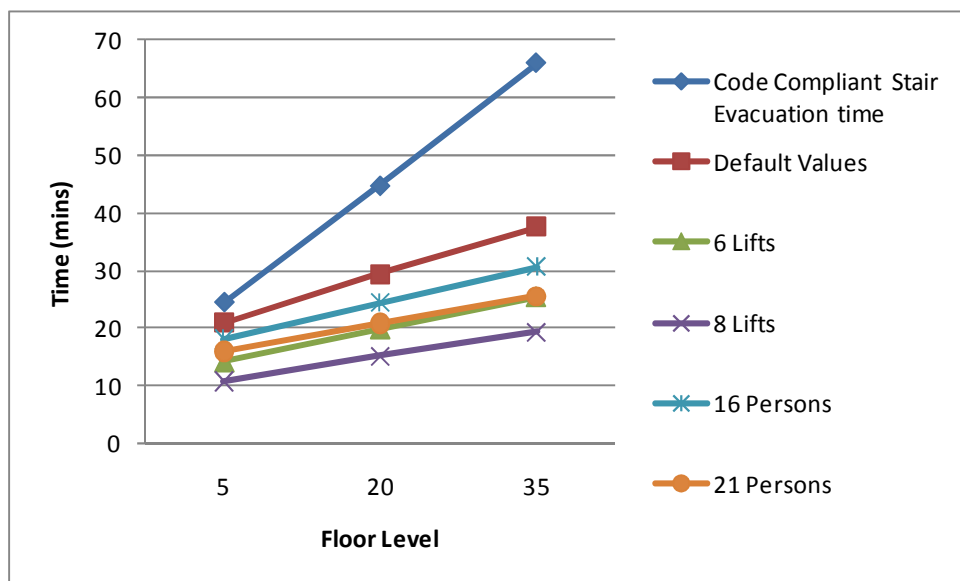
Figure 7.4.1.2 (a) – Comparison of code compliant evacuation time with lift evacuation at 10 storey intervals

Based on a 15 storey separation distance between refuge floor levels, the lift evacuation time is generally longer than the associated stair evacuation time at 50% occupancy. This is considered to be a result of the reduced occupant capacity in the stair, such that a higher flow rate is maintained throughout the stair, without increasing the lift specification.

The only exception to the above observation is when 8 lifts are provided to serve each floor level, such that the whole building evacuation time using lifts is less than the equivalent stair evacuation time. However, the evacuation time from the lower refuge floor levels (5<sup>th</sup>

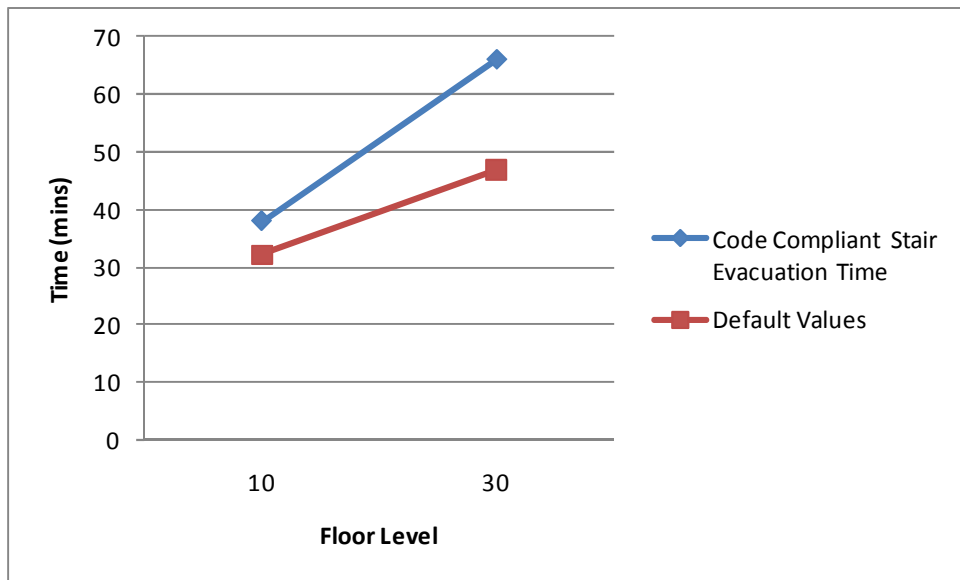
and 20<sup>th</sup>) using stairs remains lower than that required using lifts. **Once the interval between refuge floors exceeds 15 storeys the whole building evacuation time using lifts significantly exceeds the associated stair evacuation time.**

However, whilst the lift evacuation time exceeds that of the associated stairs, this evacuation strategy provides a lower total building evacuation time than the code compliant stair evacuation time. The lift evacuation time is also lower than the code compliant stair evacuation time from the lower refuge floor levels, as shown in Figure 7.4.1.2 (b).



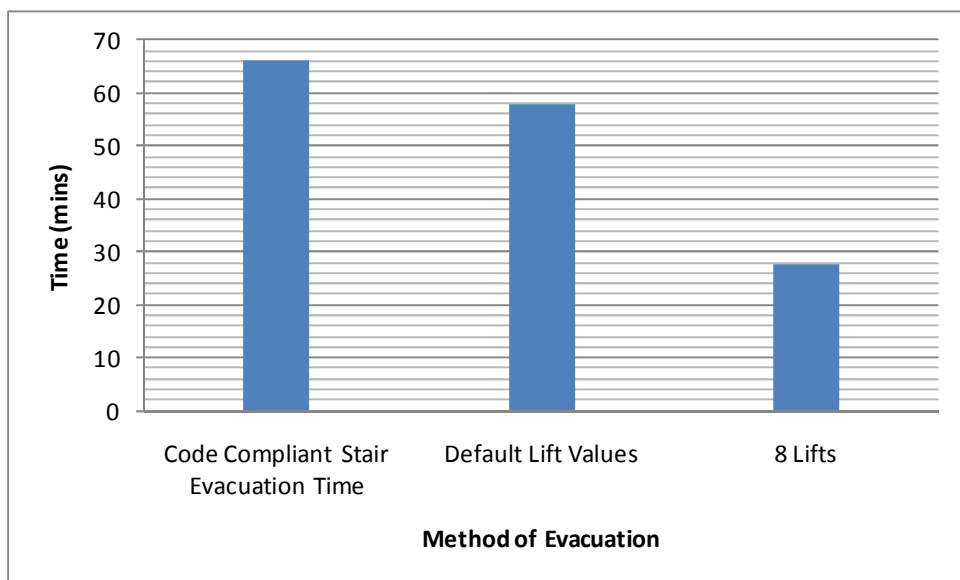
**Figure 7.4.1.2 (b) – Comparison of code compliant evacuation time with lift evacuation at 15 storey intervals**

Based on a 20 storey separation distance, the lift evacuation time from both refuge floor levels is less than the code compliant stair evacuation time based on the use of the default values. Lift evacuation is approximately 28.9% less than stair evacuation for the whole building.



**Figure 7.4.1.2 (c) – Comparison of code compliant evacuation time with lift evacuation at 20 storey intervals**

Evacuation from the 25<sup>th</sup> refuge floor level may also be completed in less time than that required when using code compliant escape stairs to evacuate, based on the use of lifts with the default lift performance values (lifts are approximately 17.7% faster than stairs). However, the lift evacuation time may be reduced to 41.8% of the code compliant stair evacuation time, based on the provision of 8 lifts serving the refuge floor, as shown in Figure 7.4.1.2 (d) below.



**Figure 7.4.1.2 (d) – Comparison of code compliant evacuation time with lift evacuation at 25 storey intervals**

## 7.4.2 Evacuation Zone

### 7.4.2.1 *Stair evacuation times*

The time for evacuation from an evacuation zone is based on the occupants of that zone seeking to simultaneously seeking to escape via the escape stairs as well as any occupants of the refuge zones below. Therefore, the time for evacuation from each refuge zone varies depending on the number of occupants in the refuge zone as well as the number of occupants on the floor levels below the evacuation zone. The time for evacuation of 50% of the theoretical buildings occupants is shown in Table 7.3.3.1 (a) to 7.3.3.1 (d), below.

The most onerous of the evacuation times for each separation distance have been compared to the code compliant stair evacuation times, as listed in Section 7.2.2.1.

<b>Lowest floor in zone</b>	<b>Time (mins)</b>
10	12.3
20	19.1
30	25.8
40	33.2

**Table 7.4.2.1 (a) - Time for evacuation by stairs from 10 storey evacuation zone**

<b>Lowest floor in zone</b>	<b>Time (mins)</b>
5	12.3
20	22.4
35	33.2

**Table 7.4.2.1 (b) - Time for evacuation by stairs from 15 storey evacuation zone**

<b>Lowest floor in zone</b>	<b>Time (mins)</b>
10	19.1
30	33.2

**Table 7.4.2.1 (c) - Time for evacuation by stairs from 20 storey evacuation zone**

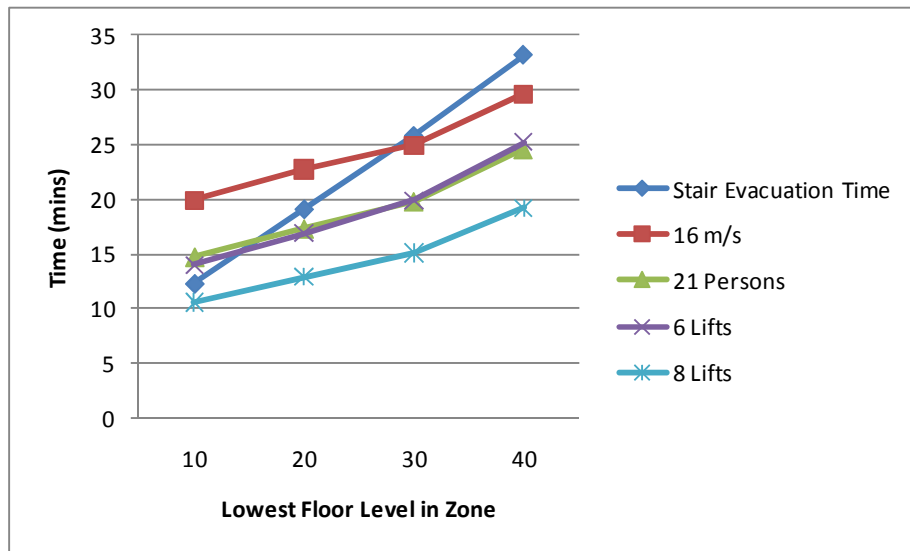
Lowest floor in zone	Time (mins)
25	33.2

**Table 7.4.2.1 (d) - Time for evacuation by stairs from 25 storey evacuation zone**

**7.4.2.2 Results of calculations**

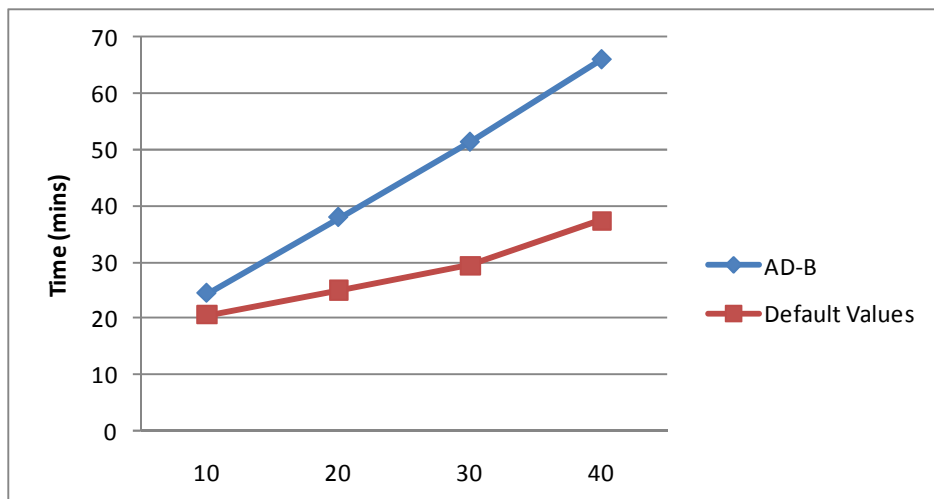
Based on a 10 storey evacuation zone, the lift evacuation time is slightly in excess of the evacuation time for stairs when using the default values. However, based on an increase in these values, the whole building evacuation time using lifts is less than the time using stairs only, for the following situations:

- Evacuation time from the upper two evacuation zones is less than the evacuation time via stairs only based on a lift velocity of 16m/s.
- Based on the provision of a 21 person lift capacity, the lift evacuation time from the three highest evacuation zones is less than the time required using stairs. However, the evacuation time from the lowest zone is less by stairs, where lift evacuation requires an additional 2.4 minutes (16.3%).
- The lift evacuation time from the 20<sup>th</sup> – 40<sup>th</sup> evacuation zones is less than the stair evacuation time, based on the provision of 6 lifts serving the evacuation zone. However, the evacuation time via stairs from the lowest evacuation zone is approximately 1.7 minutes (12.1% difference) less than the evacuation time using lifts.
- Based on the provision of 8 lifts, the evacuation time from each zone is less than the stair evacuation time.



**Figure 7.4.2.2 – Comparison of lift and stair evacuation from 10 storey evacuation zones**

- Based on the use of the default values, the combined evacuation time (i.e. via stair and lifts) is faster than the code compliant stair evacuation time each refuge floor level, as shown in Figure 7.4.2.2 (a) below.



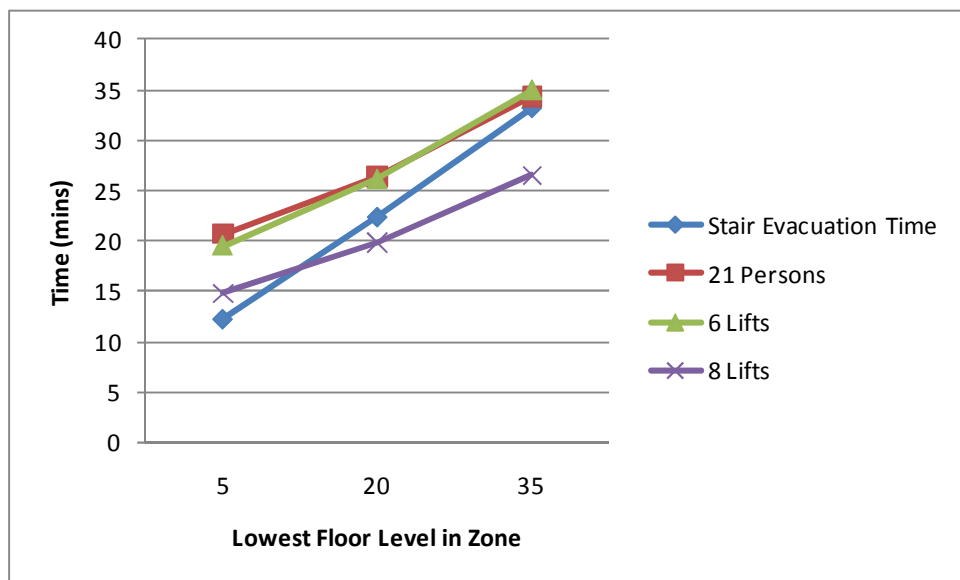
**Figure 7.4.2.2 (a) – Comparison of code compliant evacuation time with lift evacuation at 10 storey intervals**

Based on the provision of a 15 storey evacuation zone, the lift evacuation time from the building is significantly in excess of the equivalent stair evacuation time for most variables, with the following exceptions.

- Based on a lift capacity of 21 persons the whole building evacuation time is approximately equal for stair and lift evacuation (stairs are 3.2% faster). In

addition, the evacuation times from the lower evacuation zones are less based on stair evacuation.

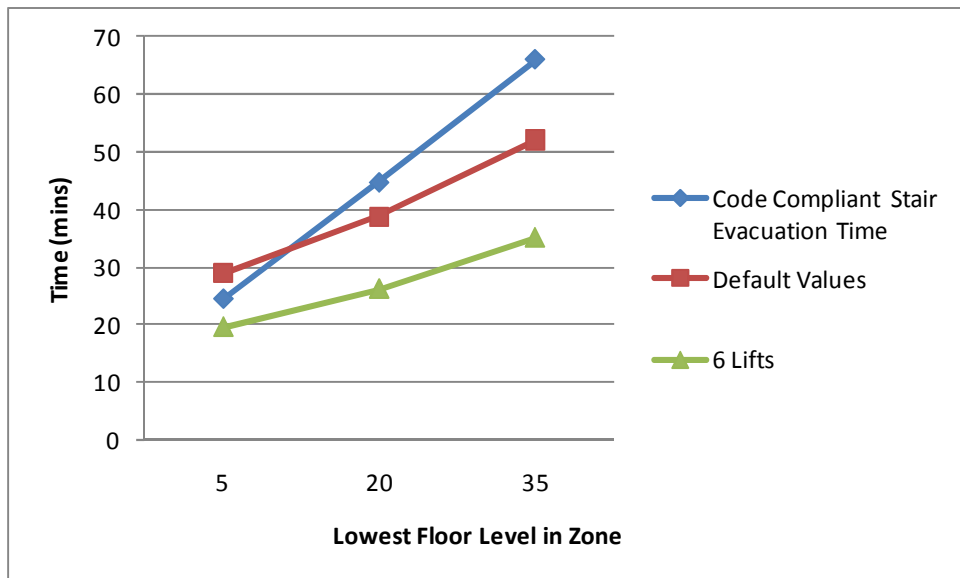
- The whole building evacuation time is approximately equal for stair and lift evacuation based on the provision of 6 lifts (stairs are 5.1% faster).
- The lift evacuation time for the whole building is 6.7 minutes (approximately 20.2%) less than the stair evacuation times, based on the provision of 8 lifts serving each evacuation zone. The evacuation times from the mid refuge zone is also less than the stair evacuation time. However, the lift evacuation time from the lowest evacuation zone is approximately 2.5 minutes less (stairs are 16.9% quicker) than the lift evacuation time.



**Figure 7.4.2.2 (b) – Comparison of stair evacuation time with lift evacuation at 15 storey intervals**

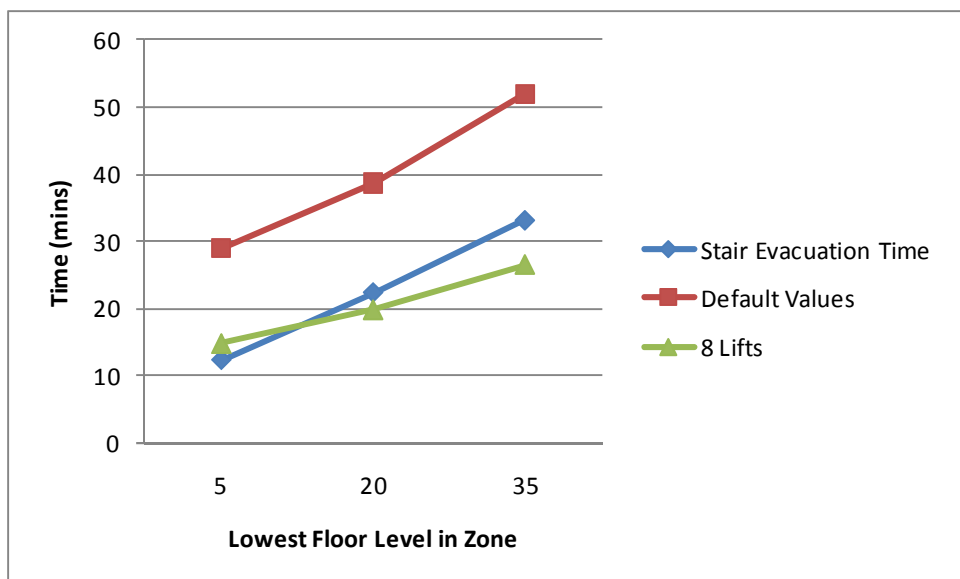
The lift evacuation time is less than the code complaint evacuation time from the 20<sup>th</sup> and 35<sup>th</sup> evacuation zones based on the use of the default values. However, evacuation is faster from the lower zone via code complaint stairs, with the exception of 6 or more lifts, or a lift capacity of 21 persons.





**Figure 7.4.2.2 (c) – Comparison of code compliant evacuation time with lift evacuation at 15 storey intervals**

Once the interval between evacuation zones exceeds 15 storeys the evacuation time using lifts generally significantly exceeds the associated stair evacuation time. The only exception is for a 20 storey evacuation zone where the evacuation time with 8 lifts is less than the associated stair evacuation time from the 20<sup>th</sup> and 35<sup>th</sup> evacuation zones.



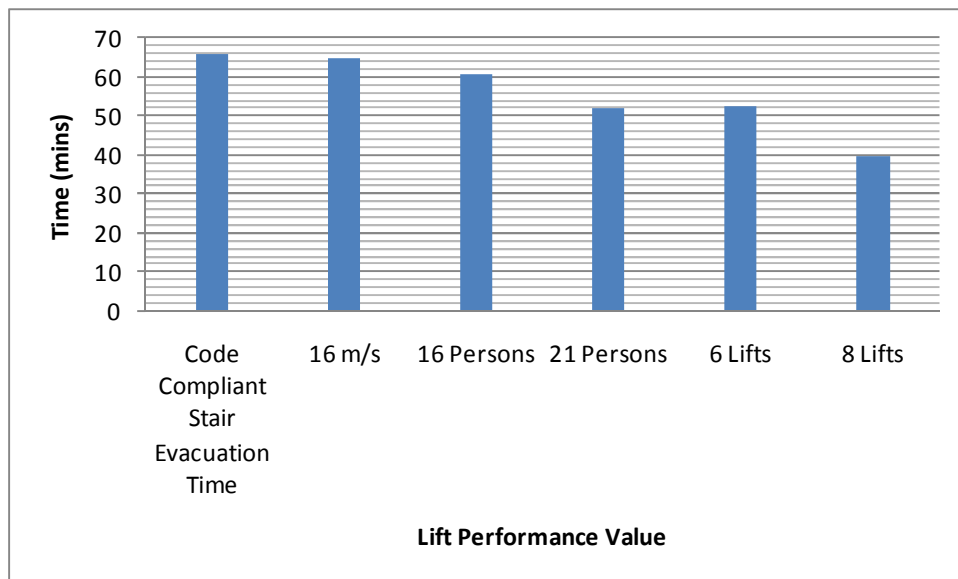
**Figure 7.4.2.2 (d) – Comparison of stair evacuation time with lift evacuation at 20 storey intervals**

Nevertheless, the lift evacuation times is less than the code complaint stair evacuation time when using the default lift performance values up to a maximum evacuation zone size of 20

storeys. Once the evacuation zone exceeds 20 storeys the whole building evacuation is faster via code compliant stairs.

However, the lift evacuation zone may increase up to 25 storeys and maintain lift evacuation times which are less than the code compliant evacuation times based on the provision of the following lift performance values:

- Lift speed of 16m/s
- 6 or more lifts
- Capacity of 16 persons or greater



**Figure 7.4.2.2 (e) – Comparison of code compliant evacuation time with lift evacuation at 25 storey intervals**

#### 7.4.2.3 Comparison of results

Based on a 50% reduction in the number of building occupants seeking to escape via lifts the lift evacuation time also reduces by approximately 50%. However, it is noted that the lift evacuation time generally exceeds the evacuation time of the remaining 50% of occupants escaping via the associated stairs, particularly from the lower levels.

Based on a comparison of results for the two strategies, using the default values discussed in Chapter 5, the whole building evacuation time for the evacuation zone strategy (i.e. lifts serve multiple floors within a zone) requires between 27.6% and 30.7% longer than that using the refuge floor strategy.

As previously discussed, the evacuation time from an evacuation zone may be considered as the total evacuation time compared to that from a refuge floor. The evacuation time from a refuge floor does not take into account the time for occupants to reach the refuge floor. However, based on the small additional increase in the overall evacuation time from a refuge floor based on the requirements for occupants to travel via stairs to the refuge floor, it is considered reasonable to directly compare.

#### 7.4.2.4 Summary

Based on the slowest whole building evacuation time (i.e. lift or stair evacuation), the whole building evacuation is generally less than the code compliant stair evacuation time. This assessment has demonstrated that based on a reduction in the number of occupants using the lifts by half, allows for refuge floors to and evacuation zone to be provided which serve 25 storeys, without the requirement for unfeasible number of lifts shafts or lift car capacities.

### 7.5 Analysis of Combined Lift Performance Values

The lift evacuation times listed in Section 7.2 to Section 7.4 are based on varying a single lift performance value, to determine its impact on the evacuation time. However, it is noted that a lift used for the evacuation of a building is likely to be provided with a number of increased performance values. For example, the lifts used in the evacuation of Taipai 101 are provided with a constant speed of approximately 17 m/s and a capacity of 24 persons<sup>[30]</sup>.

On this basis, it is assumed that the actual lift evacuation times may be significantly less than those calculated as part of the assessment above, and therefore, greater numbers of occupants may be able to escape via the lifts, allowing a greater refuge floor separation distance or evacuation zone. On this basis, it is proposed to calculate the evacuation times for a combination of two of the lift performance values, for both methods of evacuation, based on the assumption that all of the occupants escape via the lifts. The evacuation times will be assessed based on the following combination of lift performance values:

- Speed of 16 m/s and lift capacity of 21 persons
- Speed of 7m/s and acceleration of 1.5m/s<sup>2</sup>

- 8 lifts with a capacity of 21 persons each

The details of the assessment are provided in the tables below for comparison

Refuge floor separation distance	Refuge floor level	Default evacuation time	Code compliant evacuation time	16 m/s & 21 persons	7 m/s & 1.5 m/s <sup>2</sup>	8 lifts & 21 persons
10	10	30.6	24.4	22.4	29.2	11.6
	20	37.6	37.9	25.3	35.2	13.7
	30	44.6	51.3	27.6	41.2	15.8
	40	51.6	66	29.5	47.2	17.9
15	5	41.1	24.4	31.1	39.7	14.5
	20	57.9	44.6	38.7	54.2	20.8
	35	74.1	66	43.7	68.1	25.5
20	10	63.7	37.9	46.3	60.9	23.7
	30	93	66	57	86	32.2
25	25	107.9	66	69	100.4	37.8

**Table 7.5 - Comparison of evacuation times based on the use of refuge floors**

Evacuation zone size	Refuge floor level	Default evacuation time	Code compliant evacuation time	16 m/s & 21 persons	7 m/s & 1.5 m/s <sup>2</sup>	8 lifts & 21 persons
10	10	38.3	24.4	27.9	36.2	14.7
	20	46.4	37.9	31.1	43.1	17.3
	30	54.4	51.3	33.7	50.0	19.9
	40	69.1	66	39.6	62.9	24.3
15	5	54.1	24.4	39.9	53.2	20.8
	20	72.2	44.6	47.2	66.9	26.5
	35	96.8	66	56.2	88.3	34.4
20	10	84	37.9	58.2	78.7	31.2
	30	122.5	66	72.3	112.1	43.5
25	25	146.3	66	87.8	134.1	52

**Table 7.5 (a) - Comparison of evacuation times based on the use of evacuation zones**

Based on the provision of 8 lifts with a capacity of 21 persons, it is possible to evacuate the whole building faster than the code compliant evacuation time for either evacuation method up to the maximum separation distance of 25 storeys.

Whilst it is noted that this will require a large amount of the building plan area to be taken up by lift shafts, this method will save on floor space as it will allow the construction of a building with fewer number of refuge floors, or group of lifts, depending on the evacuation method used.

## 7.6 Comparison of Calculation Methods and Lift Variables on the Evacuation Time

The calculation methods described in Section 3.3 provide different values for the lift evacuation time. However, it is considered necessary to compare the differences between each calculation method and the impact each variable has on the resulting output.

### 7.6.1 Refuge Floors

Based on the evacuation of the buildings occupants from a refuge floor the differences between the lift evacuation times as a result of the different lift performance variable are as follows:

#### 7.6.1.1 *Variable Speed*

- The difference between the ELVAC evacuation time and the analytical methods increases with an increase in speed. However, the evacuation time from the lowest refuge floor level is approximately equal for each lift velocity. This is considered to be limited by the acceleration required to reach maximum speed over the shorter distance to this refuge floor, which is taken into account by each method, such that the maximum speed is not achieved prior to the lift arriving at the refuge floor, irrespective of the lift speed.
- The difference between the lift evacuation times calculated by the Siikonen and Sekizawa methods decreases when the lift speed is increased.

#### 7.6.1.2 *Variable Acceleration*

- The difference between the lift evacuation times calculated by ELVAC and the Sekizawa method are equal for both acceleration values.

#### 7.6.1.3 *Variable Capacity*

- The difference between evacuation times based on the ELVAC and Siikonen calculation procedures is approximately equal for each value of the lift capacity.

The average of the difference between the values at each refuge floor level for the 10 person capacity lift and the 21 person capacity lift is equal to 7.9%.

- The difference between the evacuation times calculated using the methodologies determined by Siikonen and Sekizawa increases with the lift capacity.

#### 7.6.1.4 *Variable Lifts*

- The difference in evacuation times between the ELVAC and Siikonen calculation methodologies is approximately equal for each grouping of lifts. The average value of the difference between the two methods decreases by 1.3% when the number of lifts doubles from 4 to 8.
- The difference between the evacuation times calculated using the methodologies discussed by Siikonen and Sekizawa decreases by 0.3% for the same scenario.

#### 7.6.2 Evacuation Zone

Based on the evacuation of the buildings occupants from an evacuation zone the differences between the lift evacuation times as a result of the different lift performance variable are as follows:

##### 7.6.2.1 *Variable Speed*

- At lower lift speeds the evacuation time calculated using the method developed by Siikonen is in excess of the time calculated using ELVAC. However, at 16m/s the evacuation time in accordance with Siikonen is less than the evacuation time calculated using the ELVAC method. The average difference between the two calculation methodologies for each evacuation zone at 10 storey intervals is 26% based on a lift speed of 16m/s.
- The difference between the evacuation times calculated using the ELVAC and Siikonen methodologies with those calculated using the Sekizawa method decrease as a result of an increase in the lift speed.

#### 7.6.2.2 *Variable Acceleration*

- The difference between the lift evacuation times calculated by ELVAC and the Sekizawa method are approximately equal for both acceleration values for each evacuation zone size.

#### 7.6.2.3 *Variable Capacity*

- The difference between the evacuation times calculated using the ELVAC and Siikonen methodologies as a result of an increase in the lift capacity is greater than that from refuge floor levels.

#### 7.6.2.4 *Variable Lifts*

- The difference between the evacuation times calculated in accordance with the ELVAC and Siikonen methodologies is minimal for each variable number of lifts in a group.

#### 7.6.3 Summary

As demonstrated above, the evacuation time is dependent on the method of calculation and the lift performance values used. Based on the above, the greatest variance between results is provided between the variable lift speed assessments. This is considered to be the result of the calculation of the travel time within each method, such that the difference in results is greatest when high values are used for the lift speed.

### 7.7 **Analysis of Results**

Based on the results of the evacuation simulations discussed above, it has been demonstrated that lift evacuation can evacuate the entire occupancy of a building in less time than that required when using code compliant stairs required to facilitate phased evacuation. As demonstrated by the results in this section, lift evacuation may be facilitated for the entire occupancy of the buildings using the default values discussed in Chapter 5. However, this will require a small separation distance between refuge floors or evacuation zones.

To allow the provision of lift evacuation to be economically feasible it is noted that the refuge floor separation distance should be as great as possible. Therefore, to allow an increase in refuge floor or evacuation zone separation distance, it is necessary to supplement lift evacuation with stair evacuation. Based on an equal distribution between the lift and the stair, it is possible to provide lift evacuation which is 17.7% less than the code compliant stair evacuation time for the whole building, when using the default lift performance values in a building provided with refuge floor evacuation.

Whilst it is possible to provide lift evacuation in less time than the code compliant stair evacuation time in a building provided without a refuge floor (i.e. from evacuation zones), this requires an increase in the default lift performance specification required for the refuge floor model.

***On this basis, the optimum lift evacuation method is considered to be via refuge floors.***

Due to the limited number of stops in a building provided with lift evacuation from a refuge floor, the lift speed and acceleration are considered to have minimal impact on the total building evacuation time. The most significant decrease in the lift evacuation times is related to the number of lifts, which is dependent on the combined capacity of these lifts, such that the total number of round trips is significantly reduced. The reduction in the evacuation time associated with the reduced number of round trips significantly exceeds that associated with a reduction in the round trip time achieved by an increased speed or acceleration value.



## CHAPTER 8 - CONCLUSIONS AND RECOMMENDATIONS

### 8.1 Comparison of Refuge Floors and Evacuation Zones

The results of the evacuation simulations have shown that, based on a relatively high floor occupancy, all of the occupants of a high rise building in the U.K may be simultaneously evacuated using lifts, faster than the time required using the number of stairs required to meet the Building Regulations.

However, depending on the number and width of stairs required, the use of lifts as a means of evacuation may provide a minimal reduction compared to the code compliant evacuation (i.e. via stairs).

For example, in the theoretical building, 50 storeys may be evacuated in 67 minutes when using the stairs (i.e. 7500 people / (1.4m wide stair x 1.33 p/m/s flow rate)). However, the stair evacuation time may be reduced to less than the lift evacuation time by simply increasing the width of the stair by an additional 200mm. Nevertheless, the resulting evacuation time still requires occupants to queue for a prolonged time on their floor of origin and within the stair.

Based on a relatively large occupancy of 150 persons per floor, as used in this study, a maximum separation distance of 15 storeys between refuge floors is considered to be the limit for the evacuation of the whole building occupancy, without increasing the lift performance values to outside of those used in this study.

In order to permit a greater separation distance between refuge floor levels it is considered necessary for a percentage of the occupants to evacuate via the stairs. However, the assessment has shown that while the use of the lifts for evacuation by 75% of the building occupancy reduces the overall evacuation time, there is a significant difference between the evacuation times of those occupants using stairs with those using lifts, which may cause increased anxiety in those occupants waiting for the lift to arrive.

However, based on the evacuation of approximately half of the buildings occupants by lifts and half by stairs, it is noted that the whole building evacuation time is significantly reduced. On this basis, it is considered reasonable to provide a maximum interval between

refuge floors and evacuation zones of 25 storeys based on the lift performance values used as part of this study.

It is noted that during a number of simulations the occupants of the lowest floor level are provided with a lift evacuation time that is in excess of those occupants using stairs. As can be seen from the charts, the time at which lift evacuation becomes more effective than evacuation by stairs may be taken at the point at which the lines intersect. It is noted that some of the lines do not intersect within the boundaries of the assessment. On this basis it is assumed that these intervals between refuge floors are not as effective as evacuation via stairs only or, would require an extremely tall building before this method of evacuation becomes effective.

To ensure that the most efficient strategy is implemented it is necessary to increase the separation distance between the discharge floor and the lowest evacuated floor, such that the occupants of the lowest floor do not queue for longer than the equivalent code compliant evacuation time.

The evacuation of occupants from an evacuation zone (i.e. where occupants are evacuated from their own floor level) requires additional time compared to that from a refuge floor. This is considered to be the result of a number of factors, which includes:

- Increase in the travel distance to higher floors within the refuge zone,
- Increase in the number of trips without a full occupancy

The travel distance of a lift serving an evacuation zone is considered to effect the total evacuation time on the basis that the total distance travelled by the lift is in excess of that of a lift serving a refuge floor, due to the incremental increase in the height of the floors served in the evacuation zone, which increases the time for evacuation, compared to evacuation from a refuge floor.

The use of a lift to evacuate a single floor level, before moving up to serve the next floor, creates an increase in the number of trips which are not full to capacity and therefore, increase the total number of round trips required to evacuate the building, compared to a lift serving a refuge floor, which is required to make one trip which is not at full capacity (i.e. final trip).

However, it is noted that work carried out by Siikonen and Hakonen<sup>[33]</sup> on a simulated 20 storey building, with a significantly lower occupancy (60 persons per floor), showed very little difference in the time taken to evacuate the building using the refuge floor and evacuation zone methods. However, this difference is considered to be the result of the small amount of time taken for the evacuation due to the lower number of occupants per floor, and the number of floors, such that the number of round trips and maximum travel distances between methods is significantly less.

It is not considered unreasonable to directly compare the evacuation times from a refuge floor with those of an evacuation zone in this study, based on an identical separation distance. Whilst the refuge floor level is at the lowest floor level of the zone of floors it serves, it is considered reasonable to directly compare the evacuation time to that of an evacuation zone on the basis that this method of evacuation serves a similar number of occupants, with the exception that the refuge floor method does not include occupants on the refuge floor.

The evacuation time from an evacuation zone may be considered as the total evacuation time, compared to that from a refuge floor, which does not take into account the time for occupants to reach the refuge floor. However, based on the small additional increase in the overall evacuation time from a refuge floor, due to the requirements for the first occupants to reach the refuge floor to travel a single flight of stairs, it is considered reasonable to directly compare the evacuation strategies.

## **8.2 Calculation Methods**

### **8.2.1 Stair Evacuation**

The results of the stair evacuation calculations demonstrate that evacuation times calculated using the method by Pauls<sup>[38]</sup> and the stair flow rates used in Approved Document B are very similar.

However, this is considered to be a result that neither the method detail by Pauls or the Approved Document B flow rates take into account the effective width of the stair, as required when calculating the evacuation times using the method described by Nelson and Mowrer<sup>[3]</sup>. Therefore, based on a reduced stair width (approximately 17% smaller) to take

into account the effective width and a lower building flow rate, the difference in the evacuation time between these methods and Nelson and Mowrer is significant.

Whilst it is not proposed to review the basis of the flow rates and calculation procedures for each method as part of this study, the correlation of the evacuation times using Pauls method with empirical results is considered to provide suitable validation of the results, when compared to the Approved Document B evacuation times.

Based on the close correlation of the Pauls method with those achieved in accordance with Approved Document B, it is considered reasonable to compare the lift evacuation times to the stair evacuation times determined on the stair flow rate of Approved Document B only.

### 8.2.2 Lift Evacuation

The evacuation times calculated using the Siikonen and ELVAC method are very similar based on a 10 storey separation distance between refuge floors.

The difference between these methods increases significantly based on an increase in the lift velocity and the separation distance between floor levels, such that the lift evacuation time from the 25<sup>th</sup> refuge floor level by a lift with a rated speed of 16m/s using the ELVAC calculation procedure is 40% longer than the evacuation time calculated using the Siikonen methodology. This is considered to be a result of the calculation for the delays due to acceleration and deceleration, within the Siikonen method.

Whilst the approximate value of 10 seconds for the delays associated with acceleration and deceleration is considered to be reasonable for the lower lift speeds, the delays associated with a lift with a rated speed of 16m/s and a rate of acceleration equal to  $1.2\text{m/s}^2$  increases significantly, such that the calculated evacuation time is significantly lower for the Siikonen method. However, the additional time associated with this delay has been included for within the evacuation calculator discussed in Appendix A to the nearest second, such that the evacuation time using the adapted Siikonen method is considered to be more conservative.

The difference between the lift evacuation times calculated using the calculation method detailed by Sekizawa and that by Siikonen also decreases based on an increase in the lift

speed and lift capacity. This is considered to be the result of the Sekizawa calculation taking into account the delays associated with acceleration and deceleration. However, due to the large variance in evacuation times remaining between these methods, it is not proposed to use this method of calculation.

### **8.3 Application of Lift Evacuation Strategy**

Whilst the above assessment has shown that the evacuation time from a building may be reduced based on the provision of lift evacuation or combined lift and stair evacuation, it is considered necessary to assess how the most effective lift evacuation strategy will be applied.

Based on the findings of this study, the most important factor is considered to be the method of determining which occupants are expected to use the stair and which occupants are expected to evacuate via the lifts. An important factor in determining the number of occupants able to escape via the lifts without significantly increasing the evacuation time is considered to be the lift specification. For example, the evacuation calculations have shown that, based on the use of the default values, occupants of the lower refuge floor are generally able to evacuate in a shorter time by using the stairs.

Therefore, the most effective evacuation strategy may be considered to be only those occupants of the lowest refuge floor level, who are not able to negotiate stairs, evacuate via lifts while the remaining occupants evacuate via the stairs.

However, this uneven use of the stairs for evacuation could reduce the stair flow rate due to the increased numbers of occupants at the lower floor levels merging with the occupants of the upper floor levels descending the stairs and therefore, actually increase the stair evacuation time, slightly.

Nevertheless, based on a decrease in the number of occupants evacuating from the lower refuge floor level it may be reasonable to provide fewer lift cars serving this floor level and therefore, increase the number of cars serving the upper refuge floors. On this basis, the decrease in the stair flow rate is considered to have less of an impact on the evacuation time on the basis that more occupants of the upper floor level may evacuate via the lifts. However, an enhanced scenario such as this would require additional assessment to

determine the impact of the additional number of occupants of the lower floor level using the undersized stairs.

It is considered that the method of evacuation of building occupants would be determined as part of the design strategy. However, this may be altered by the fire safety manager as required. The most effective strategy is considered to locate those occupants who require the lift to evacuate, such as those occupants in wheelchairs, on lower floors levels, where the number of occupants using the lifts is likely to be less than those levels above and therefore, are unlikely to increase the overall lift evacuation time by increasing the number of round trips required.

#### **8.4 Conclusion**

Based on the above observations, the following summary can be made with regards to lift evacuation:

- 1) ***Evacuation from refuge floors is approximately 25% quicker than that from an evacuation zone.***
- 2) Based on a refuge floor interval of 10 storeys, the evacuation time from the whole building is approximately equal for lift and stair evacuation (time for lift evacuation is 2% faster), when using the default values. Once the number of storeys between refuge floor levels increases, the evacuation time by stairs is significantly less than via lifts, with evacuation from the lower refuge floors being significantly quicker by stairs. However, evacuation using eight, 12 person lift cars, or four 21 person lift cars is more efficient than stairs. On this basis, it is considered necessary to provide refuge floors at small intervals based on an approximate occupancy of 150 persons per floor level, where all of the building occupants are assumed to evacuate via the lifts. Refuge floor separation distances and evacuation zone sizes may be increased based on a lower occupancy or increased lift performance values.
- 3) The most effective evacuation time is for an increased number of lift shafts. This is considered to be a result of the number of round trips required for eight lift cars with a capacity of 12 persons (29 round trips per lift) compared to that of four lifts with a capacity of 21 persons (32 round trips per lift).

- 4) Based on a reduction in the number of occupants using the lifts by half, allows refuge floors and evacuation zone to be provided which serve 25 storeys, without the requirement for unfeasible numbers of lifts shafts or lift car capacities.
- 5) A reduction in the number of occupants using the lifts, results in an approximate reduction of the overall evacuation time by an equal percentage. In the event that 25% of the building occupants use the stairs, the evacuation time is considered to be faster for those occupants using the stairs, irrespective of the increased lift performance values used as part of the study. This is considered to be a result of the disproportionate numbers of occupants using the lifts compared to those using the stairs. However, based on the occupants evenly distributing between the stairs and the lifts, the lift and associated stair evacuation times are approximately equal (stairs are 0.4% faster) for the default lift performance values at a 10 storey separation distance. The reduction in the lift evacuation times follows the same trends as those when 100% of the occupants use the lifts to escape.
- 6) Based on the application of evacuation zones, the associated stair evacuation time is approximately 4.5% less than the lift evacuation time, for 10 storey evacuation zones, when the default values are applied. The difference in times is considered to be the result of greater lift evacuation times due to the increased distance travelled serving each floor within the evacuation zone. The difference in evacuation times between these methods increases with refuge floor and evacuation zone separation distances.
- 7) Based on a comparison of the lift evacuation times with the code compliant stair evacuation times, it has been demonstrated that it is possible to provide lift evacuation up to 25 storey intervals in less time than the code compliant stair evacuation time, based on the use of the default values provided in Chapter 5.
- 8) The assessment detailed in Chapter 7 is considered to provide a conservative assessment as this does not take into account the increase in stair evacuation times associated with occupant fatigue as they descend multiple flights of stairs. Therefore, the stair evacuation times are considered to be lower than those likely to be achieved in real life evacuations.

- 9) Based on the review and results contained within this thesis, it is recommended that any further research into lift evacuation reviews the impact of inefficient round trips on the evacuation time, for evacuation from a refuge floor and an evacuation zone, to determine the effect of disabled occupants and poor management of the lift loading, on the total evacuation time for the building.



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## **APPENDIX A - EVACUATION CALCULATOR**

As discussed in this study, it is not considered possible to determine at what point the use of lifts for evacuation is more efficient than the use of stairs, without conducting multiple iterations of the calculations listed in Section 3.2 and 3.3.

Therefore, Visual Basic has been used to create a spreadsheet that allows the user to assess the evacuation of a building using lifts for both methods assessed in this study (i.e. refuge floors and evacuation zones), with the code compliant stair evacuation time.

This comparative method of assessment allows the user to determine if the proposed design provides an escape time which is no worse than a code compliant design.

### **Stair Evacuation Time**

The stair evacuation times are calculated based on the code compliant 1.33 persons/metre/second flow rate used in Approved Document B<sup>[1]</sup>. This allows the user to compare the lift evacuation times against the code compliant evacuation time (i.e. use of stairs only).

### **Lift Evacuation Time**

Whilst it is noted that the lift evacuation times which are considered to be most accurate are those generated by the ELVAC programme, it is not considered possible to integrate the results from this programme into the spread sheet. Therefore, based on the similarity of results between this method and the method described by Siikonen, the lift evacuation time has been calculated using the Siikonen method, as listed in Section 3.3.2.

However, based on the use of Visual Basic, the calculation has been modified to include an accurate value for the delay associated with acceleration and deceleration, to within the nearest second, to allow a more accurate comparison between results.

For example, a lift which is travelling at a speed of 6m/s with a deceleration value of 1.2m/s<sup>2</sup> will require 5 seconds to decelerate and will have travelled a total distance of 12m during deceleration. However, a lift travelling at constant speed will have travelled this

distance in 2 seconds. Therefore, the difference between the two methods is equal to 10 seconds. Based on the assumption that the lift is required to accelerate and decelerate once for each one way trip twice for each round trip, the total delay due to acceleration and deceleration for each round trip is equal to 40 seconds.

Based on the inclusion of these delays in the revised calculation method of the evacuation round trip, it is considered that more accurate evacuation times will be calculated, which closely follow the results produced using the ELVAC programme, compared to those used in this study.

### **Spread Sheet Inputs**

The spread sheet requires the following values to be provided to allow a comparison to be made between lift and stair evacuation.

- Number of floor levels above Ground
- Occupancy per floor level
- Floor to floor height (m)
- Number of stairs
- Width of stairs (m)
- Number of lifts
- Capacity of lifts (persons)
- Lift speed (m/s)
- Lift acceleration ( $m/s^2$ )
- Evacuation method (refuge floor or evacuation zone)
- Number of storeys per zone
- Highest refuge floor level (m)

### **Spread Sheet Output**

Based on the provision of the above inputs the spreadsheet will display the evacuation time from each floor level (for evacuation zone) or the evacuation time from each refuge floor level, as well as provide the information in graphs for comparison.

A screen shot of the spread sheet is shown in the Figure below.

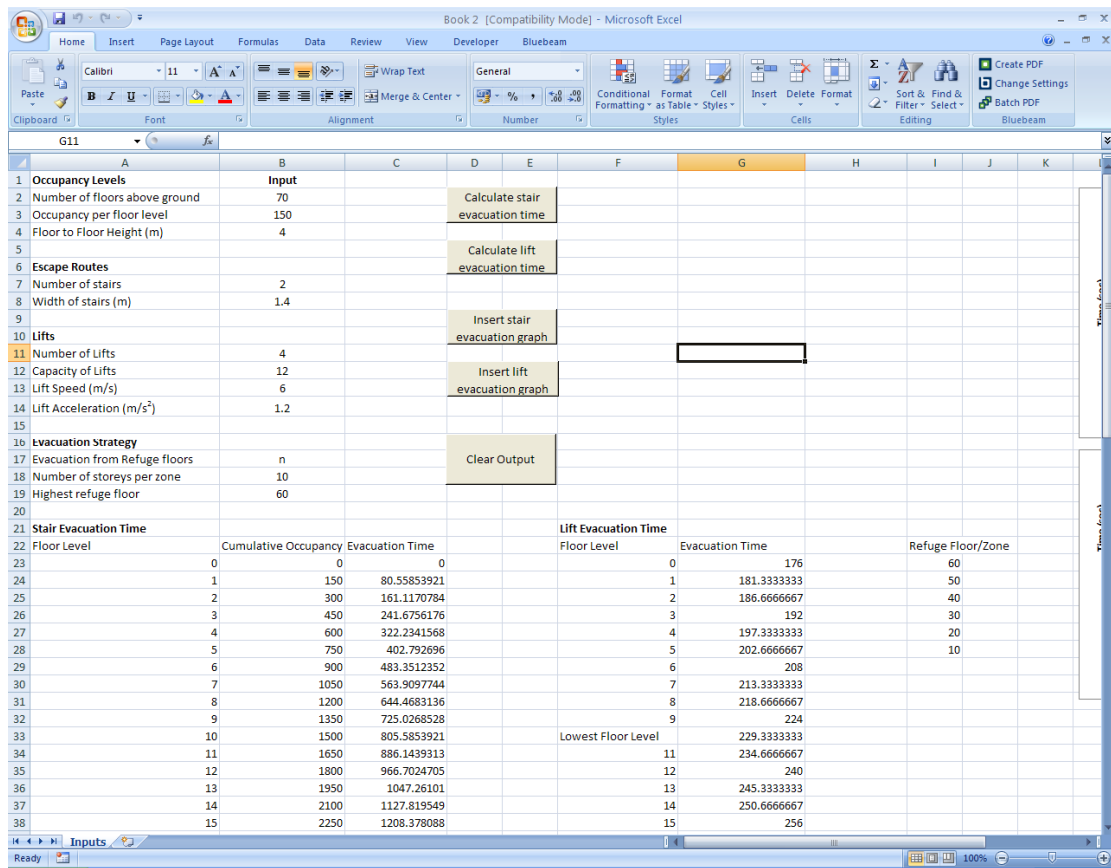


Figure A.1 - Screen snapshot of evacuation calculation spreadsheet

### Validation

The revised Siikonen calculation process includes a more accurate calculation of the delays associated with acceleration and deceleration rather than the default value of 10 seconds assumed within the assessment detailed in Chapter 7.

On this basis, it is proposed to assess the difference using both methods and compare the evacuation times for each of the studied lift speeds, at each separation distance, for both evacuation methods. The results of the assessment are shown in the Table below, along with the percentage difference between the modified calculation and that using the default delay value of 10 seconds.

Evacuation zone size	Refuge floor level	Refuge floors			Evacuation Zone		
		Default value	Modified calculation	% difference	Default value	Modified calculation	% difference
10	10	24.2	23.2	-4.13	38.1	36.8	-3.41
	20	31.9	30.9	-3.13	48.8	47.5	-2.66
	30	39.6	38.7	-2.27	59.5	58.1	-2.35
	40	47.4	46.4	-2.1	77.7	76.3	-1.8
15	5	30.8	29.3	-4.87	53.2	51.2	-3.76
	20	48.4	46.9	-3.1	77.2	75.2	-2.59
	35	66	64.5	-2.27	108.8	106.7	-1.93
20	10	50	48	-4	86.9	84.3	-2.99
	30	82	80	-2.4	137.2	134.4	-2.04
25	25	92.5	90	-2.7	162.9	160	-1.78

**Table A.1 – Comparative assessment of Siikonen calculation methods @ 5 m/s**

Evacuation zone size	Refuge floor level	Refuge floors			Evacuation Zone		
		Default value	Modified calculation	% difference	Default value	Modified calculation	% difference
10	10	22.9	21.9	4.37	35.6	34.2	-3.93
	20	29.3	28.4	3.07	44.4	43.1	-2.93
	30	35.8	34.8	2.79	53.3	52	-2.44
	40	42.2	41.2	2.37	68.9	67.5	-2.03
15	5	29.8	28.4	4.7	50	48	-4
	20	44.5	43	3.37	70	68	-2.86
	35	59.2	57.7	2.53	96.7	94.6	-2.17
20	10	47.3	45.3	4.23	80	77.3	-3.38
	30	74	72	2.7	122.3	119.5	-2.29
25	25	84.2	81.7	2.97	145.6	142.1	-2.4

**Table A.2 – Comparative assessment of Siikonen calculation methods @ 6 m/s**



Evacuation zone size	Refuge floor level	Refuge floors			Evacuation Zone		
		Default value	Modified calculation	% difference	Default value	Modified calculation	% difference
10	10	22	22.9	4.09	33.7	35	3.86
	20	27.5	28.4	3.27	41.3	42.7	3.39
	30	33	34	3.03	49	50.3	2.65
	40	38.5	39.5	2.6	62.6	64.1	2.4
15	5	29.1	30.6	5.15	47.7	49.7	4.19
	20	41.7	43.2	3.6	64.9	66.9	3.08
	35	54.3	55.7	2.58	88.1	90.2	2.38
20	10	45.4	47.4	4.4	75	77.7	3.6
	30	68.3	70.3	2.93	111.6	114.4	2.5
25	25	78.2	80.7	3.2	133.2	136.7	2.63

**Table A.3 – Comparative assessment of Siikonen calculation methods @ 7 m/s**

Evacuation zone size	Refuge floor level	Refuge floors			Evacuation Zone		
		Default value	Modified calculation	% difference	Default value	Modified calculation	% difference
10	10	18.9	29.5	56.08	27.5	42.2	53.45
	20	21.3	31.9	49.77	30.8	45.5	47.47
	30	23.7	34.3	44.7	34.2	48.8	42.69
	40	26.1	36.7	52.1	41.4	57.6	39.13
15	5	26.8	42.9	60	40	62	55
	20	32.3	48.4	49.84	47.5	69.5	46.32
	35	37.8	53.9	42.59	58.9	82.4	39.9
20	10	39	61	56.4	58.3	87.7	50.43
	30	49	71	44.9	75.6	106.4	40.74
25	25	58.1	85.6	47.3	91.4	129.6	41.73

**Table A.4 – Comparative assessment of Siikonen calculation methods @ 16 m/s**

### Summary

It is noted from Table A.1 to A.3 that the calculated evacuation time is +/- 5% of that when using the default delay value of 10 seconds for lift speeds within the recommended limits of CIBSE Guide D<sup>[27]</sup> and Fortune<sup>[31]</sup>. Based on the conservative nature of these lift evacuation times when compared to the equivalent evacuation time via stairs, it is considered reasonable to apply the values of this assessment for lift evacuation studies to proposed lift evacuation systems within the limits recommended in CIBSE Guide D<sup>[27]</sup> and Fortune<sup>[31]</sup>.

However, it is noted that once the lift speed exceeds those values recommended within CIBSE Guide D and Fortune<sup>[31]</sup>, the percentage difference between the evacuation times is significantly greater (39% - 53% greater).

Nevertheless, this is considered to be reasonable for evacuation from a refuge floor on the basis that the resulting evacuation times are less than those calculated using the more accurate ELVAC model and are therefore considered to be slightly more onerous. However, caution is recommended for the use of this programme when calculating the evacuation times for evacuation from within an evacuation zone, as these times slightly exceed the values calculated using ELVAC.

A comparison of the evacuation times for a lift with a speed of 16 m/s, calculated using the modified Siikonen equation are shown in comparison to the evacuation times calculated using ELVAC.

Evacuation zone size	Refuge floor level	Refuge floors			Evacuation Zone		
		ELVAC	Modified calculation	% difference	ELVAC	Modified calculation	% difference
10	10	24.9	29.5	18.47	37.1	42.2	13.75
	20	35.3	31.9	-9.63	42.2	45.5	7.82
	30	39.2	34.3	-12.5	46.3	48.8	5.4
	40	42.5	36.7	-13.65	55.1	57.6	5.54
15	5	41.1	42.9	4.38	52.7	62	17.64
	20	54.3	48.4	-10.87	64.5	69.5	7.75
	35	63	53.9	-14.44	78.3	82.4	5.24
20	10	63.4	61	-3.79	78.5	87.7	11.72
	30	88.7	71	-19.95	100.6	106.4	5.77
25	25	98	85.6	-12.65	121.9	129.6	6.32

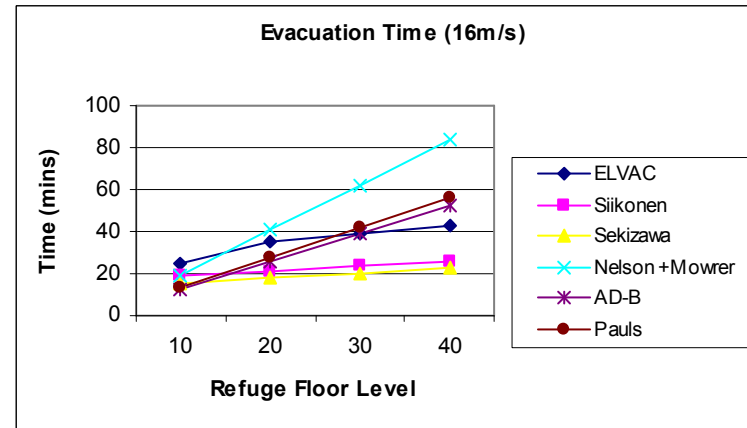
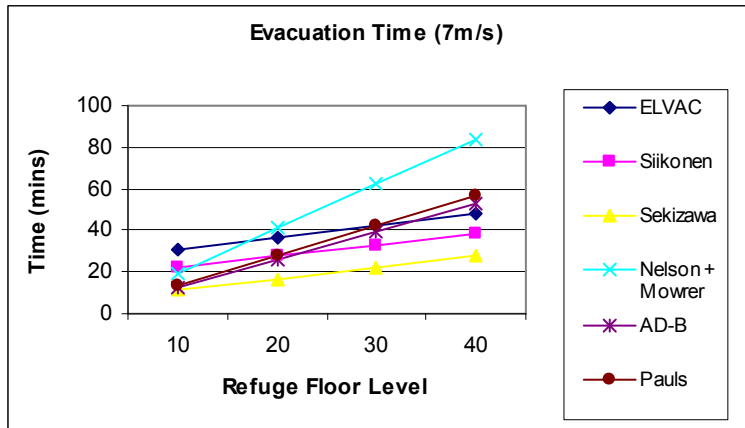
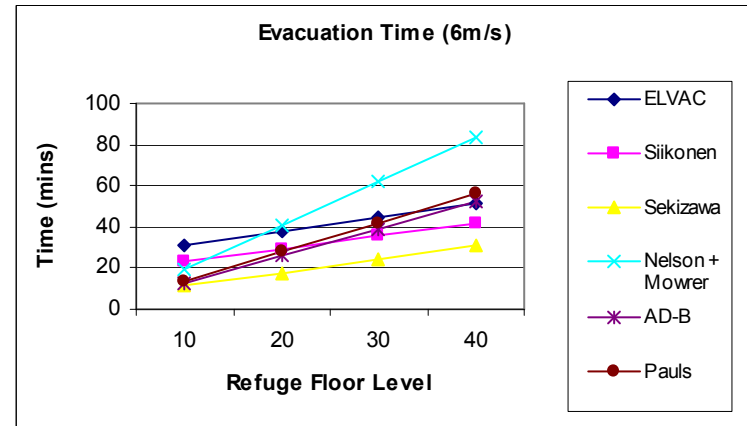
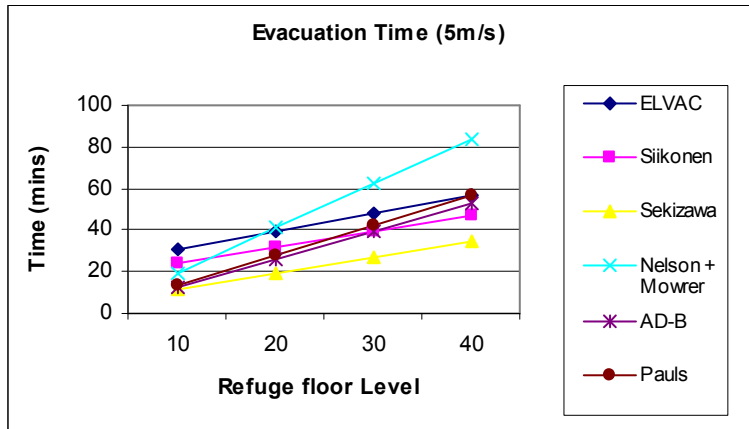
**Table A.5 – Comparison of evacuation times using modified Siikonen equation and ELVAC for lifts with a speed of 16 m/s**

Based on the difference in evacuation times from the higher evacuation zones (approximately 5%), which is the determining factor in the total building evacuation time, this is considered to be reasonable for an initial assessment tool. However, once the

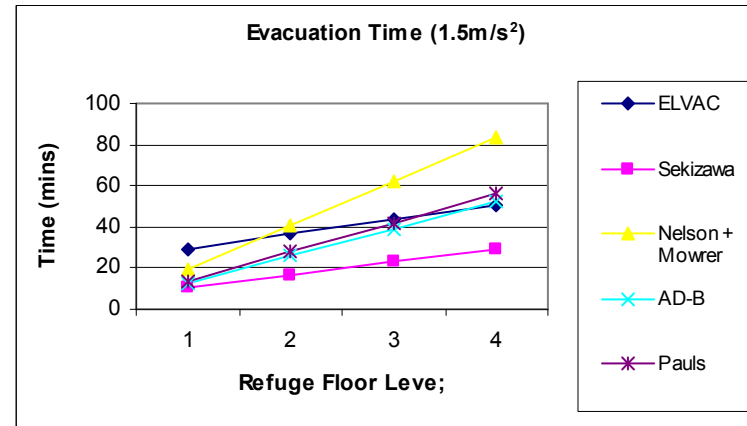
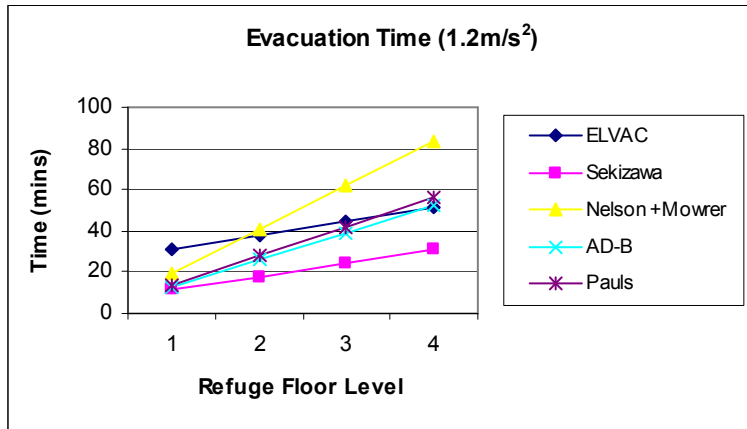
evacuation method and lift performance values are determined more detailed analysis should be undertaken using a more accurate simulation tool such as ELVAC or STEPS.

**APPENDIX B – EVACUATION TIME USING REFUGE FLOORS (100% LIFT USAGE)**

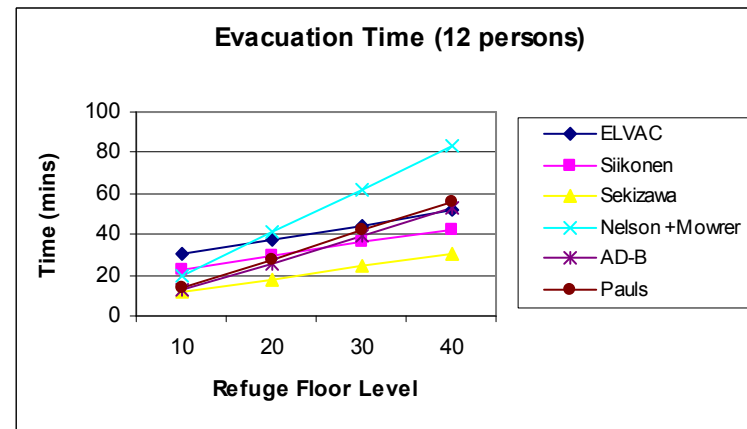
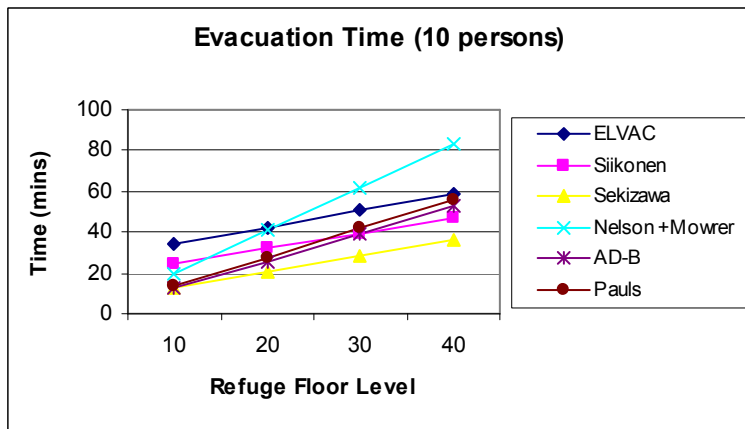
### 10 Storey Intervals – Variable Speed

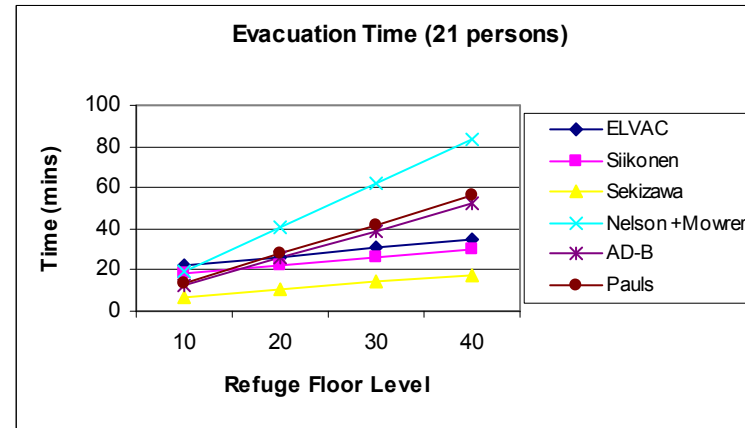
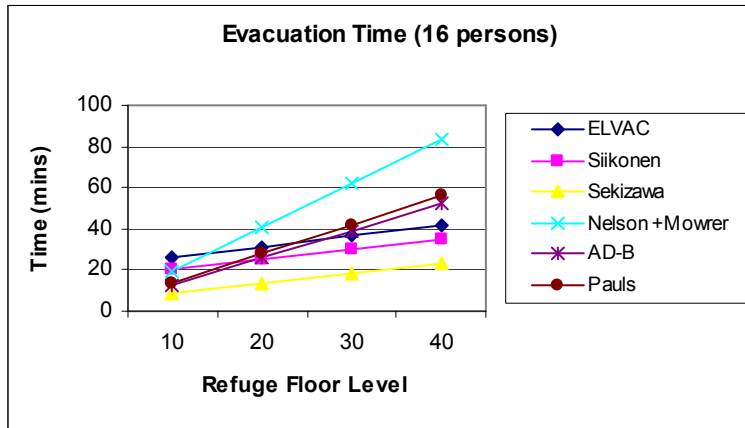


### 10 Storey Intervals – Variable Acceleration

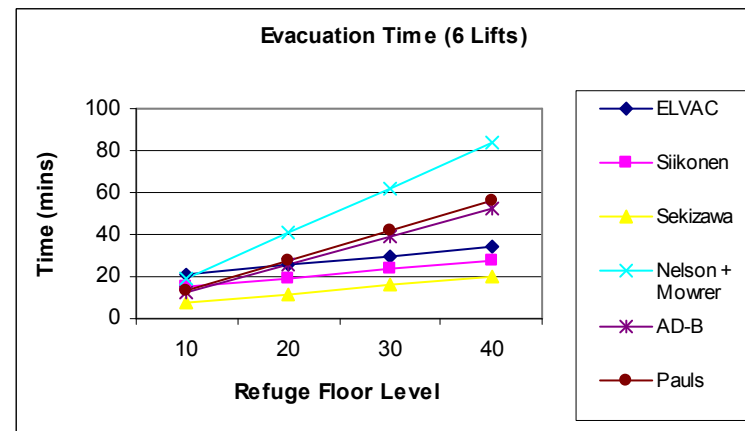
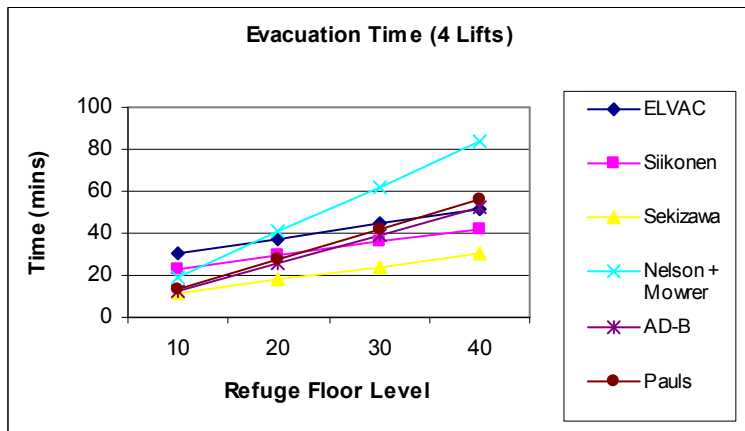


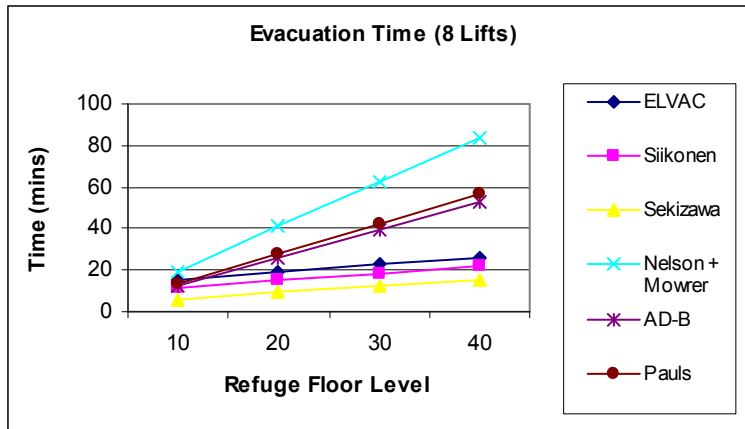
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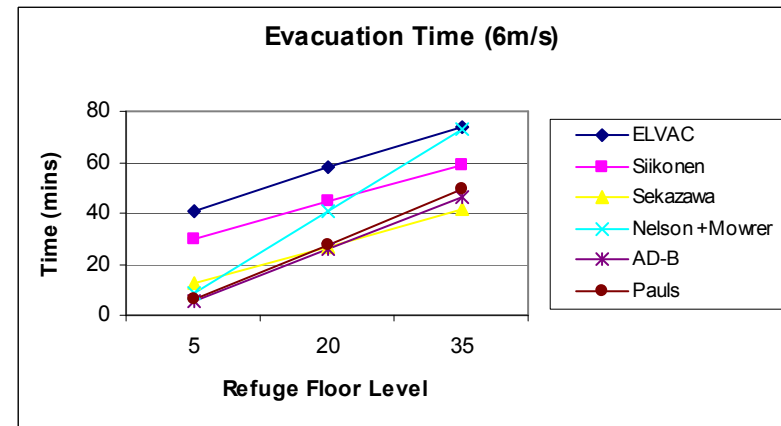
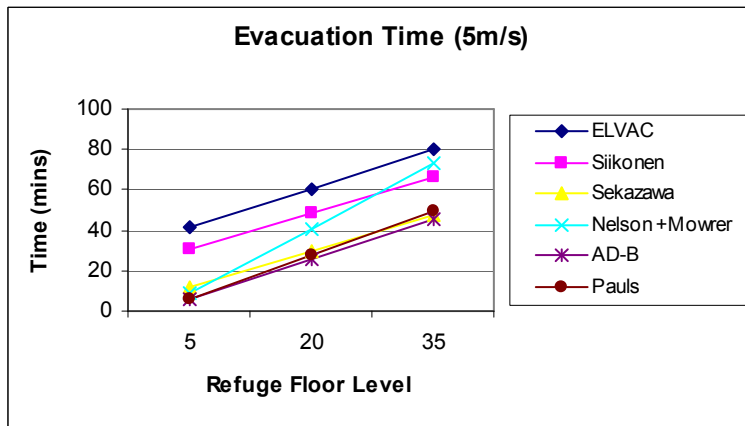


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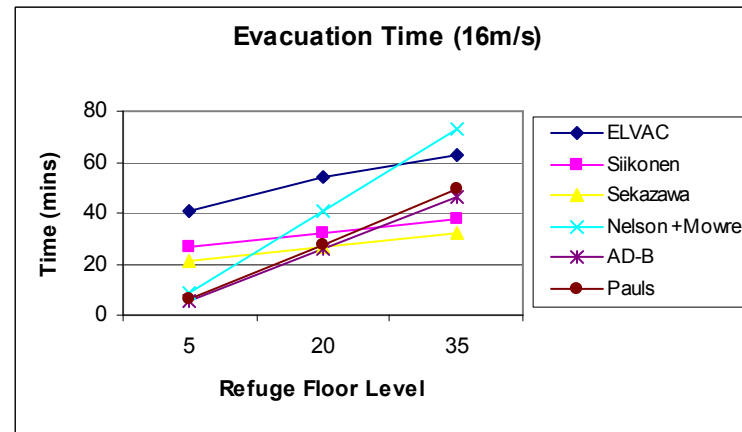
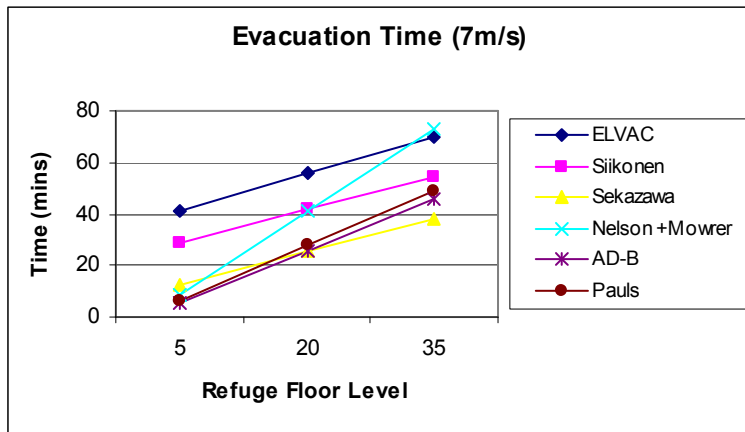




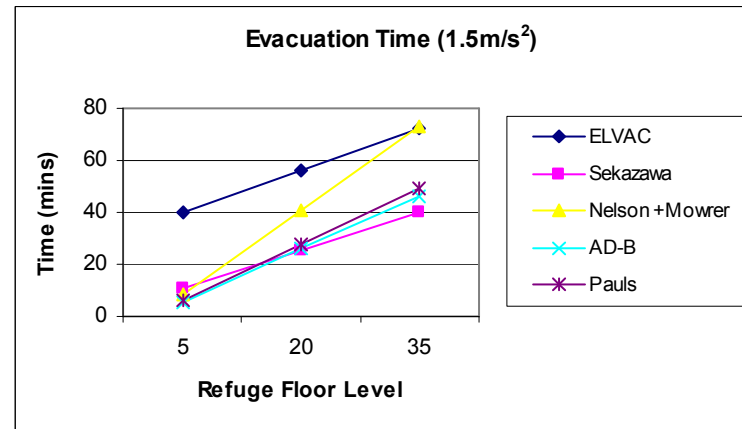
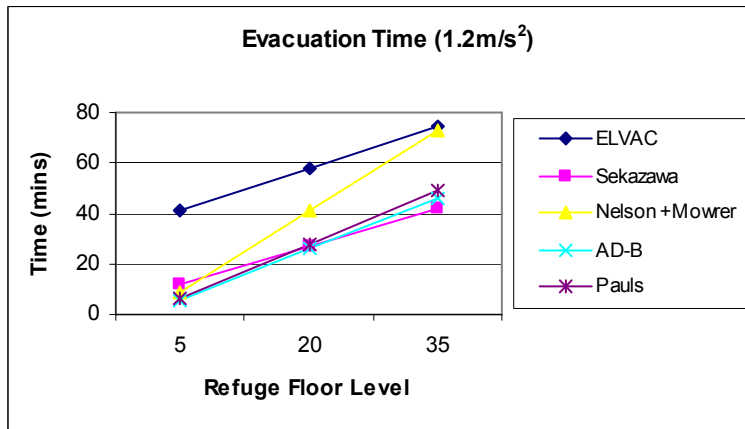
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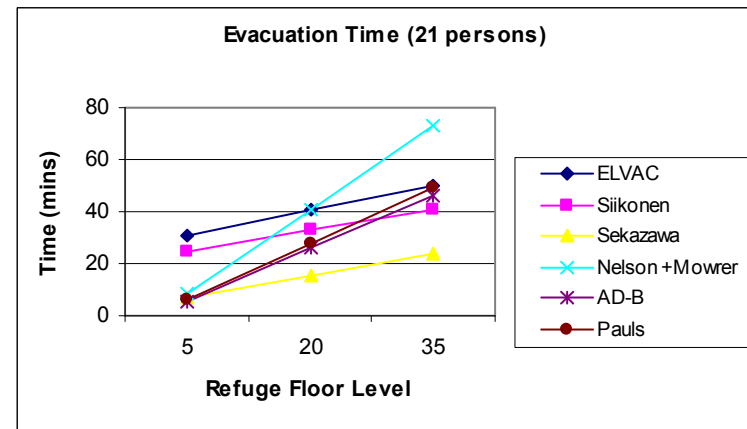
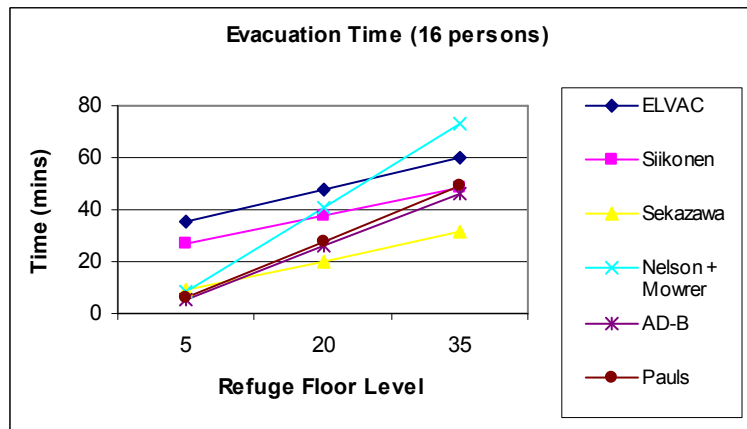
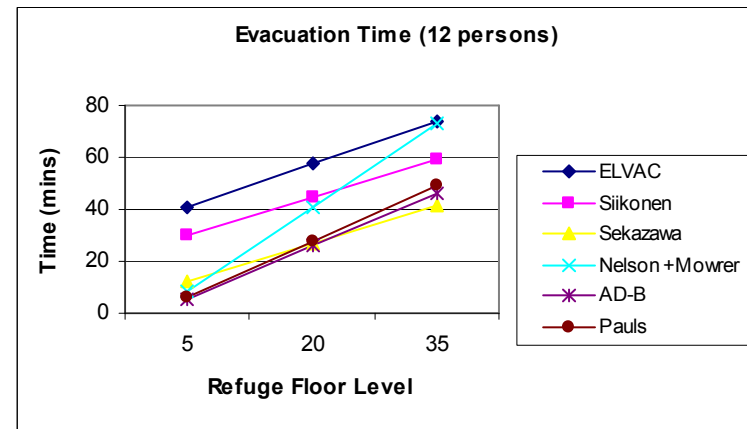
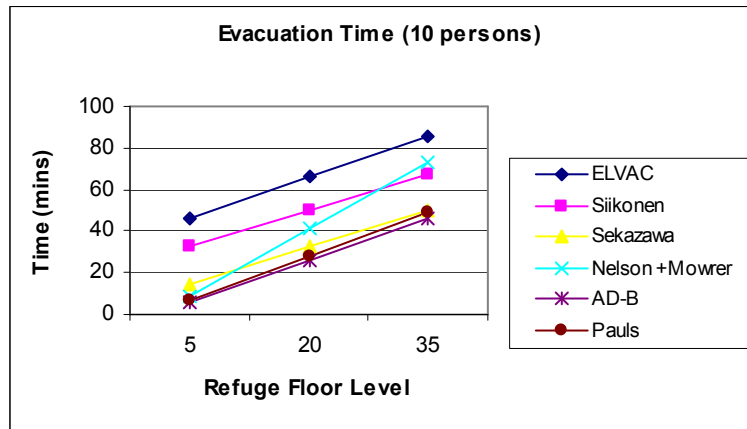




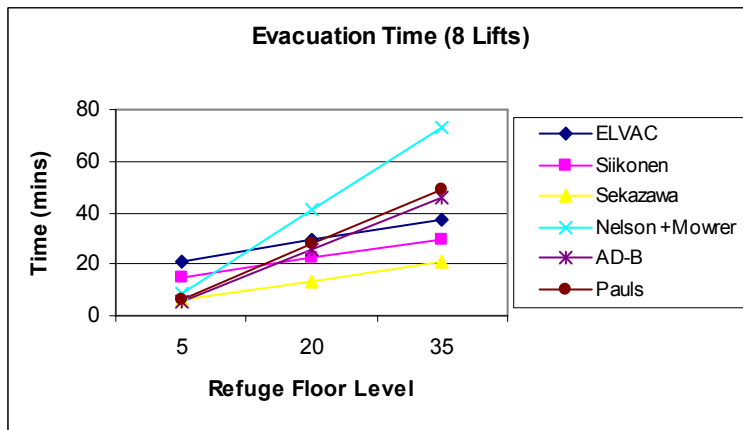
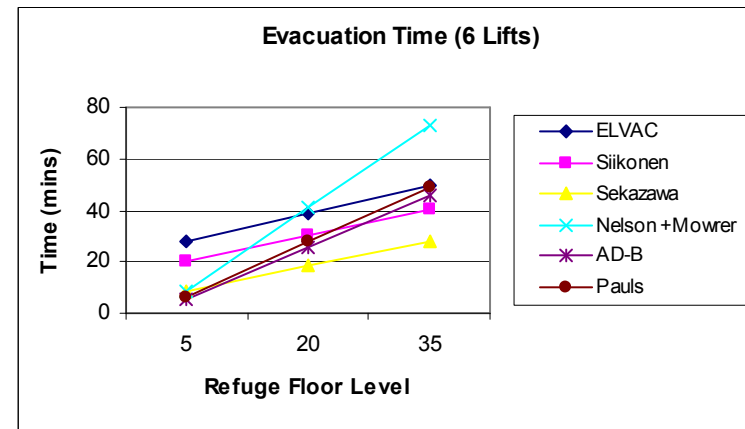
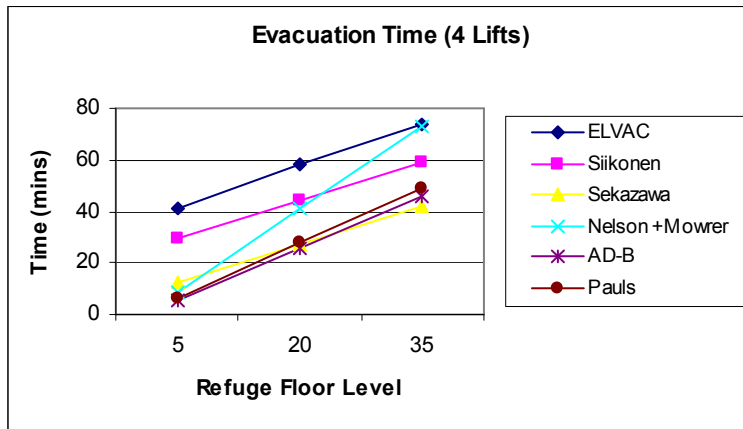
## 15 Storey Intervals – Variable Acceleration



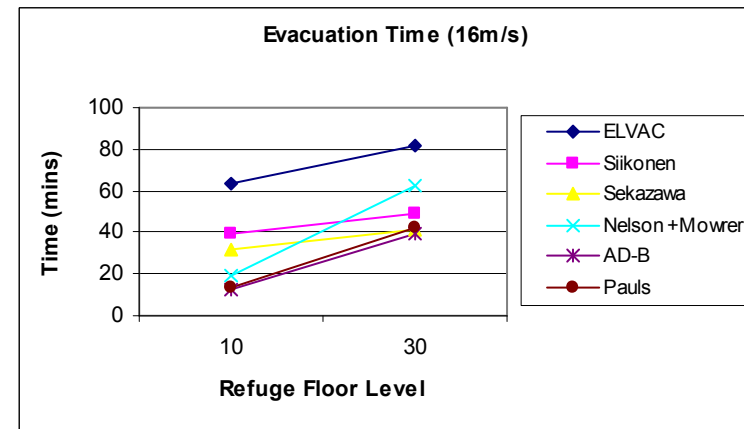
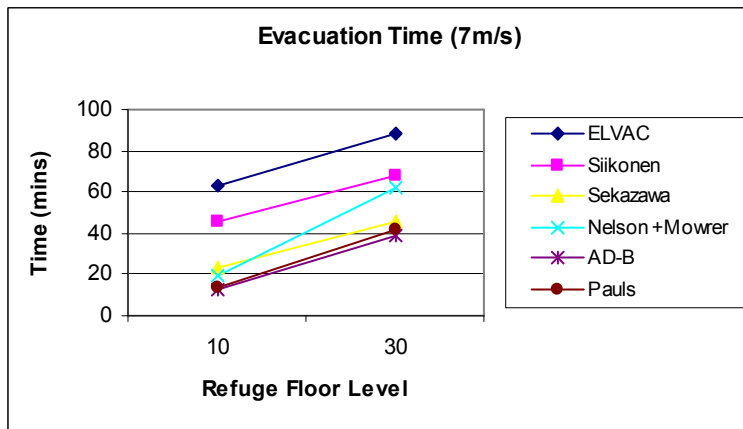
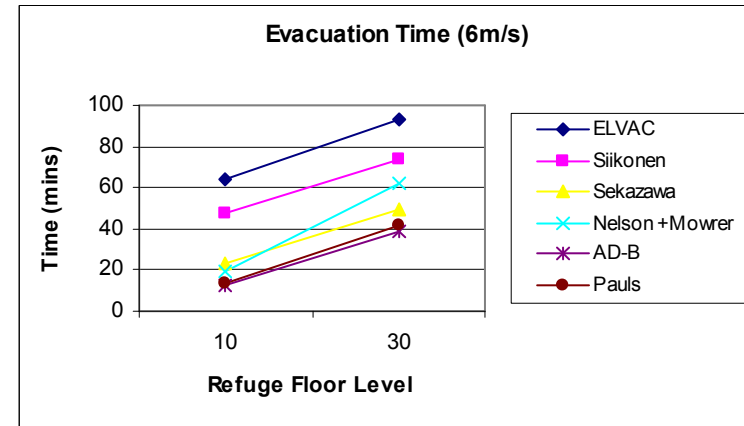
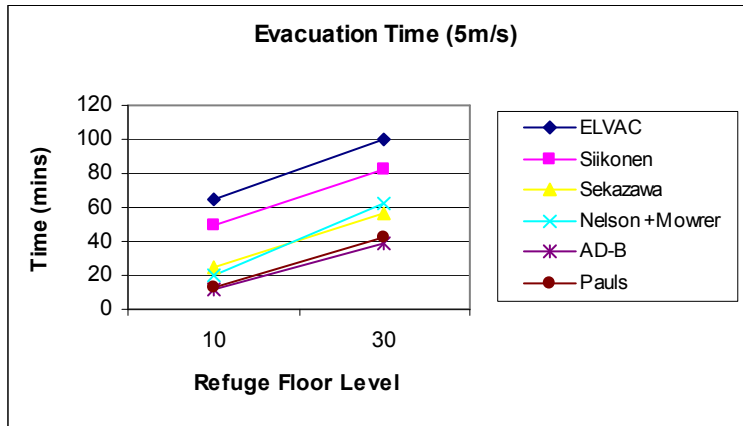
### 15 Storey Intervals – Variable Capacity



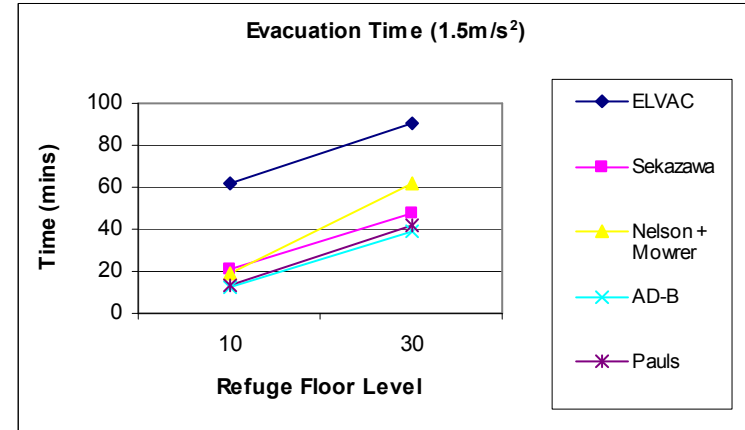
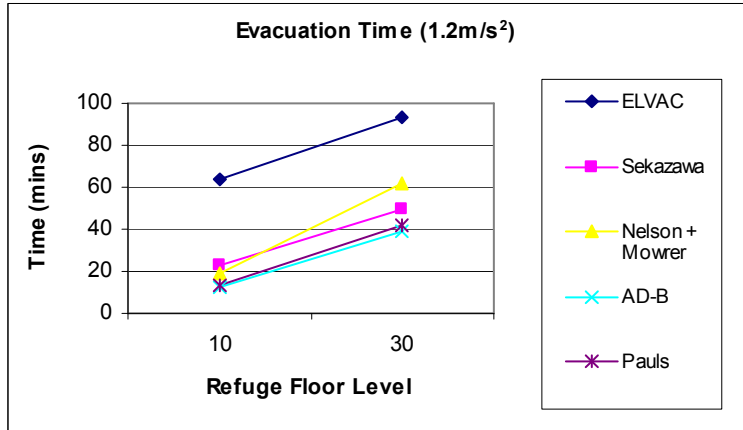
### 15 Storey Intervals – Variable Lifts



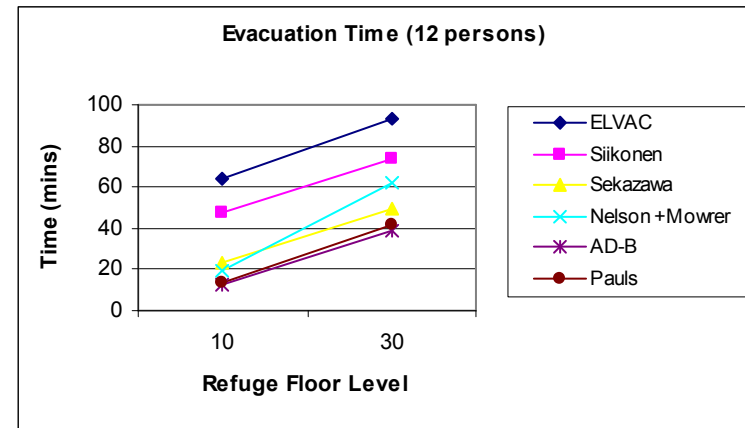
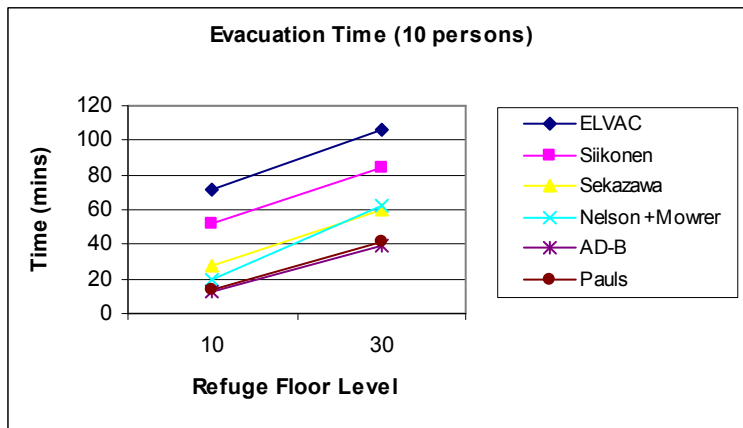
## 20 Storey Intervals – Variable Speed

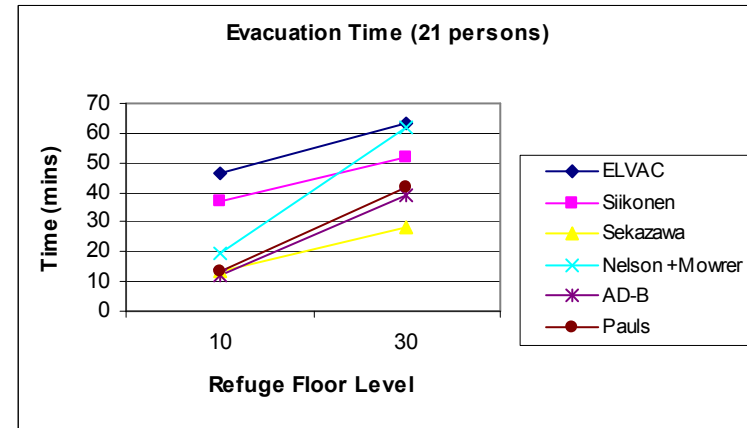
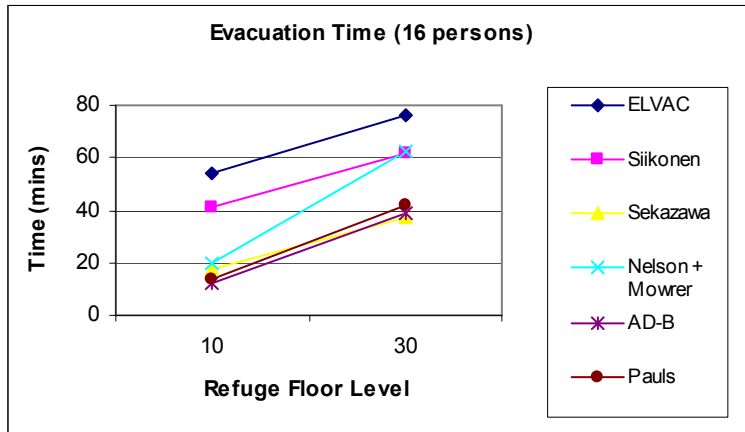


### 20 Storey Intervals – Variable Acceleration

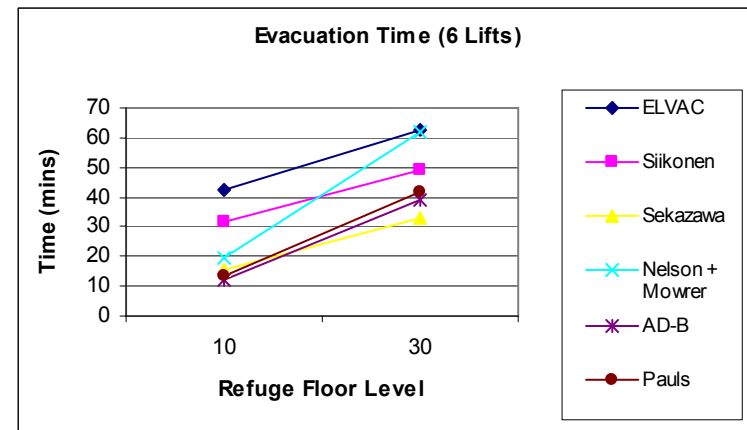
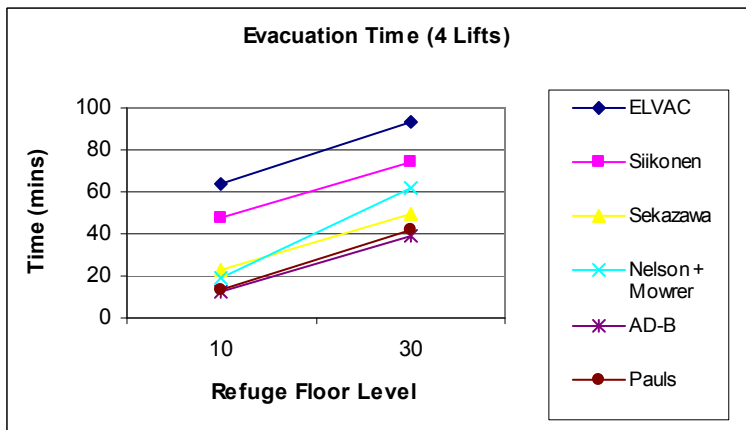


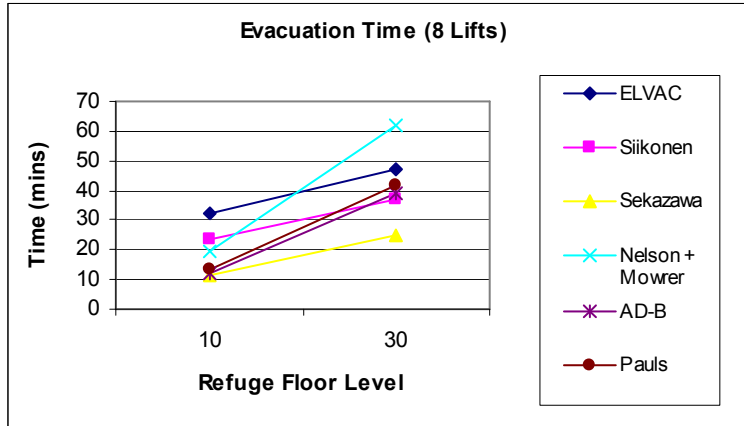
### 20 Storey Intervals – Variable Capacity



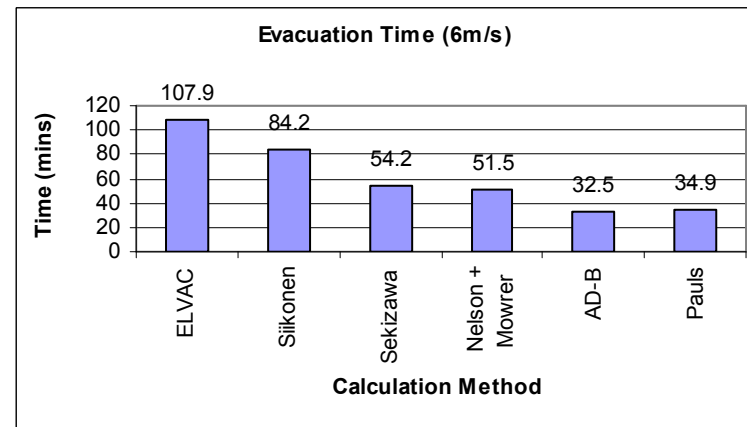
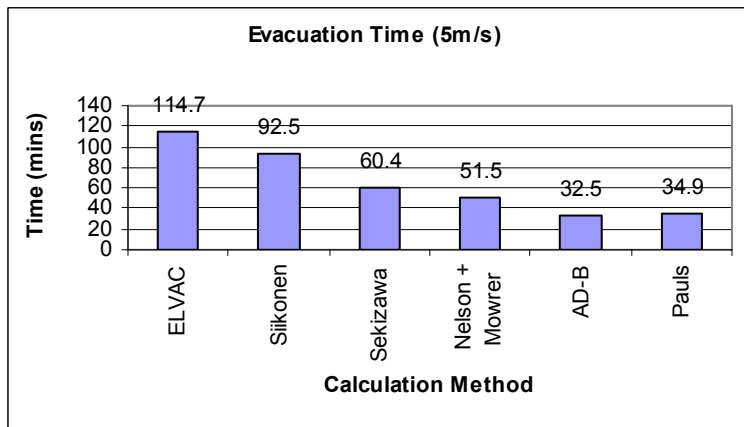


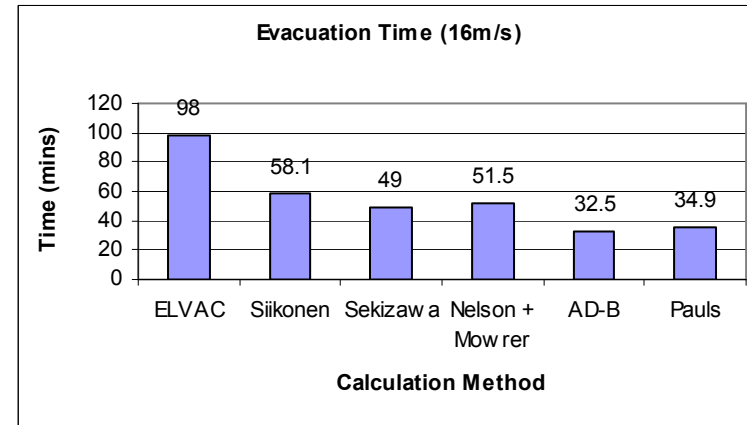
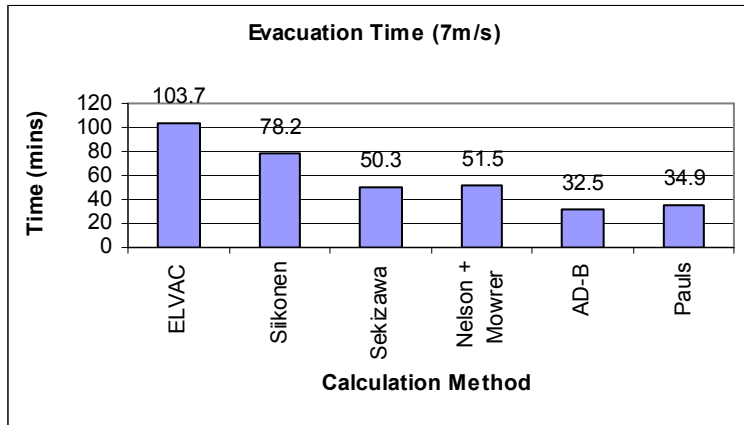
## 20 Storey Intervals – Variable Capacity



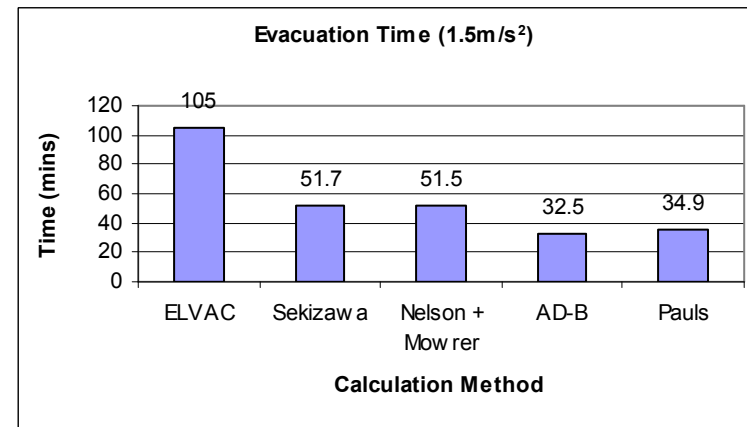
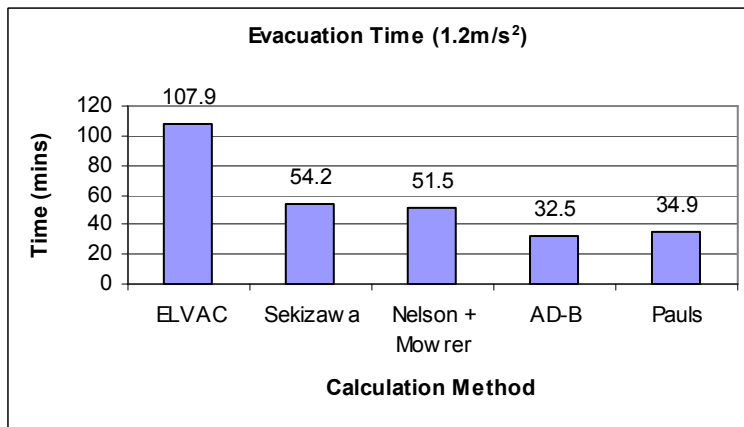


### 25 Storey Intervals – Variable Speed



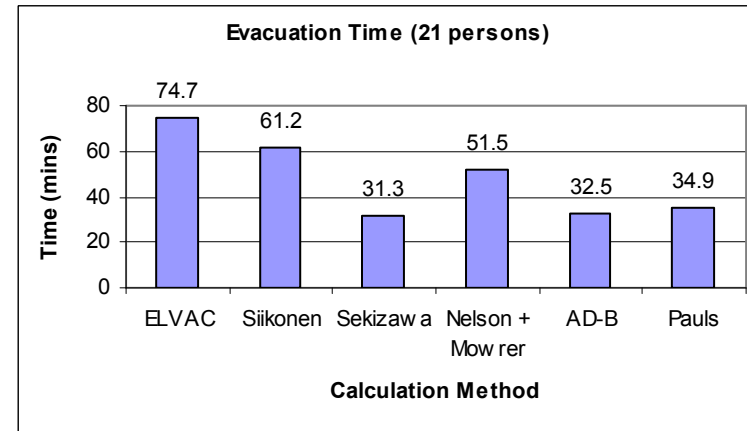
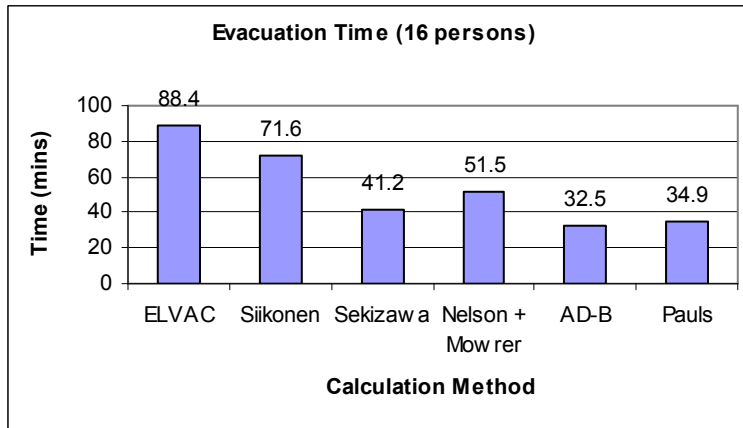
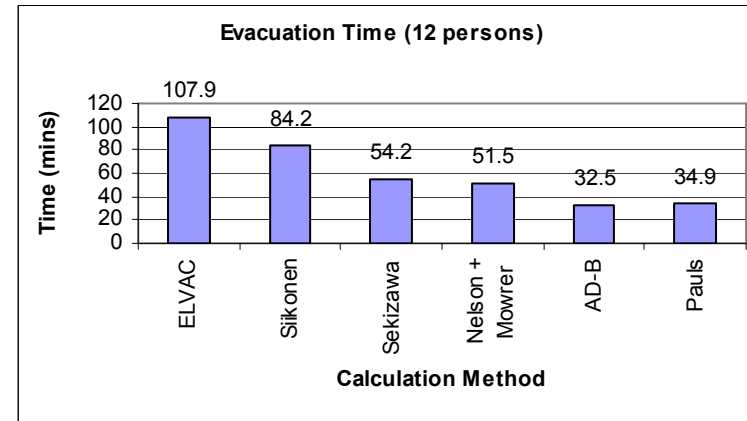
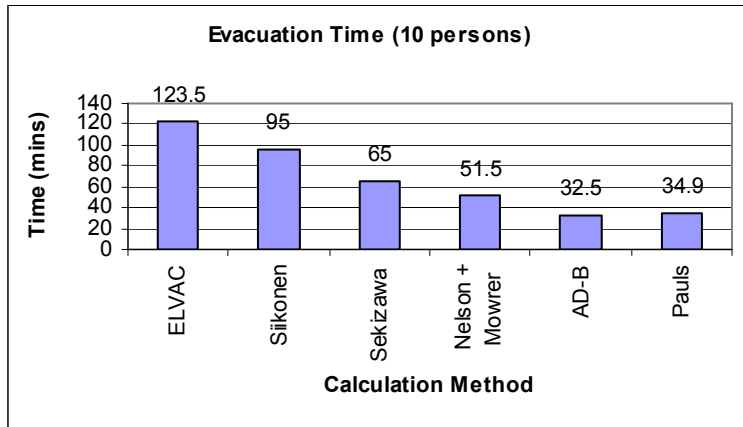


**25 Storey Intervals – Variable Acceleration**

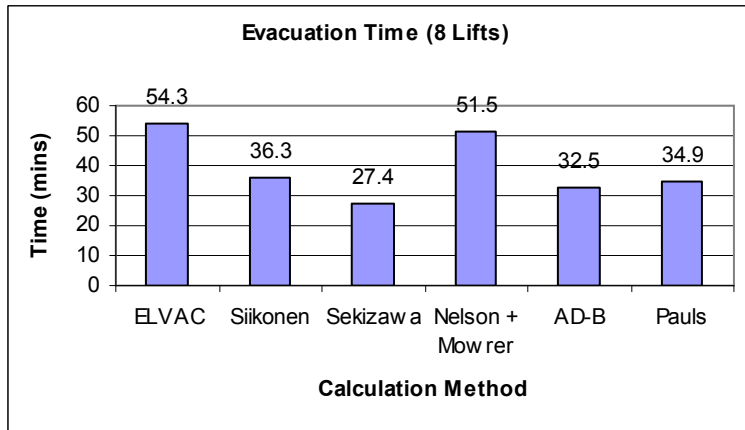
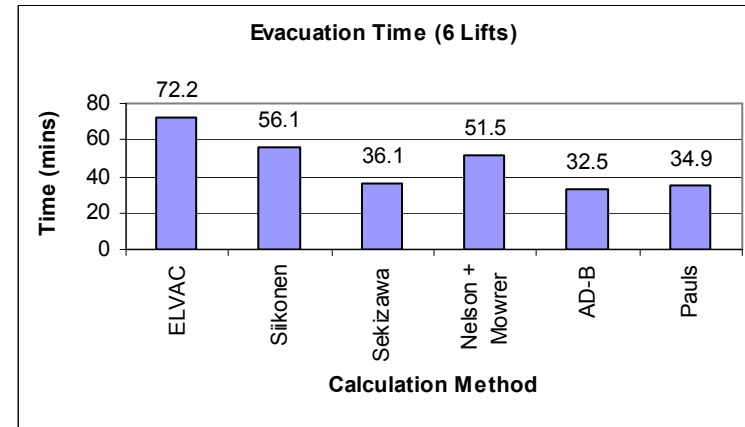
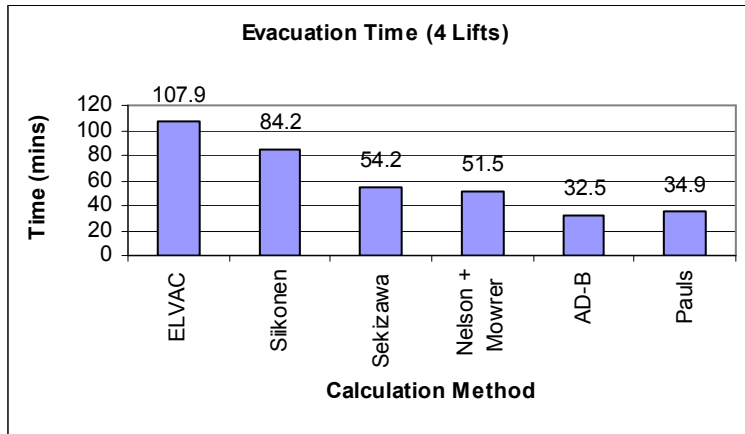




## 25 Storey Intervals – Variable Capacity

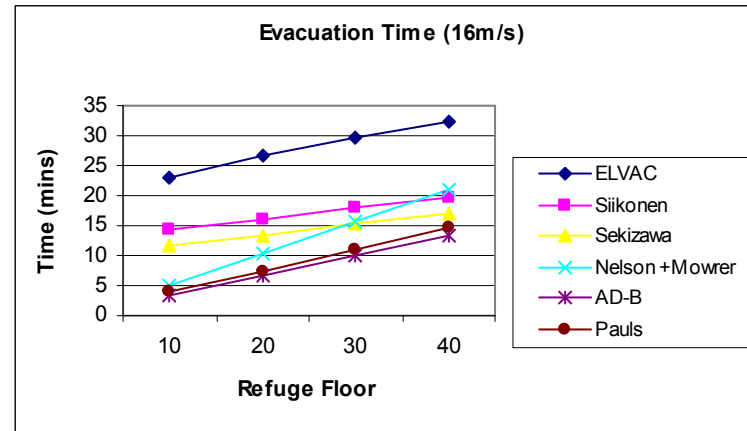
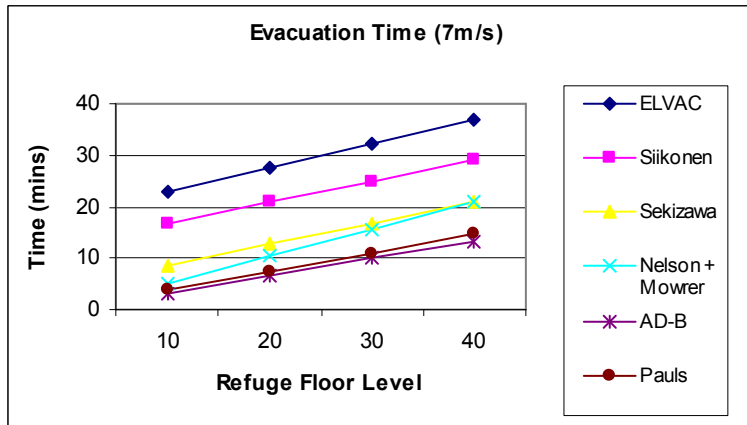
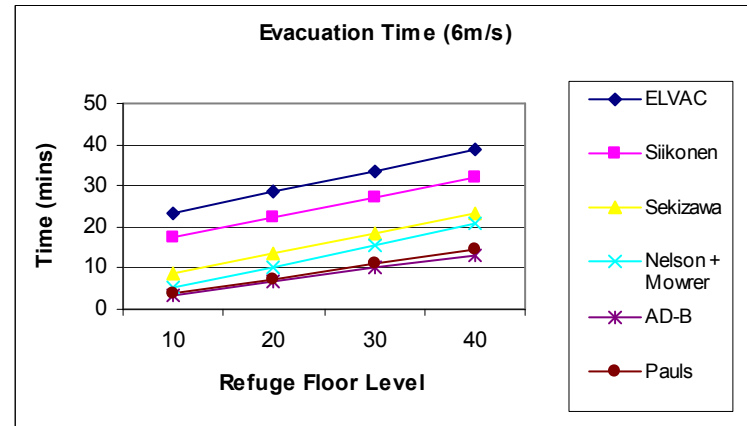
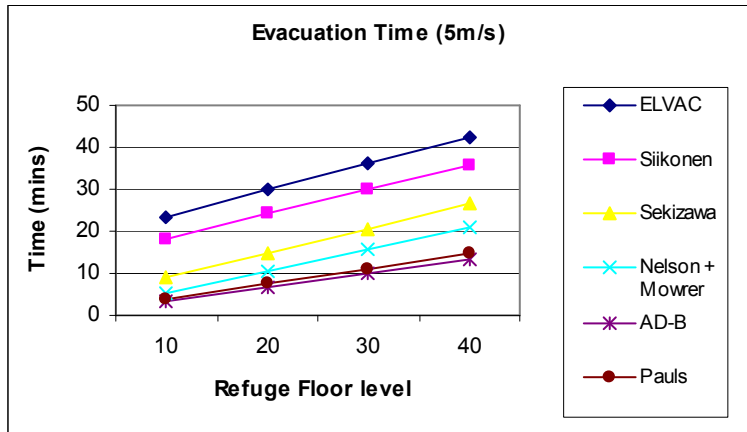


### 25 Storey Interval – Variable Lifts

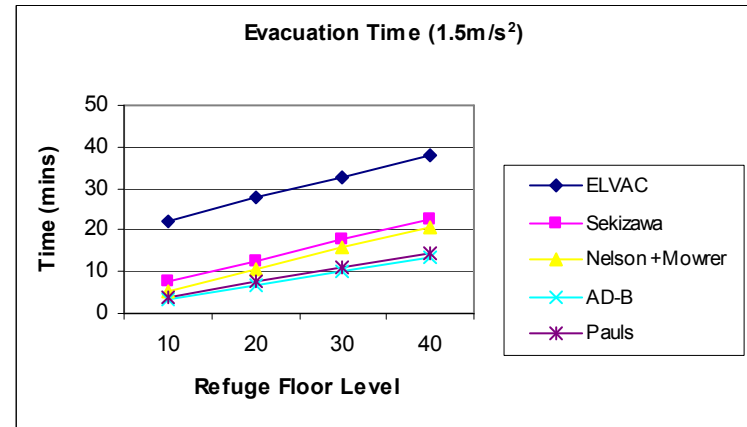
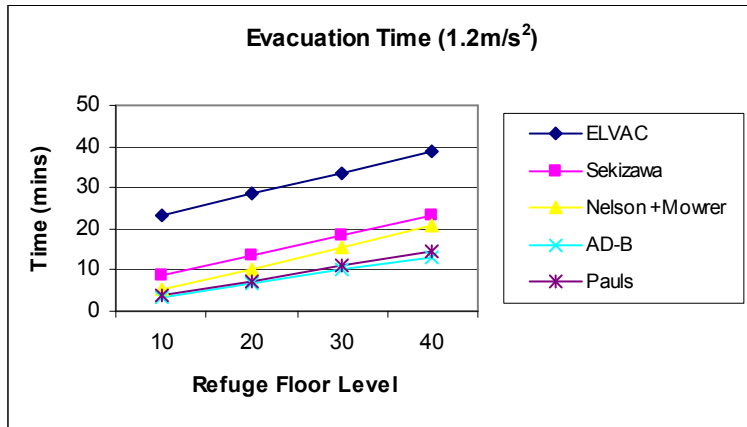


**APPENDIX B – EVACUATION TIME USING REFUGE FLOORS (75% LIFT USAGE)**

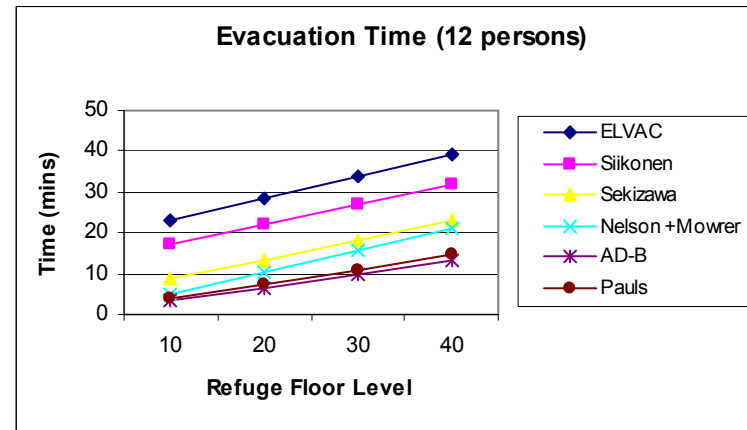
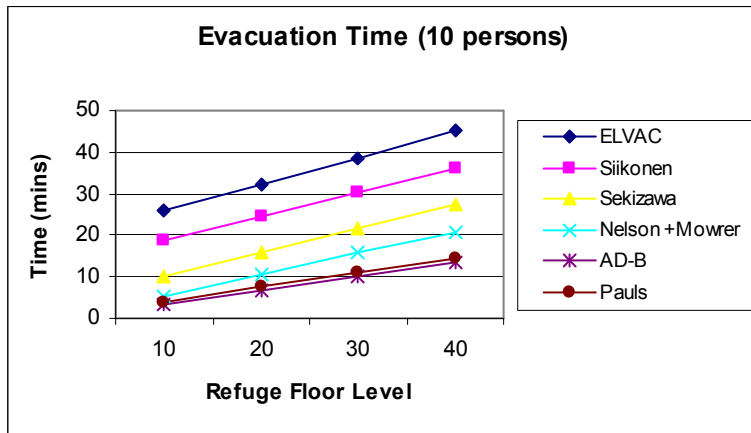
### 10 Storey Interval – Variable Speed

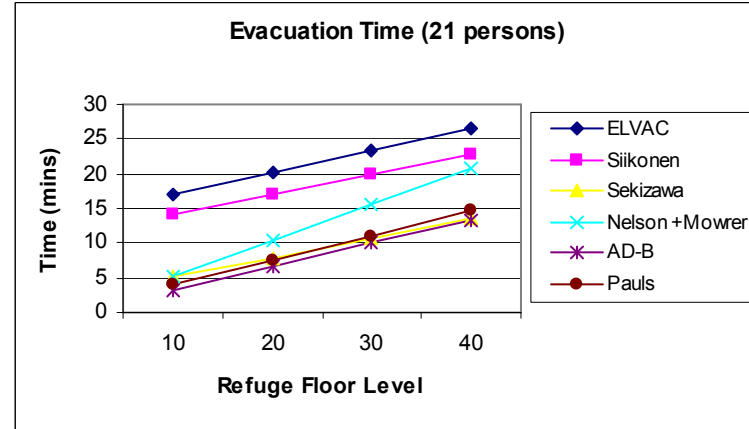
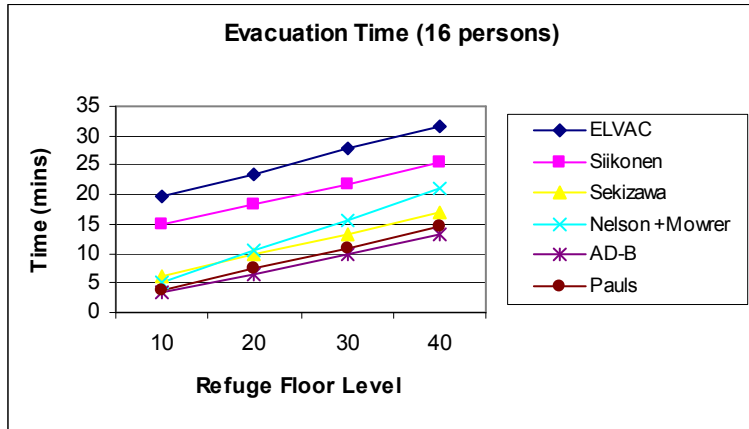


### 10 Storey Interval – Variable Acceleration

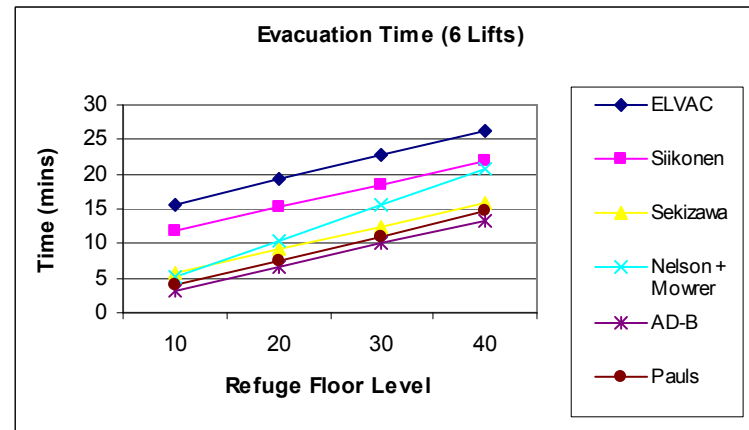
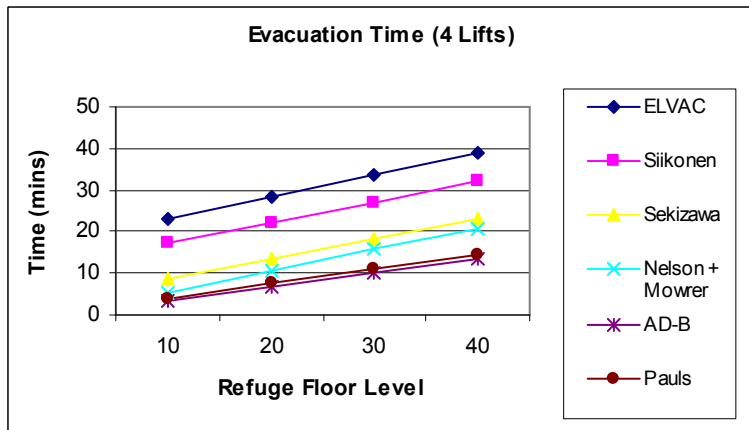


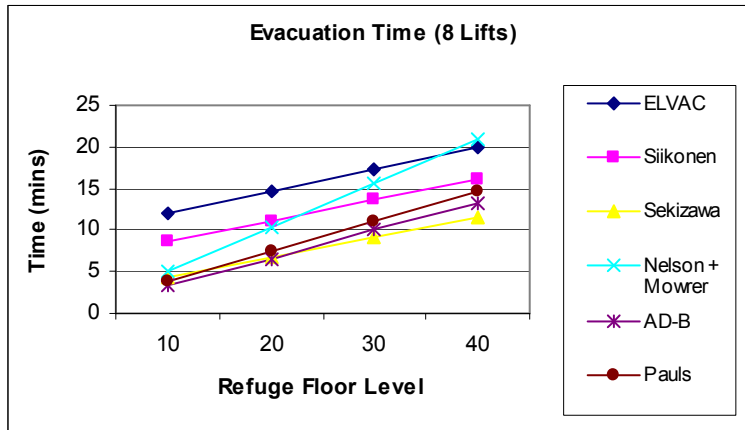
### 10 Storey Interval – Variable Capacity



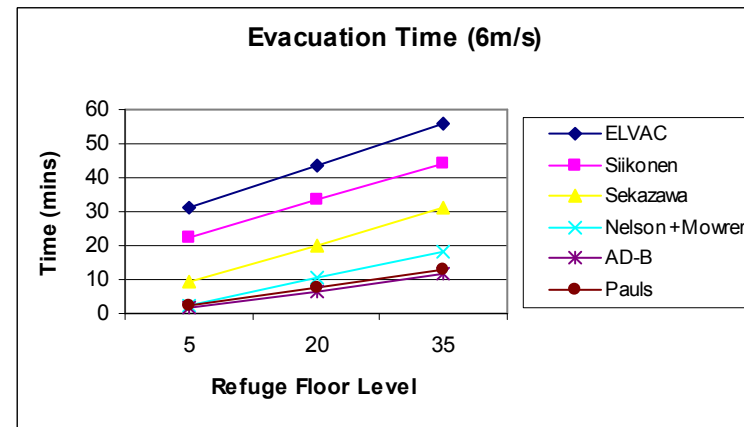
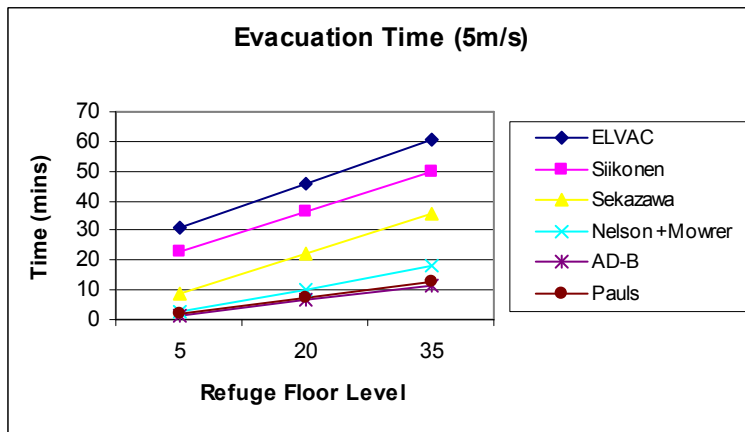


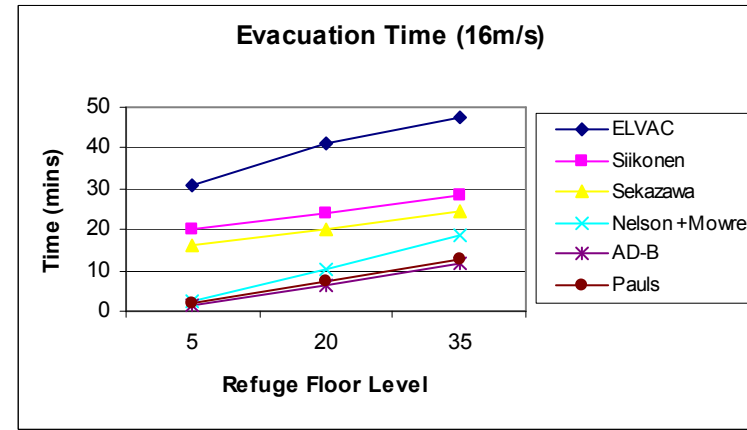
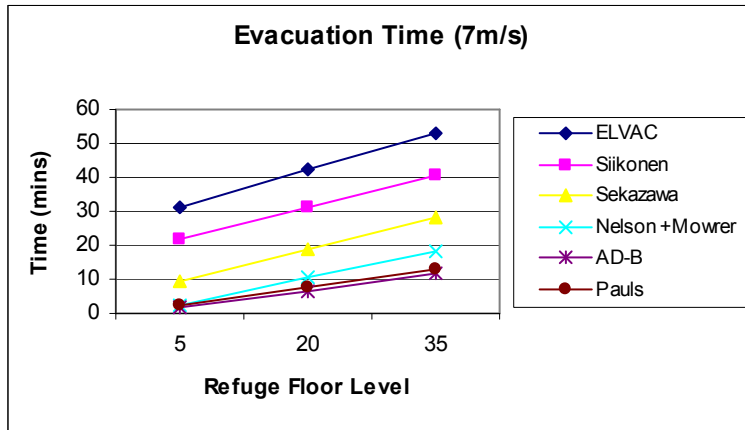
## 10 Storey Interval – Variable Lifts



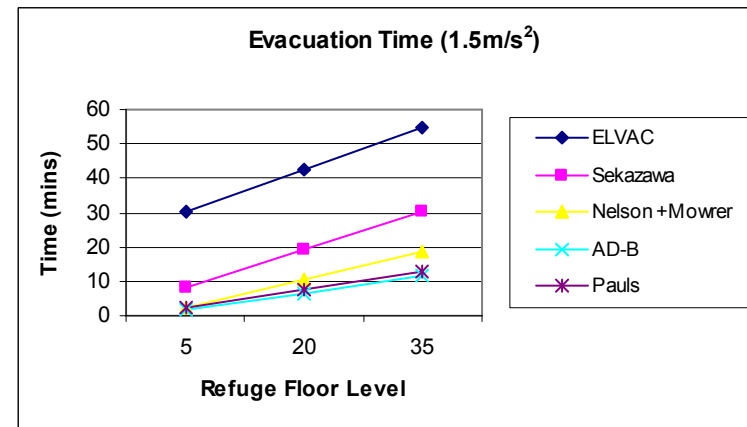
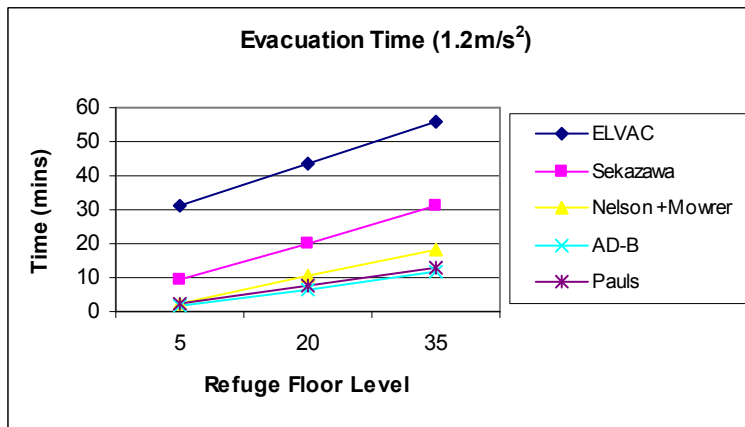


### 15 Storey Interval – Variable Speed



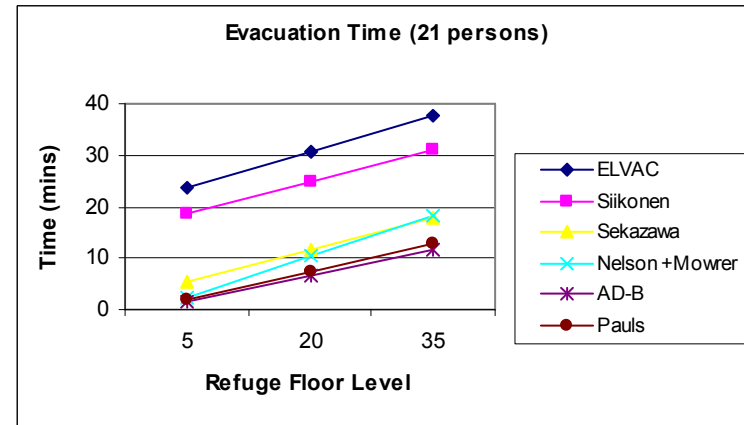
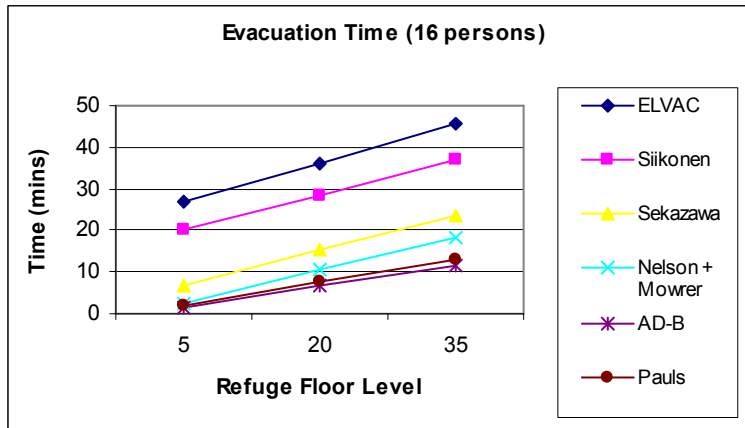
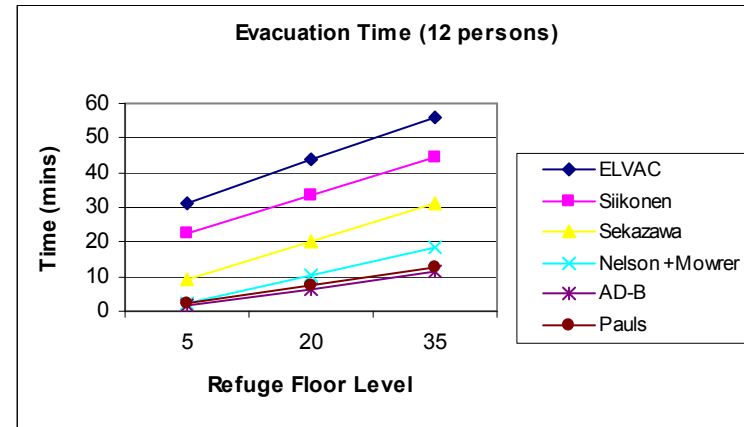
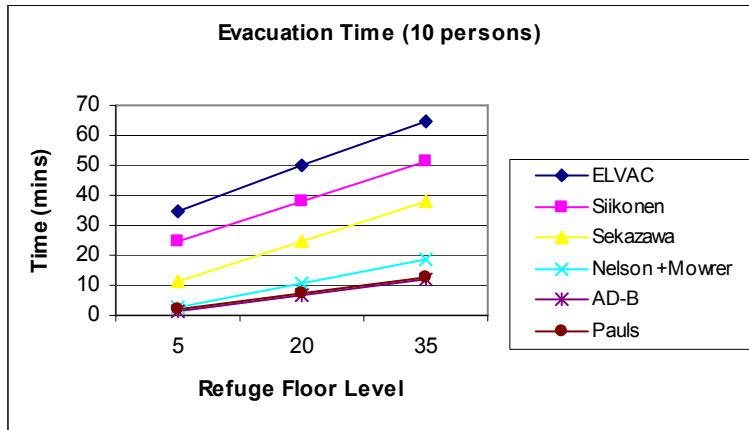


### 15 Storey Interval – Variable Acceleration

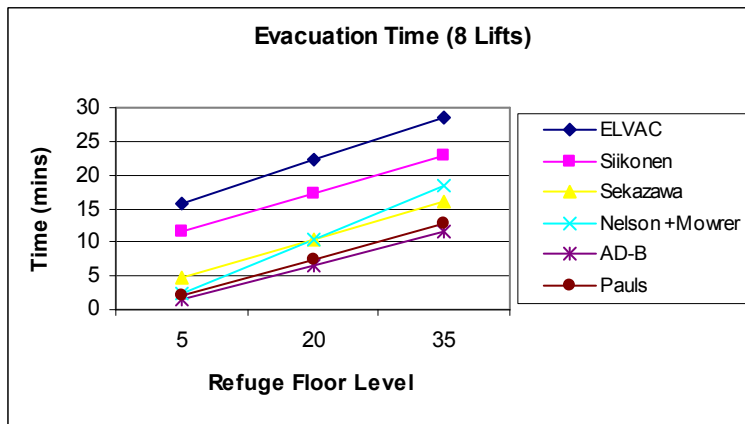
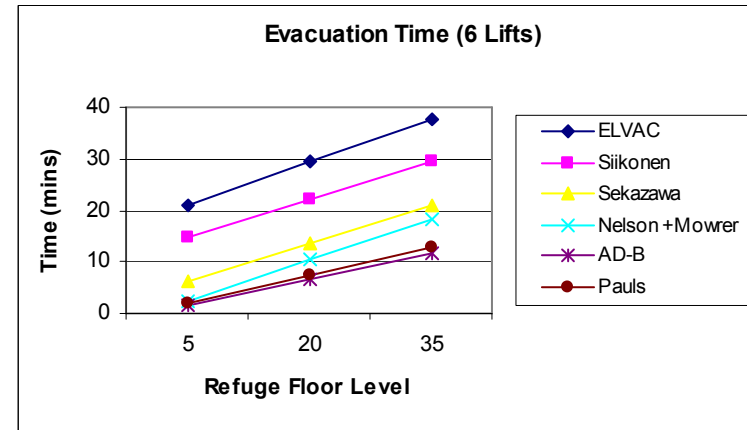
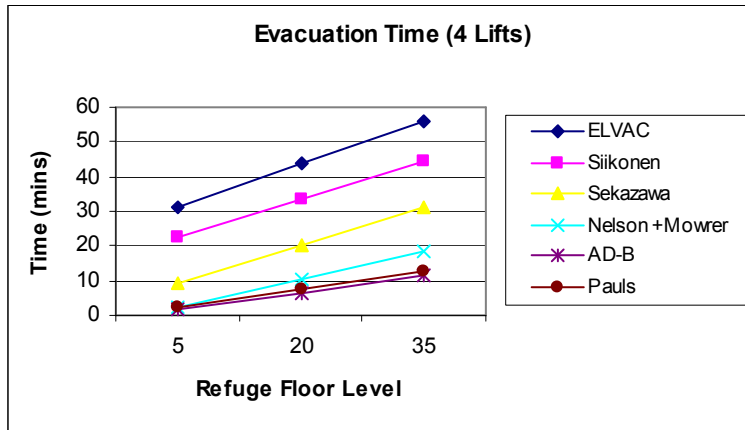




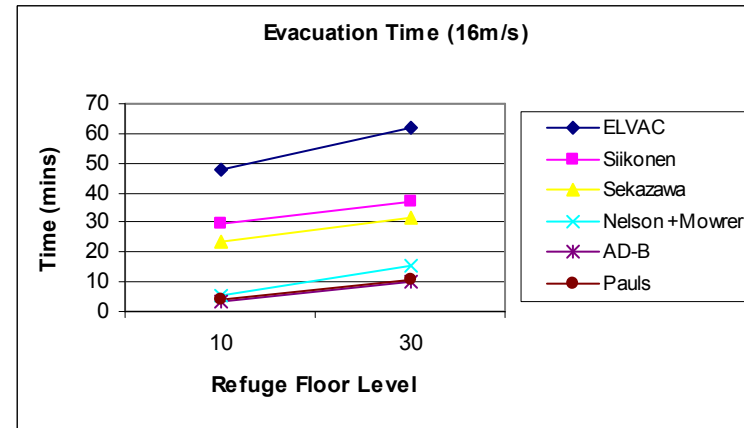
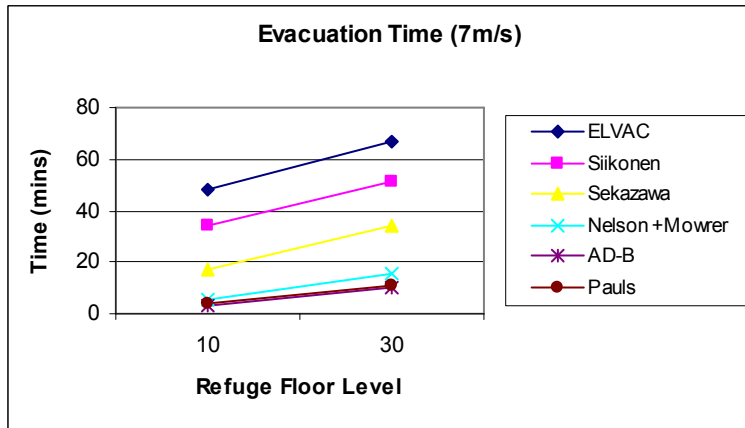
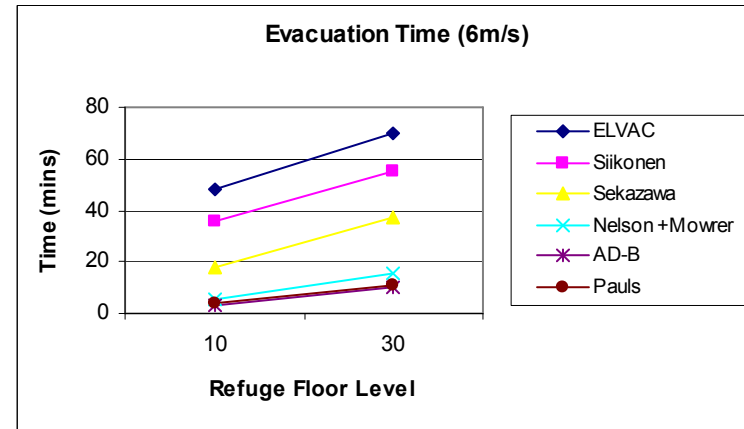
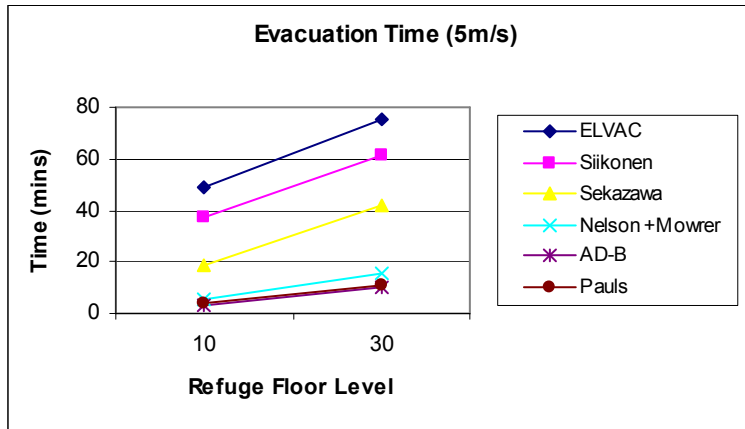
### 15 Storey Interval – Variable Capacity



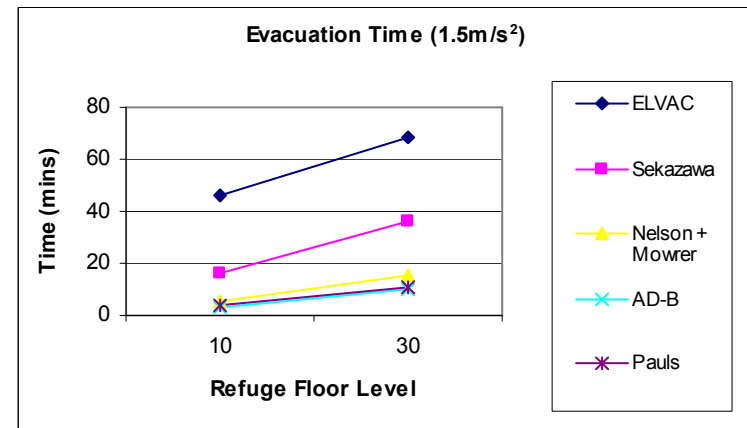
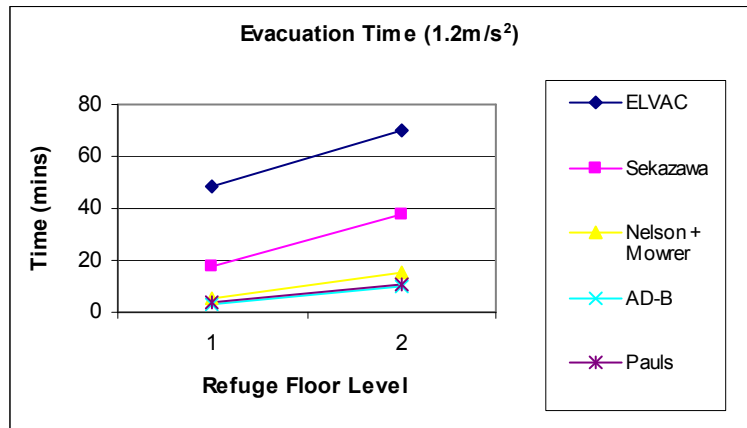
### 15 Storey Interval – Variable Lifts



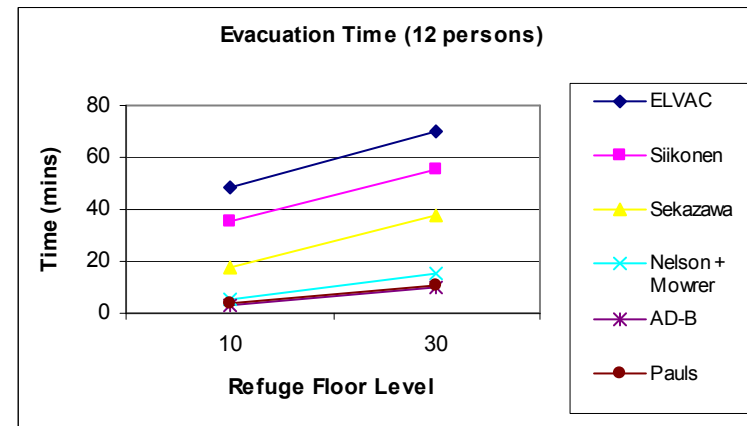
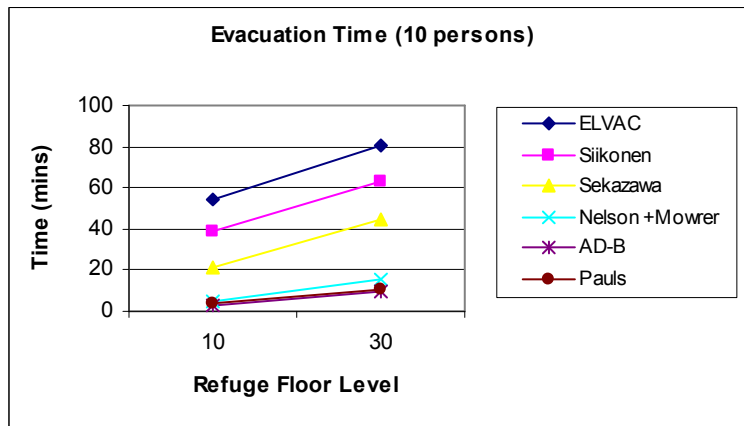
## 20 Storey Interval – Variable Speed

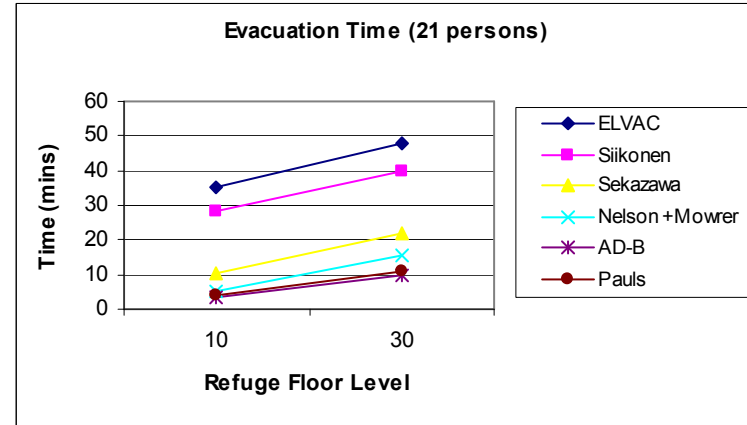
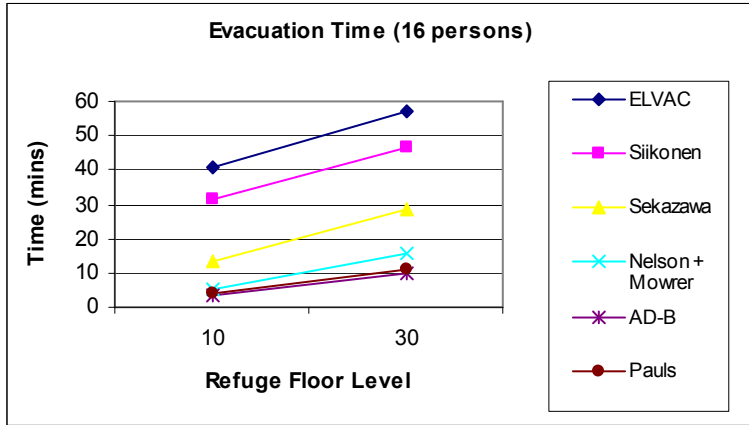


### 20 Storey Interval – Variable Acceleration

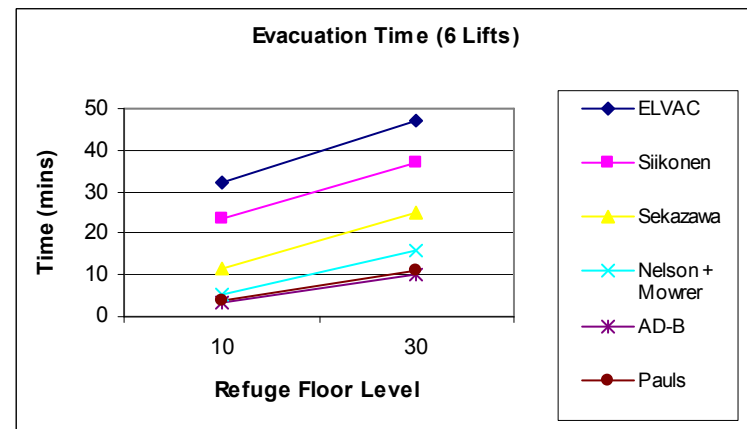
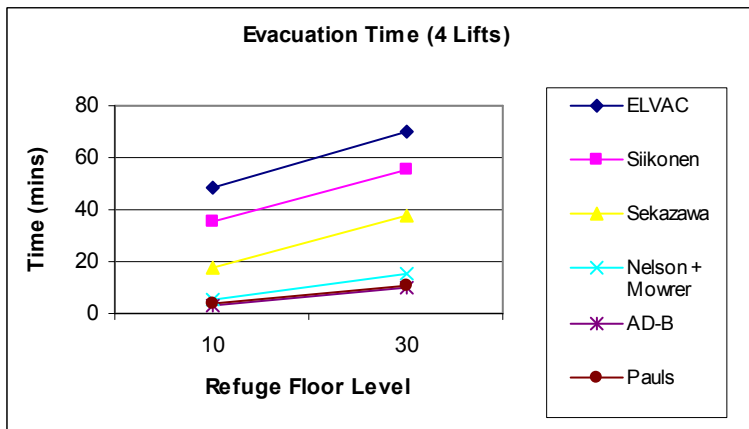


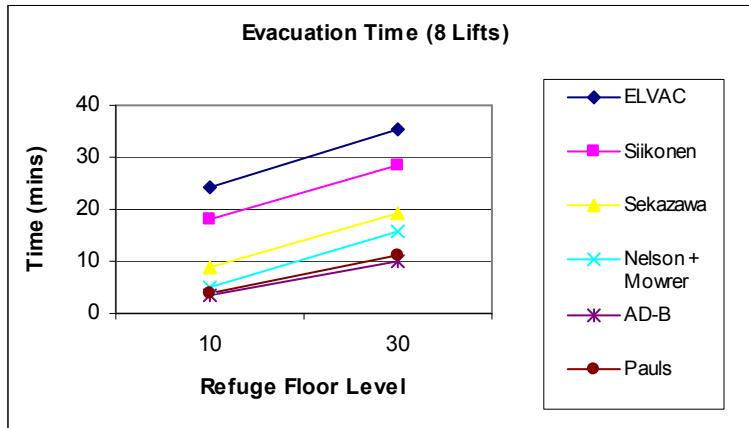
### 20 Storey Interval – Variable Capacity



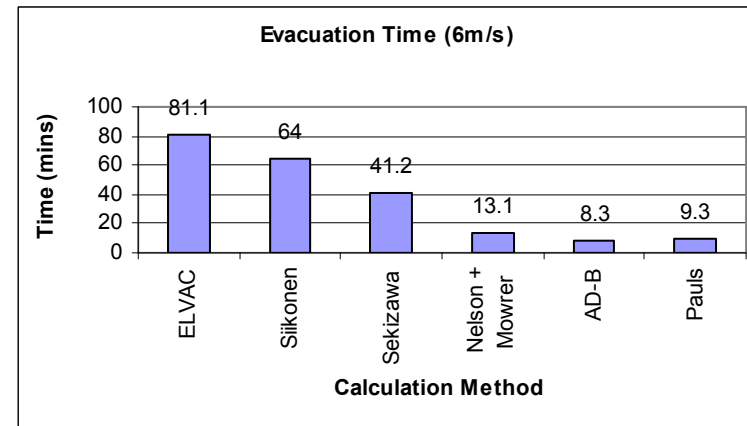
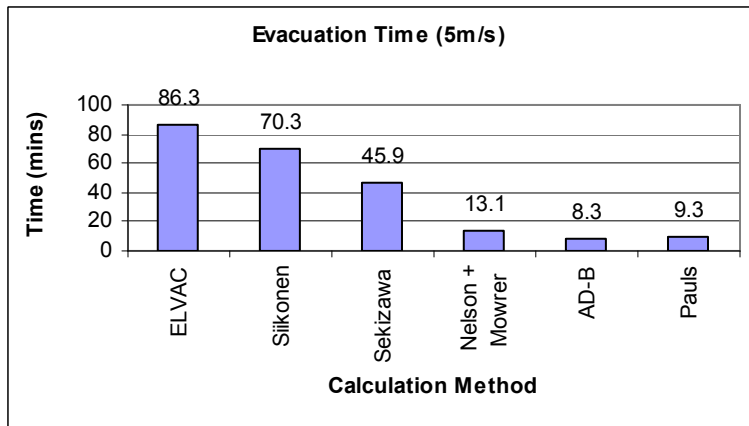


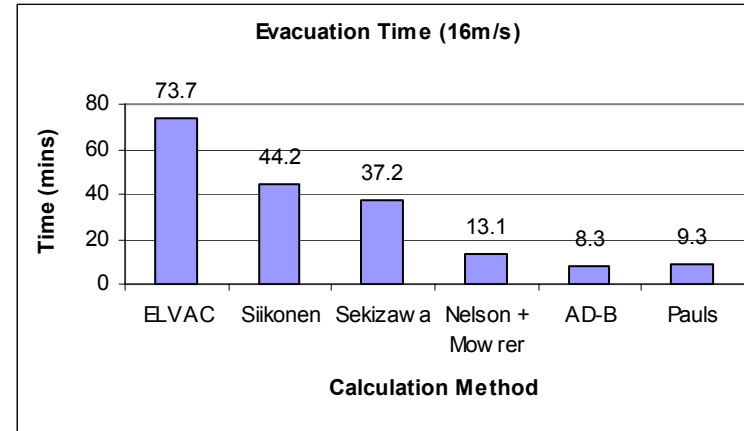
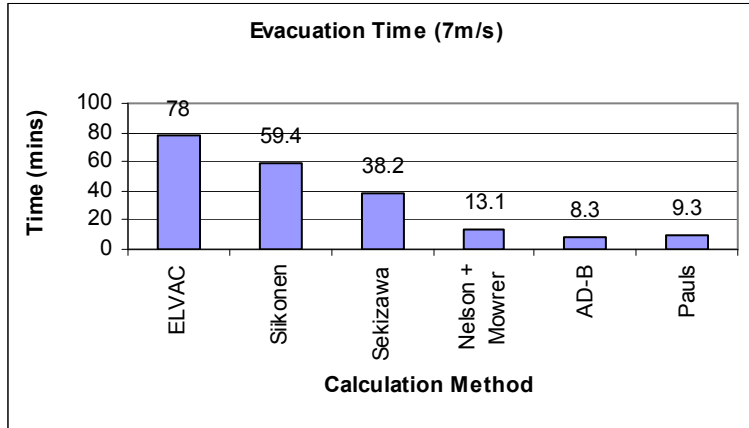
## 20 Storey Interval – Variable Lifts



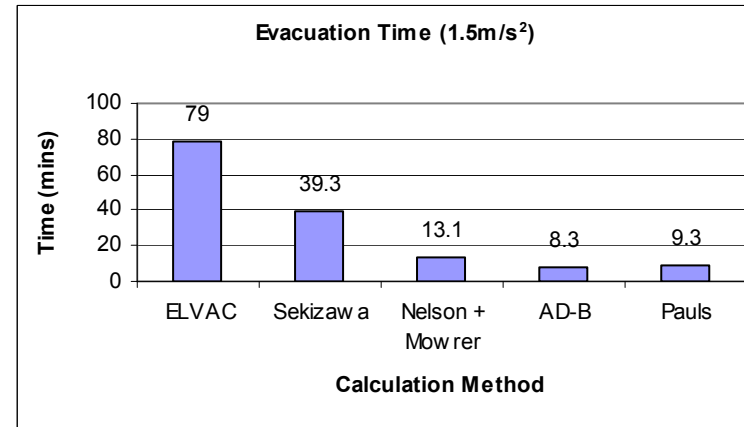
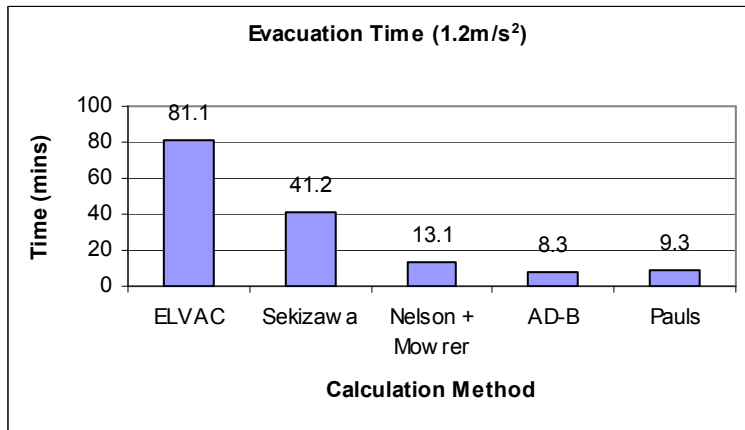


25 Storey Interval – Variable Speed

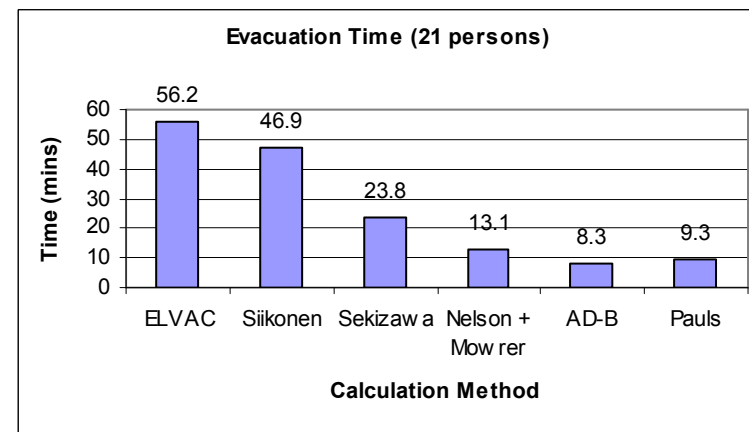
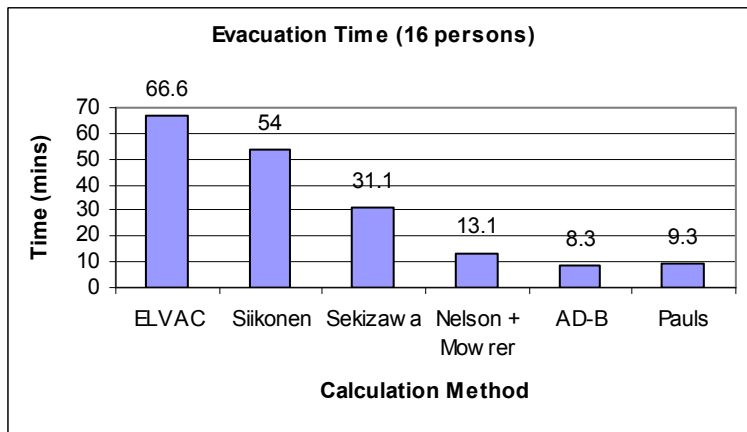
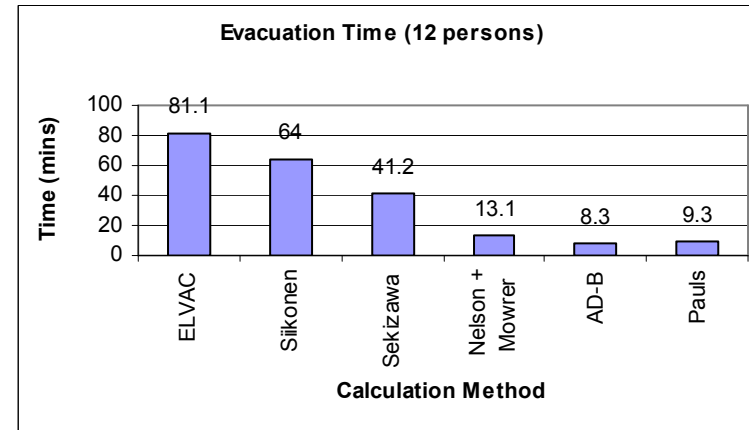
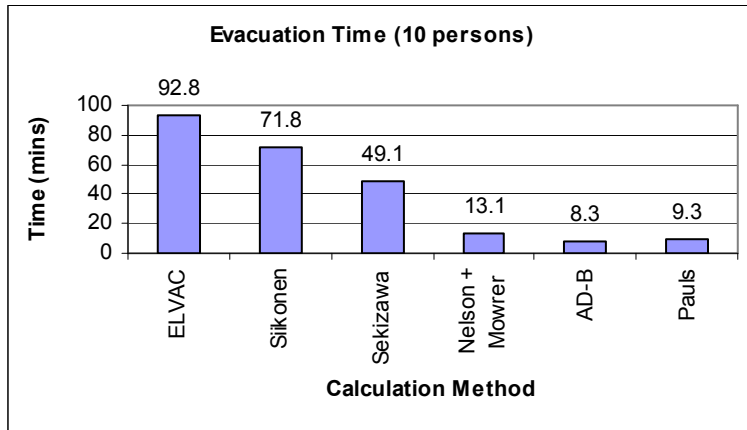




**25 Storey Interval – Variable Acceleration**

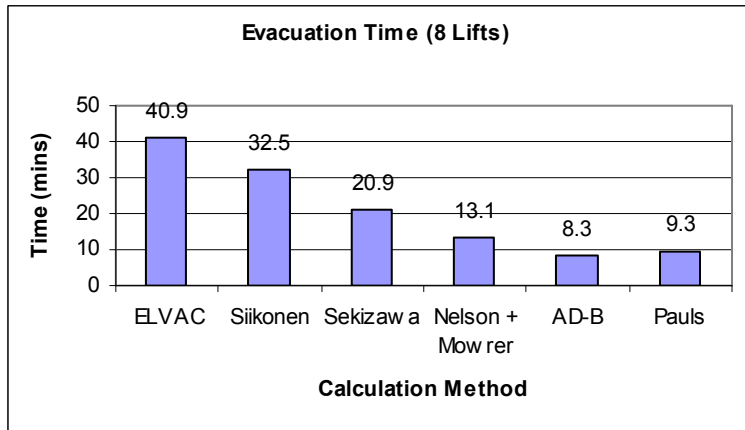
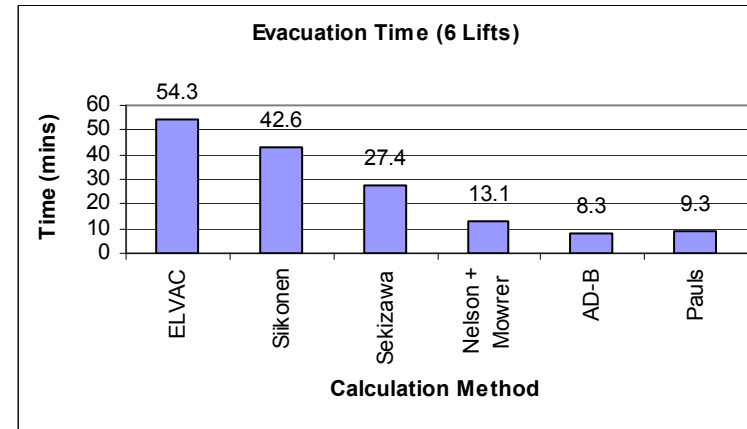
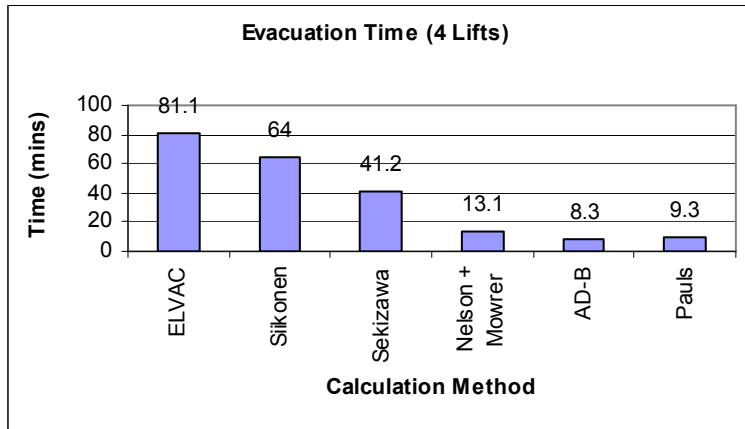


## 25 Storey Interval – Variable Capacity



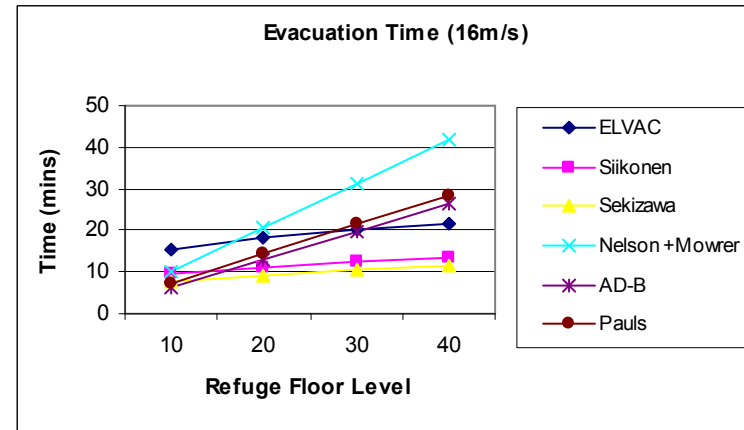
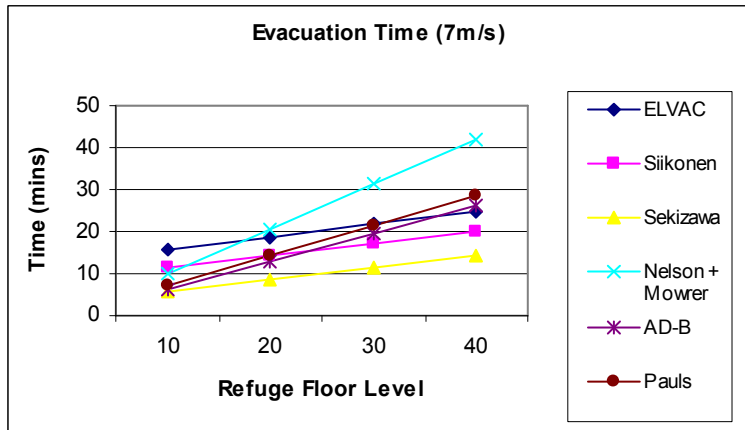
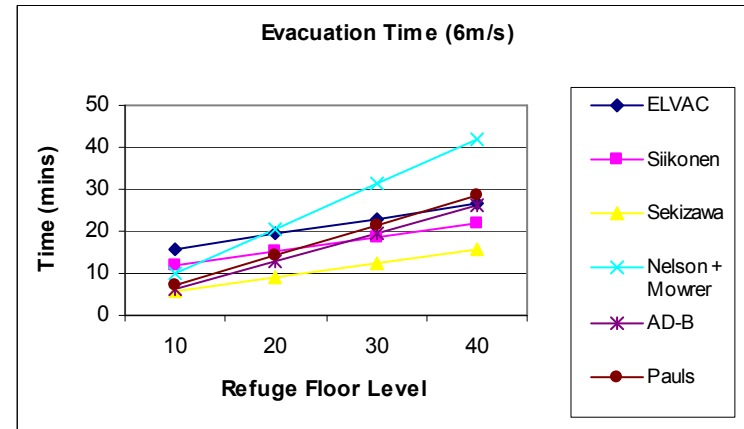
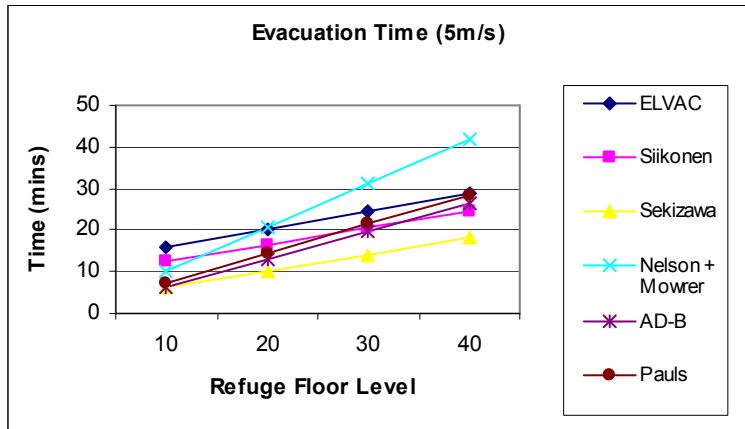


## 25 Storey Interval – Variable Lifts

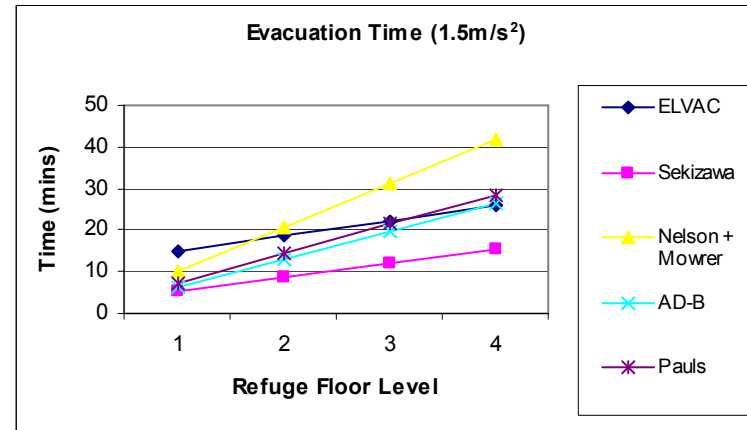
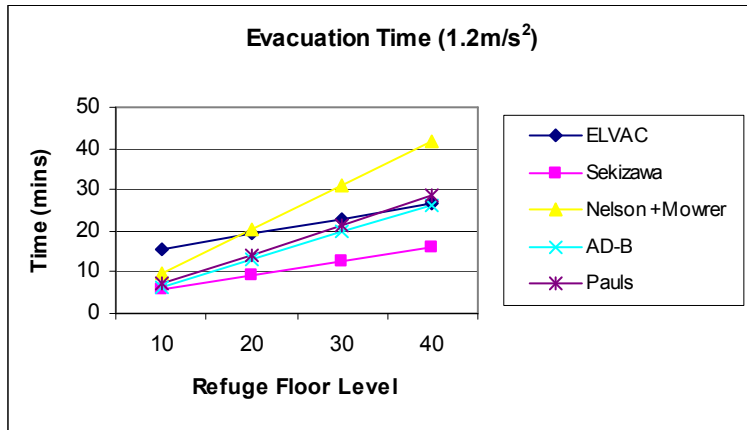


**APPENDIX C - EVACUATION TIME USING REFUGE FLOORS (50% LIFT USAGE)**

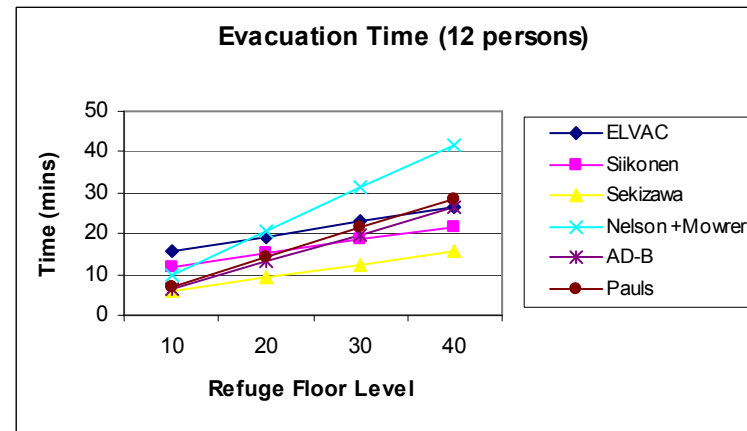
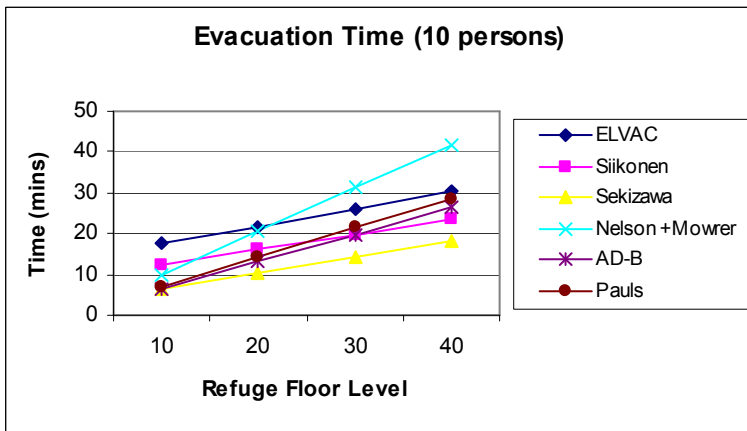
### 10 Storey Interval – Variable Speed

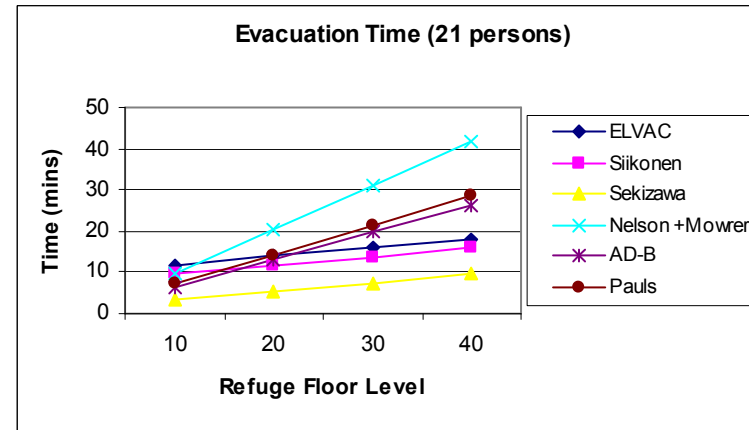
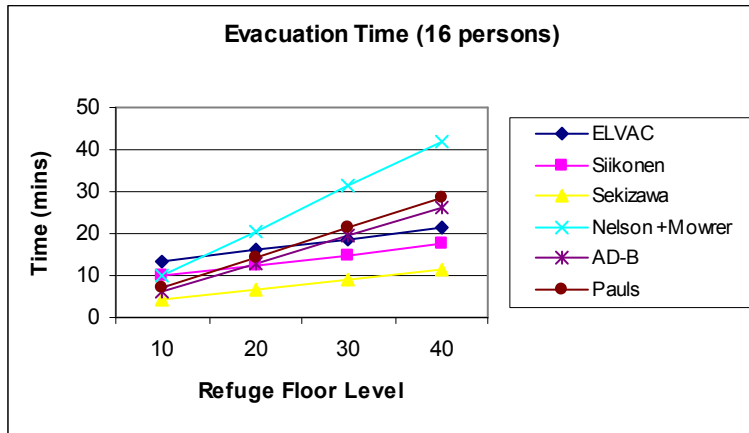


### 10 Storey Interval – Variable Acceleration

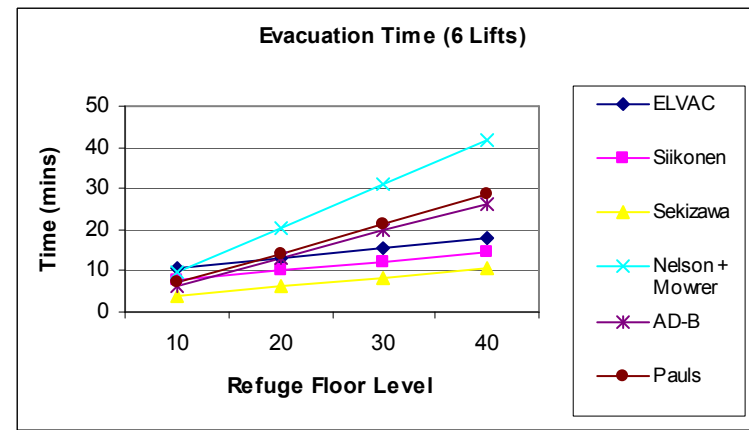
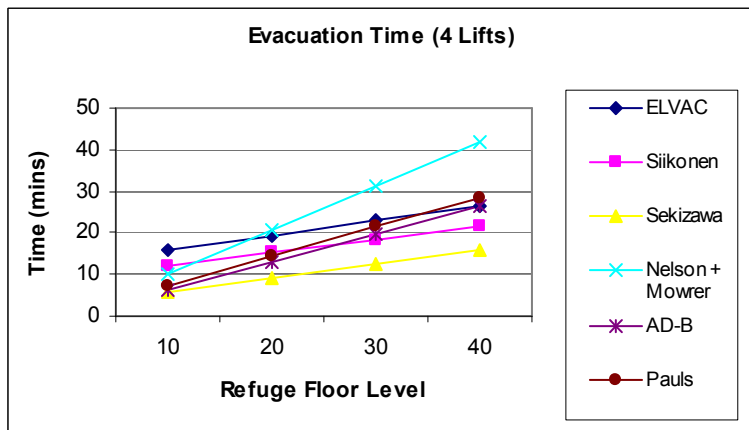


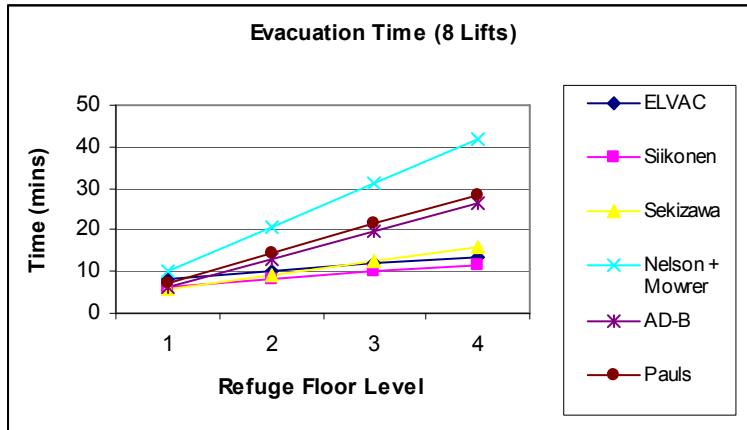
### 10 Storey Interval – Variable Capacity



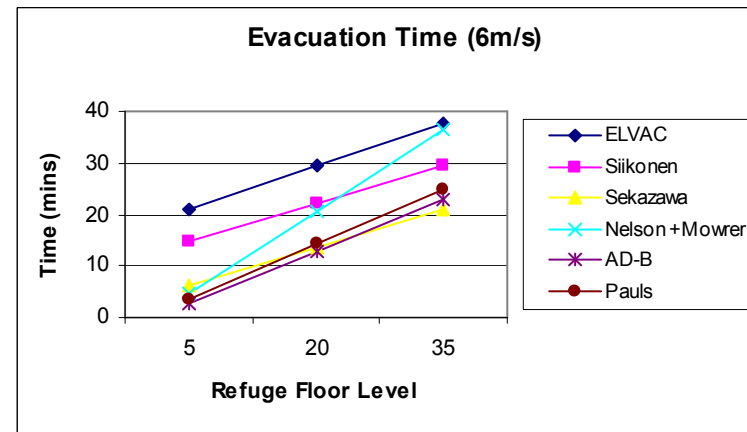
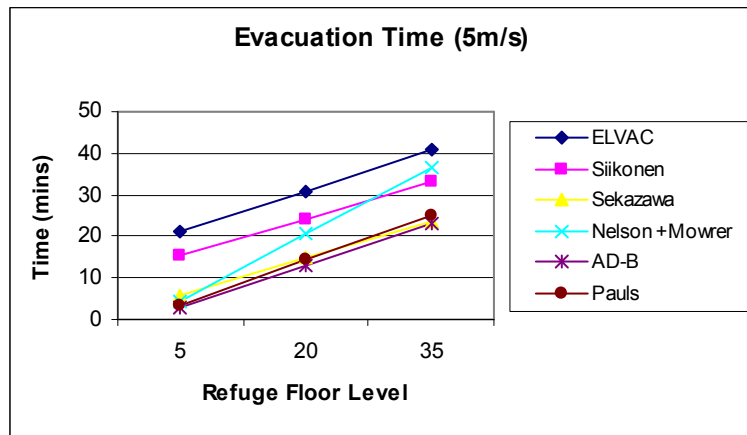


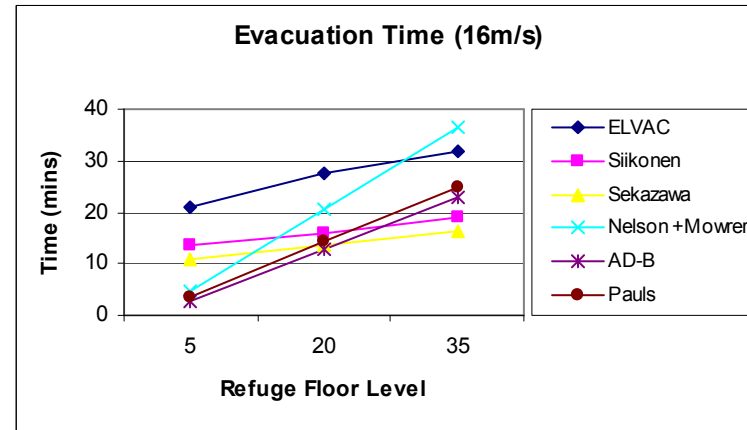
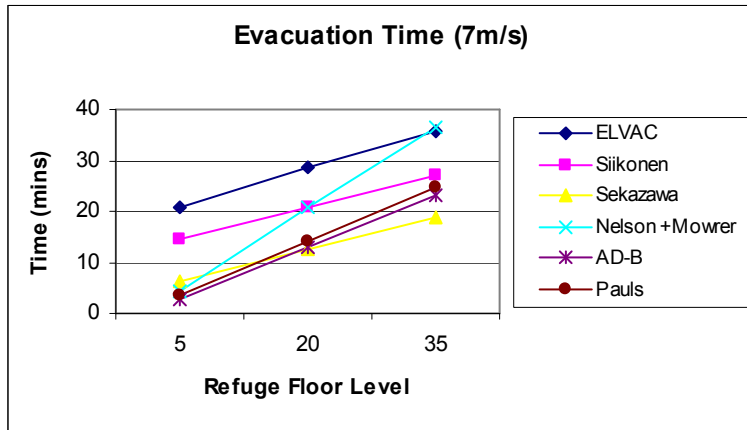
## 10 Storey Interval – Variable Lifts



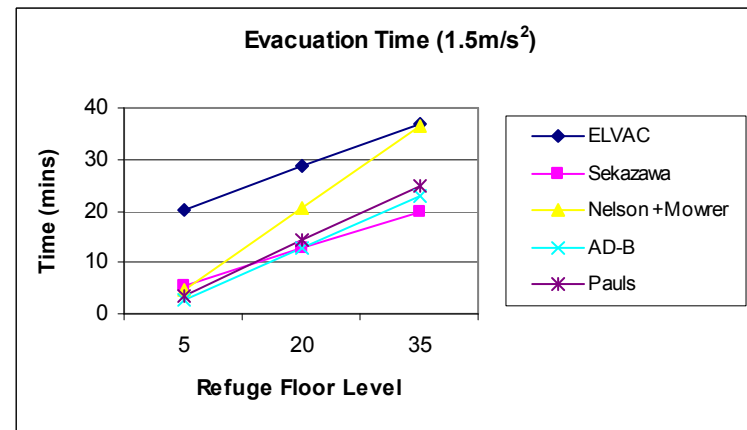
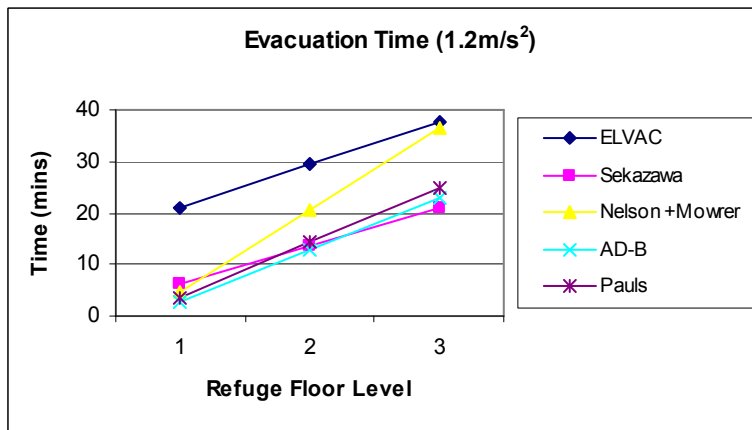


### 15 Storey Interval – Variable Speed

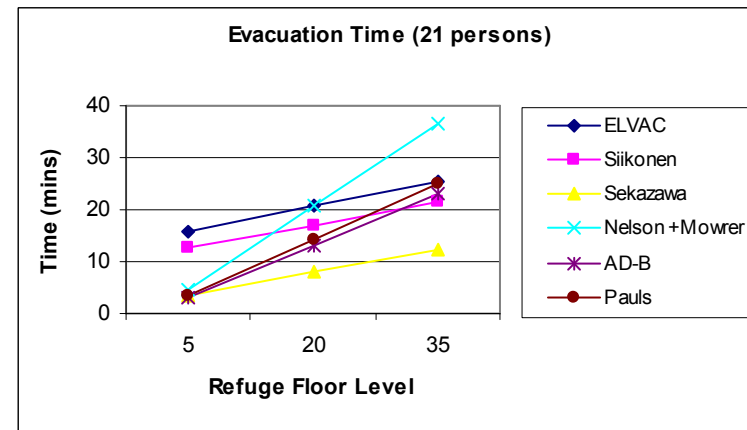
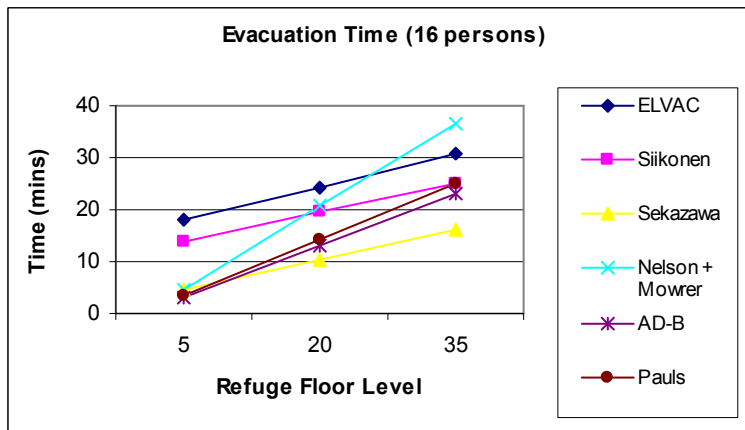
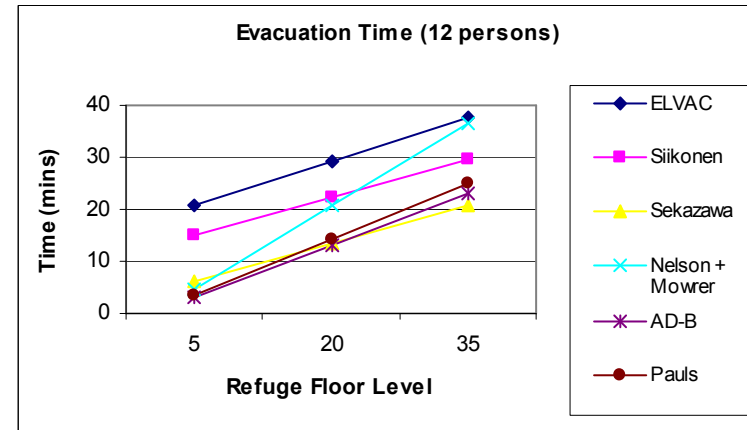
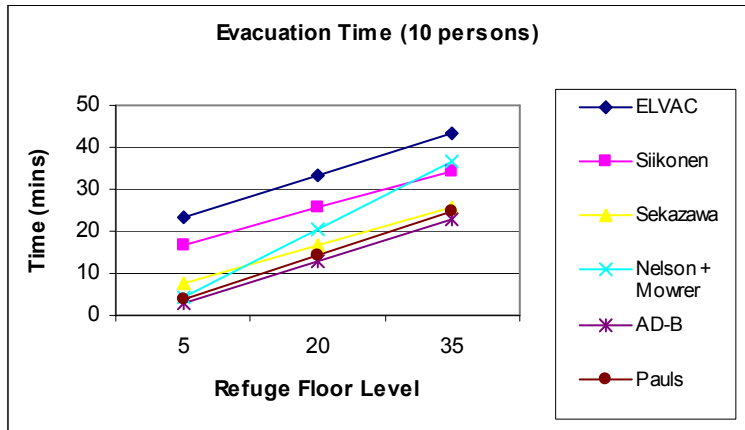




### 15 Storey Interval – Variable Acceleration

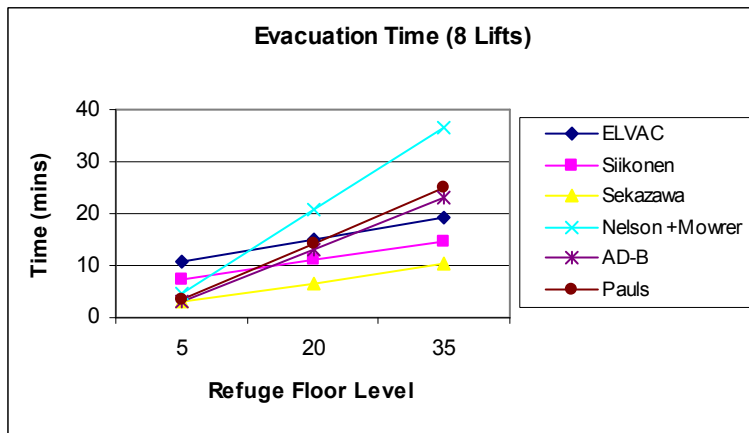
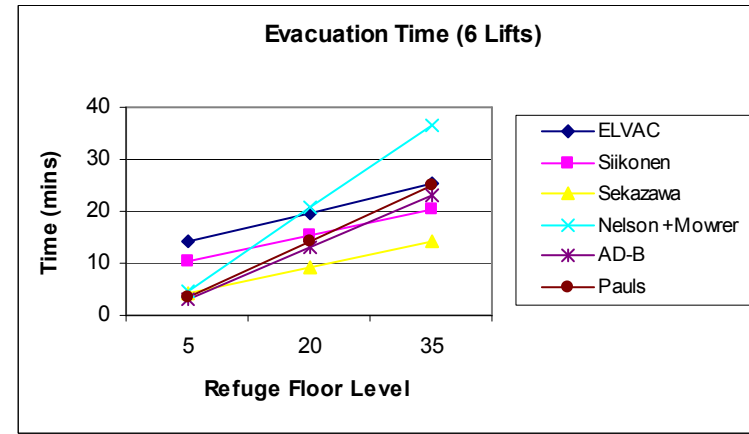
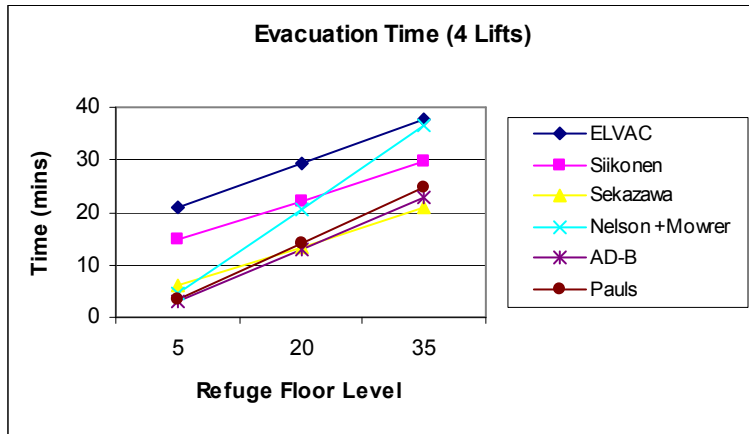


### 15 Storey Interval – Variable Capacity

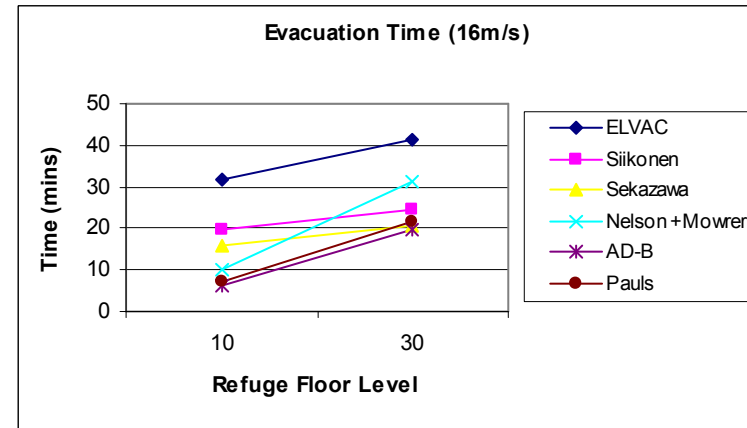
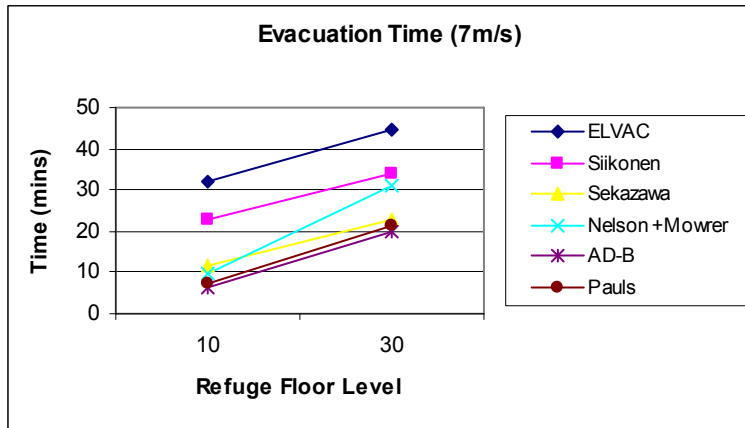
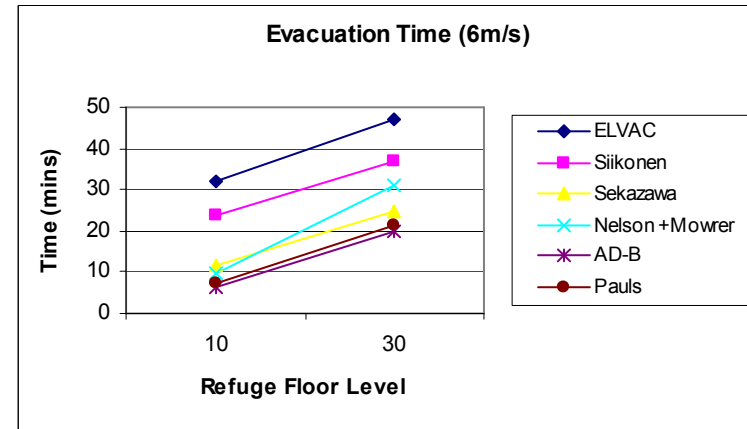
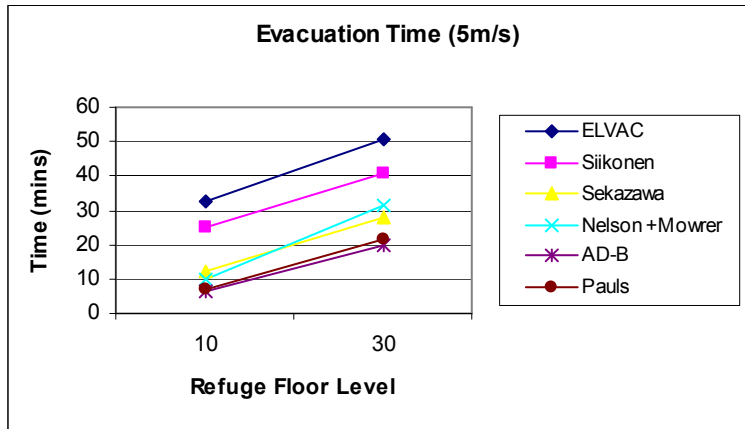




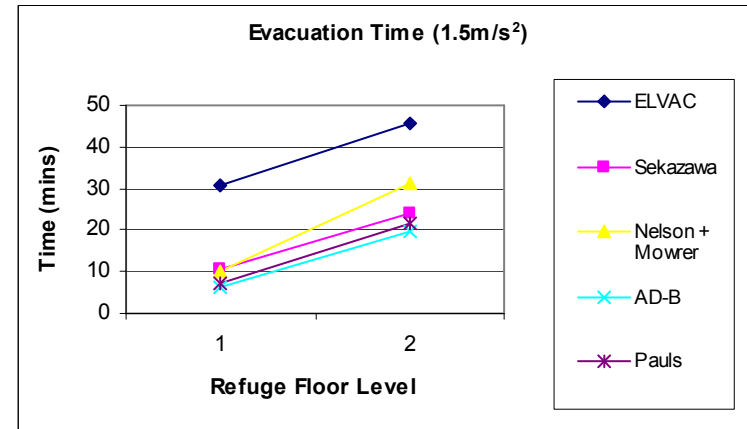
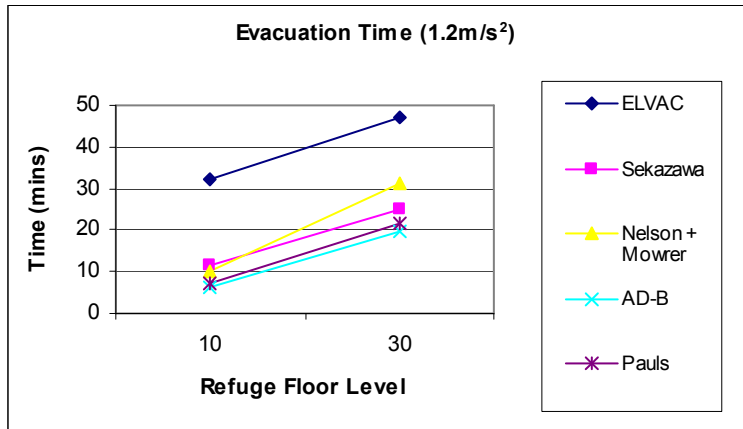
### 15 Storey Interval – Variable Lifts



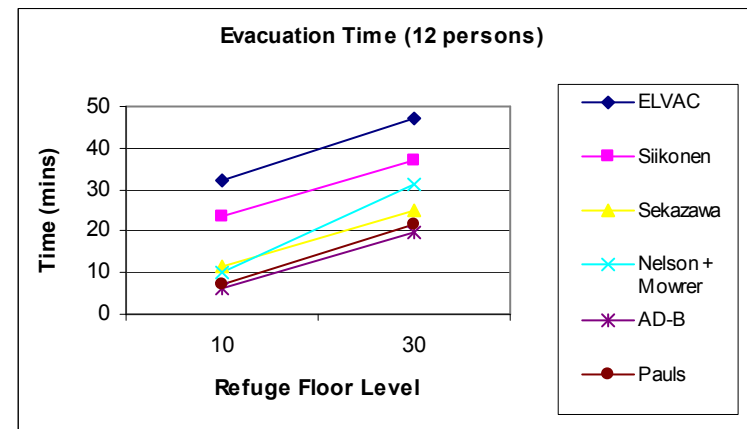
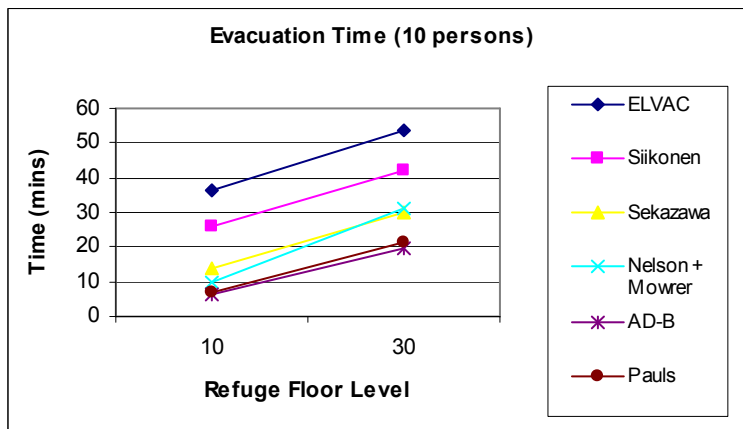
## 20 Storey Interval – Variable Speed

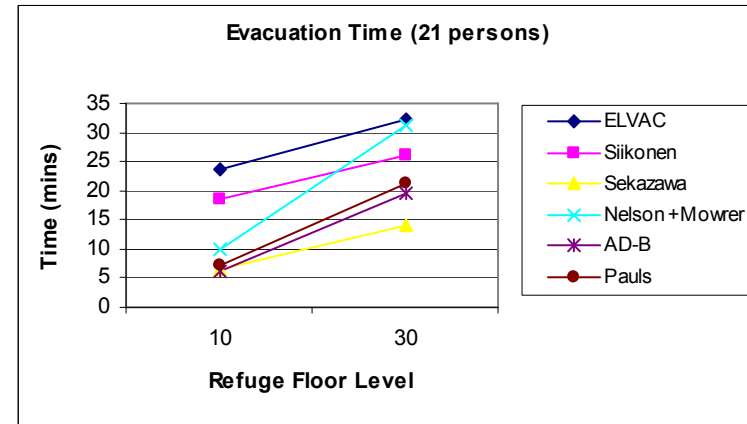
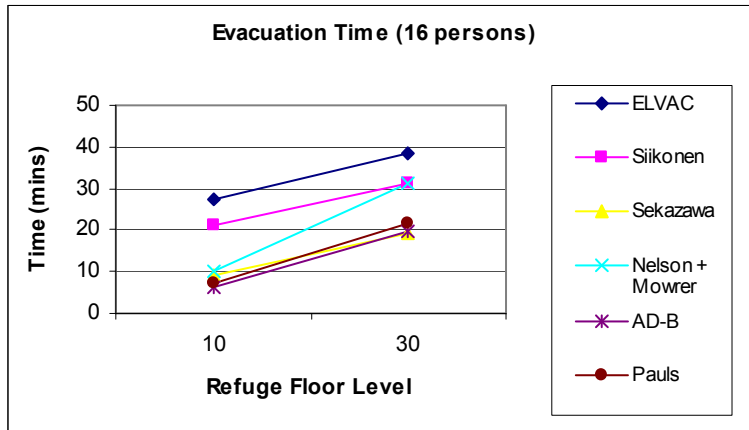


### 20 Storey Interval – Variable Acceleration

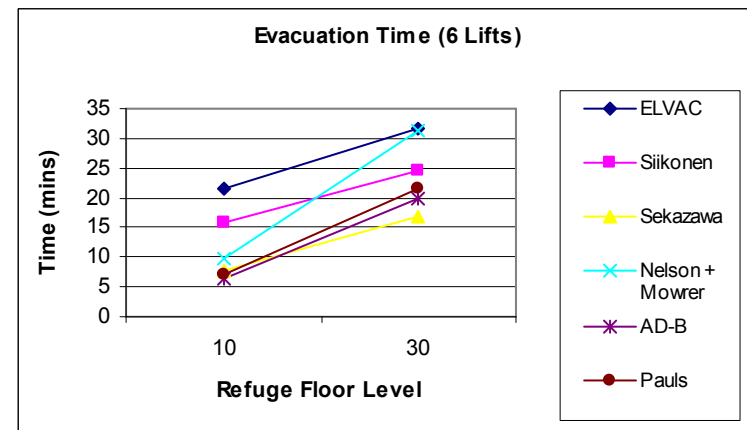
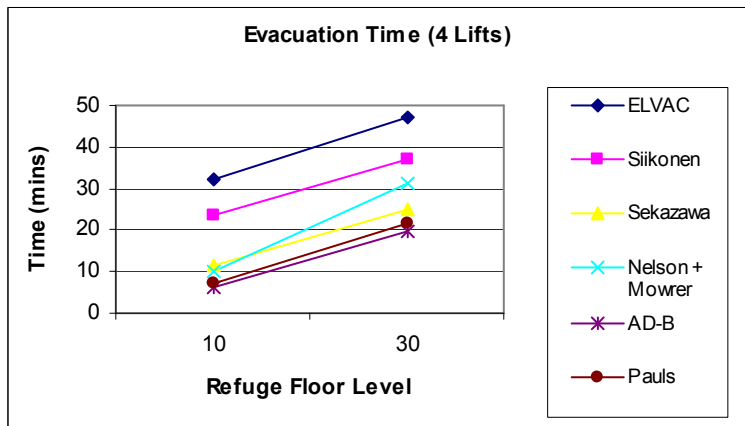


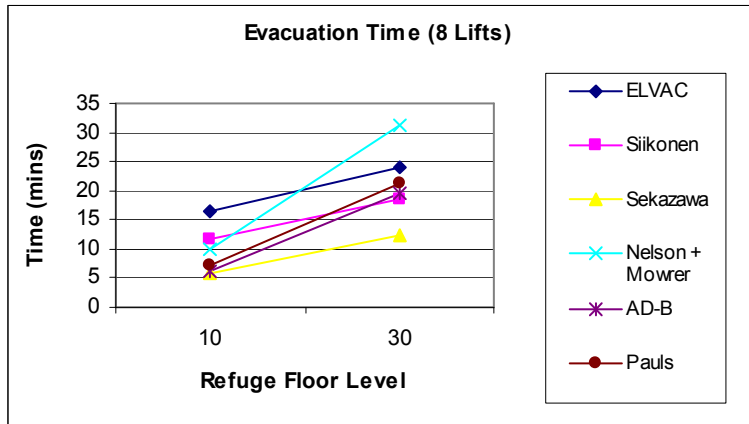
### 20 Storey Interval – Variable Capacity



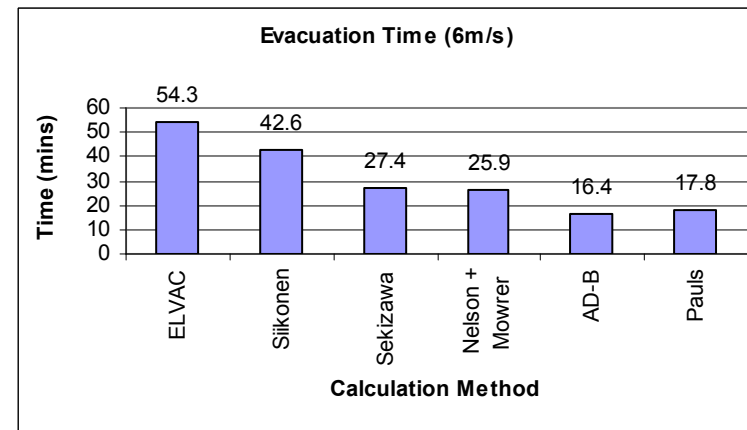
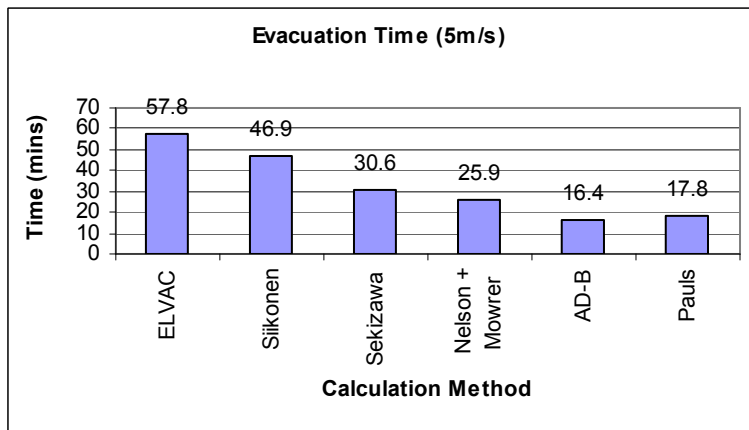


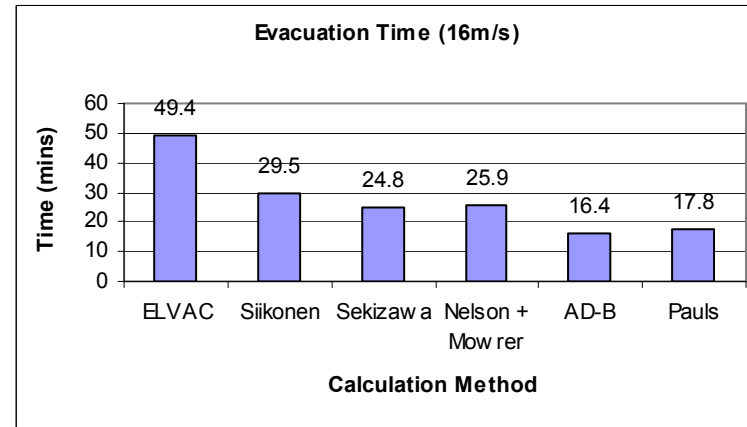
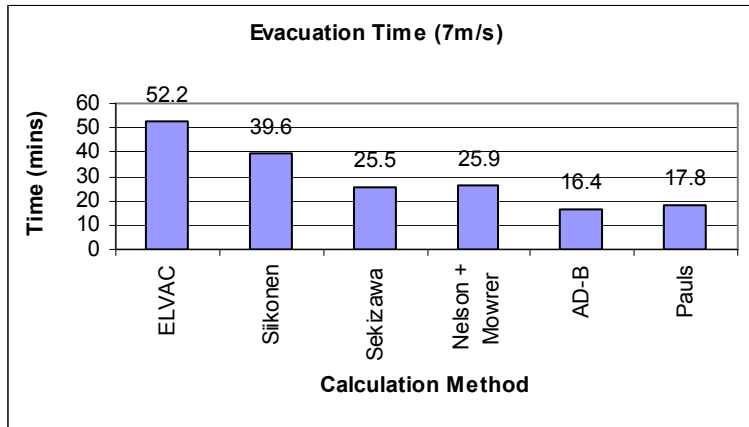
## 20 Storey Interval – Variable Lifts



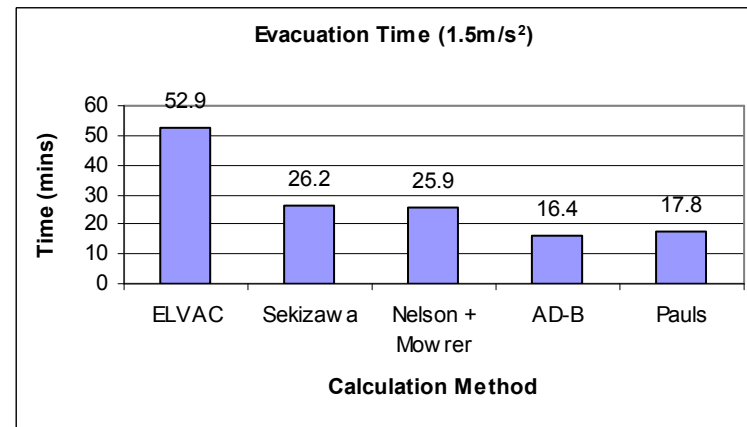
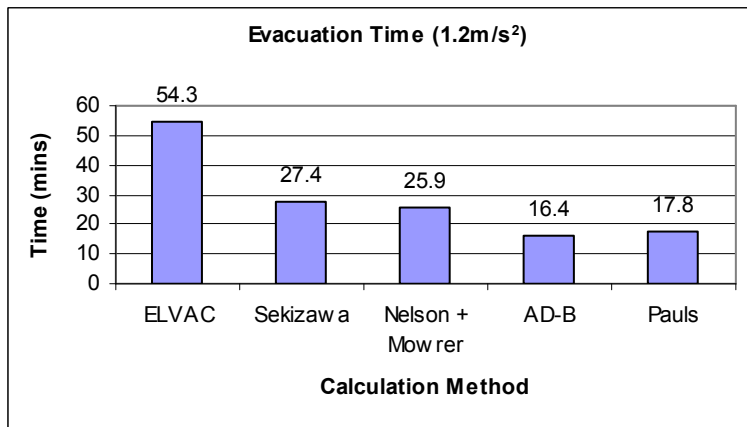


### 25 Storey Interval – Variable Speed

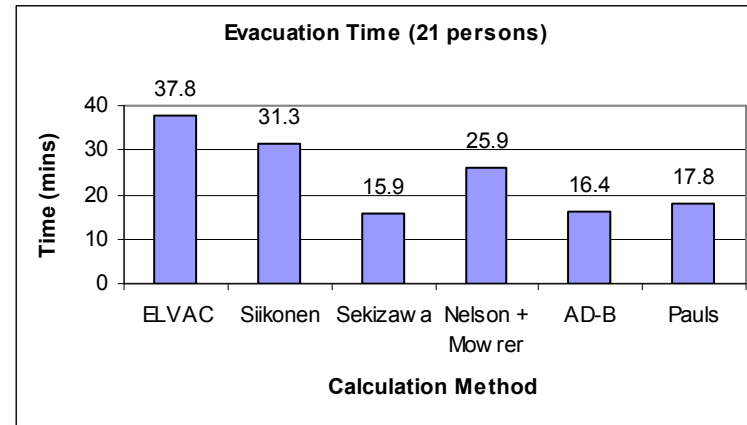
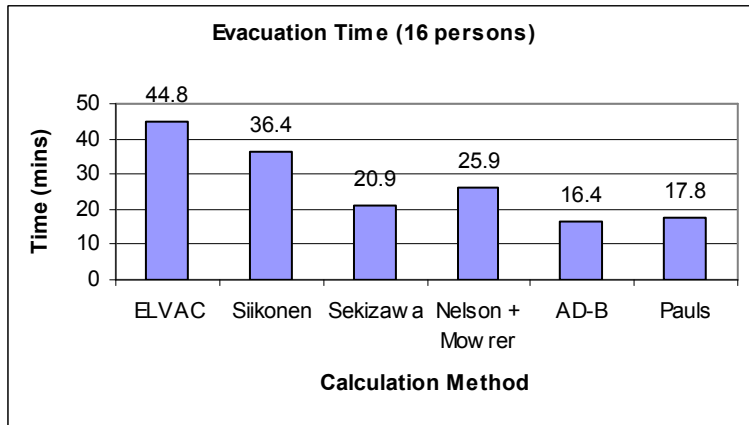
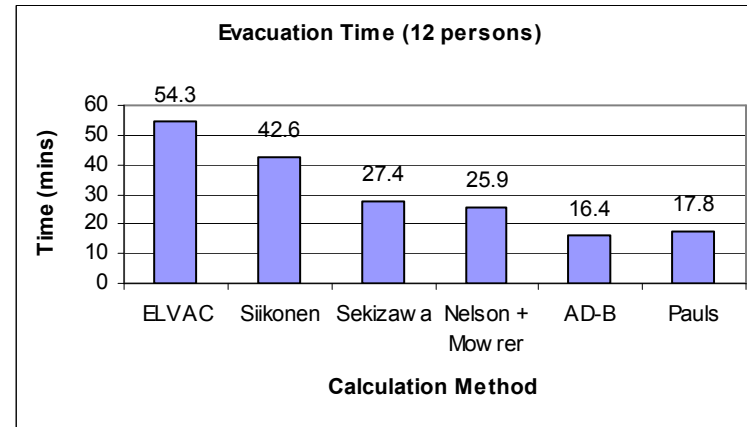
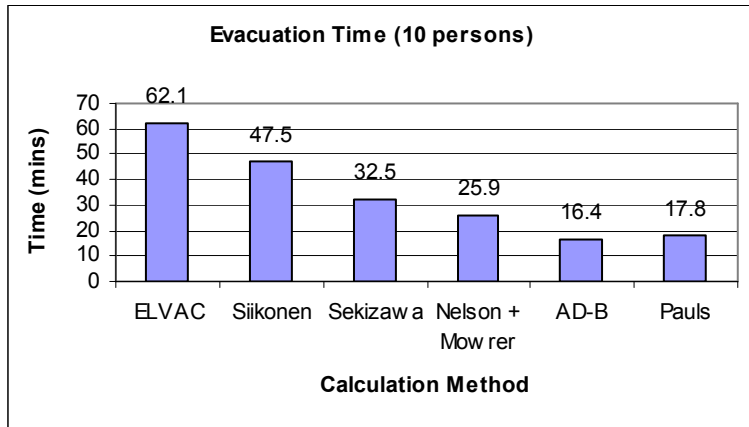




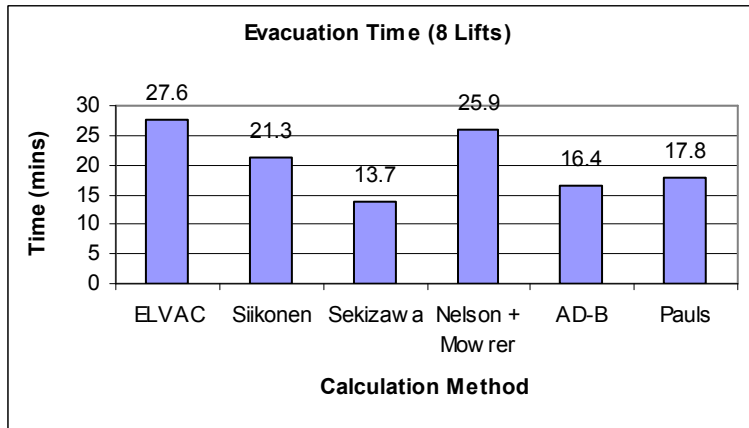
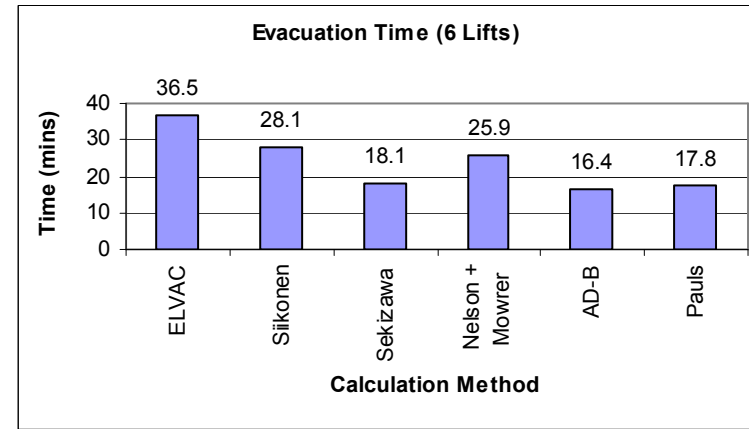
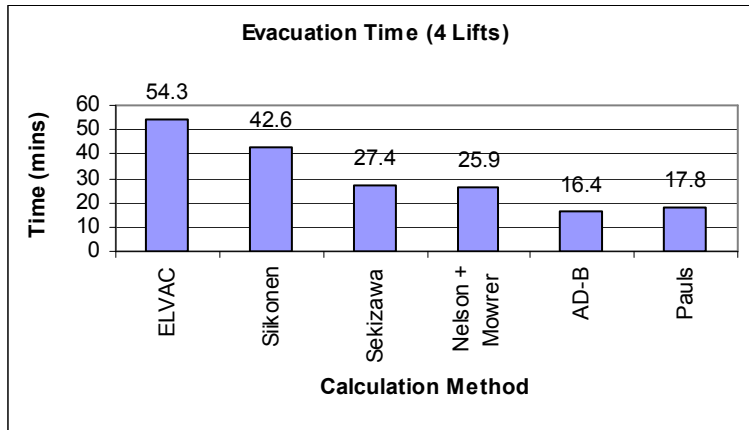
**25 Storey Interval – Variable Acceleration**



**25 Storey Interval – Variable Capacity**



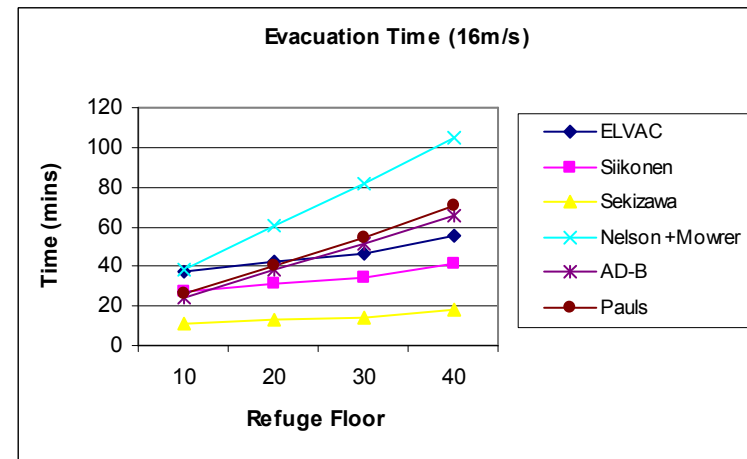
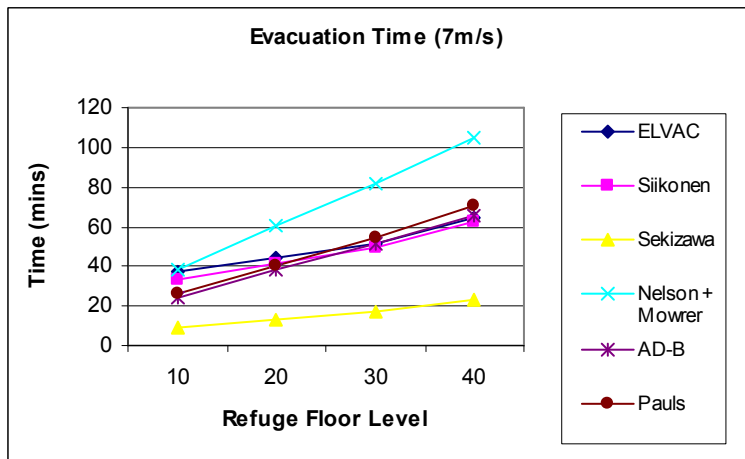
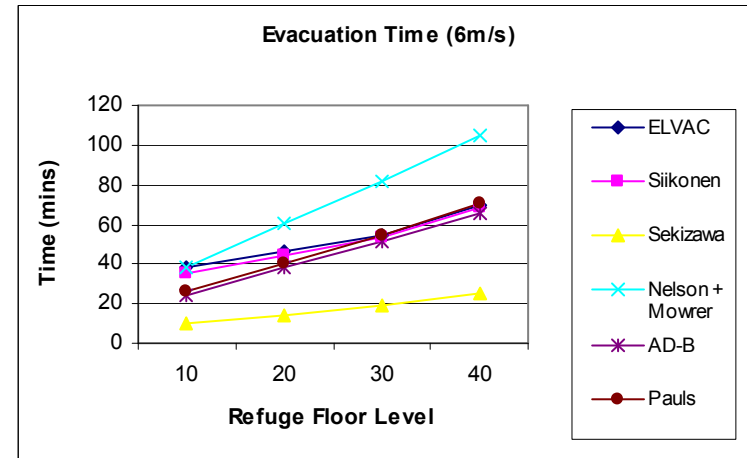
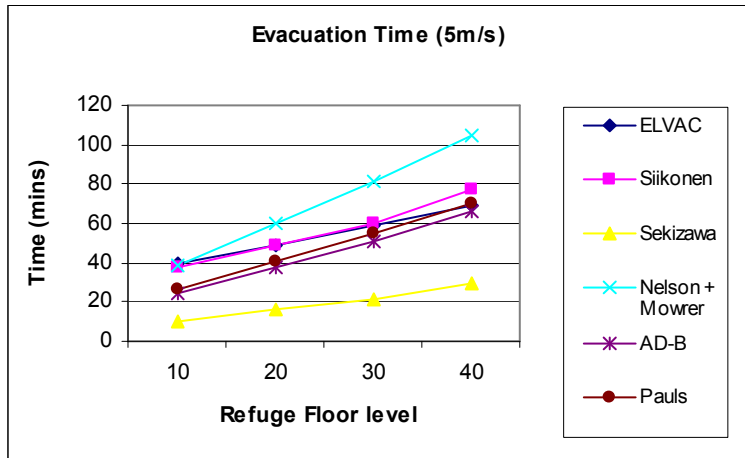
### 25 Storey Interval – Variable Lifts



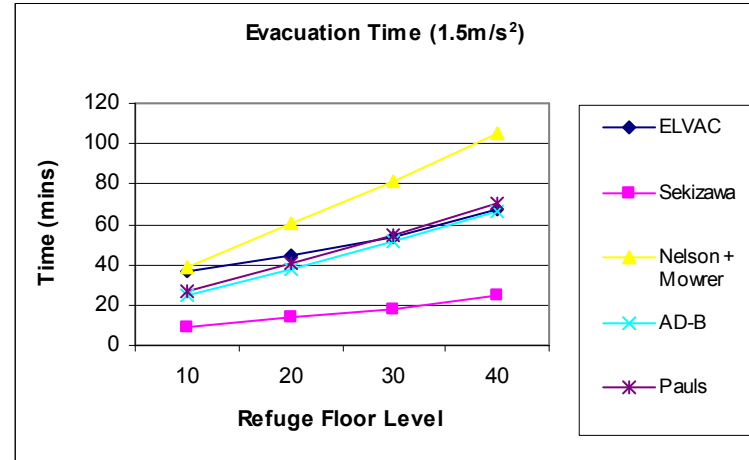
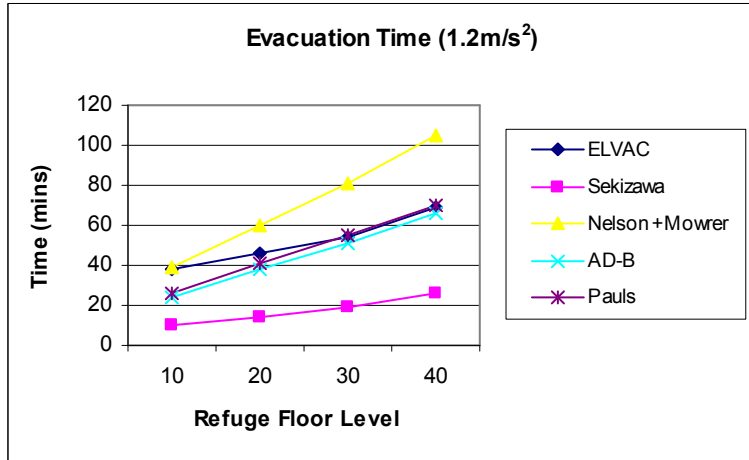


**APPENDIX D – EVACUATION FROM EVACUATION ZONE (100% LIFT USAGE)**

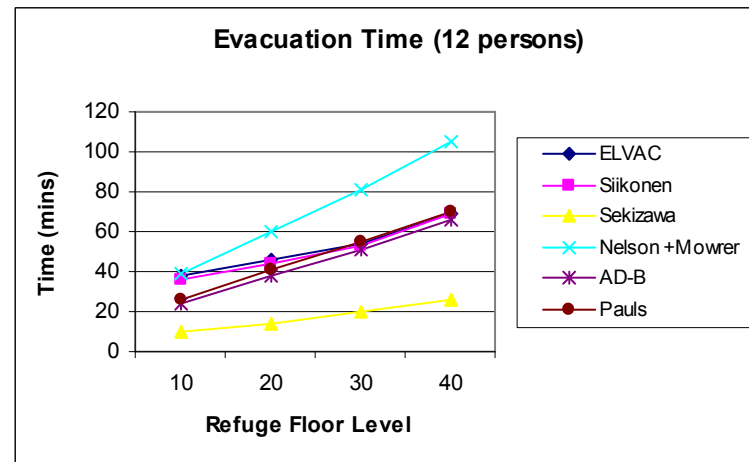
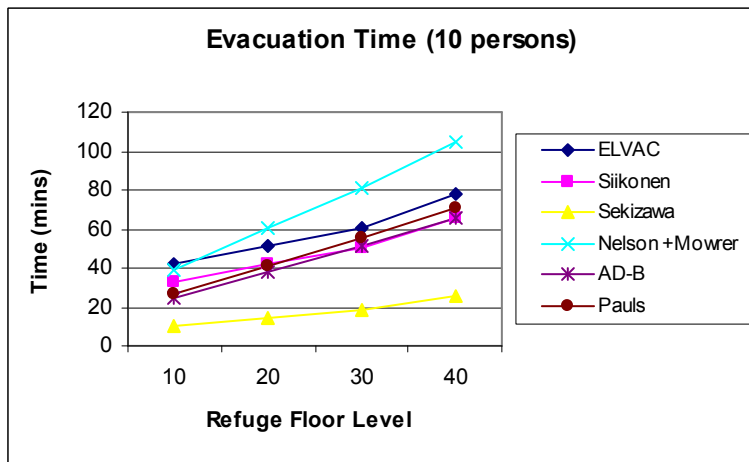
### 10 Storey Interval – Variable Speed

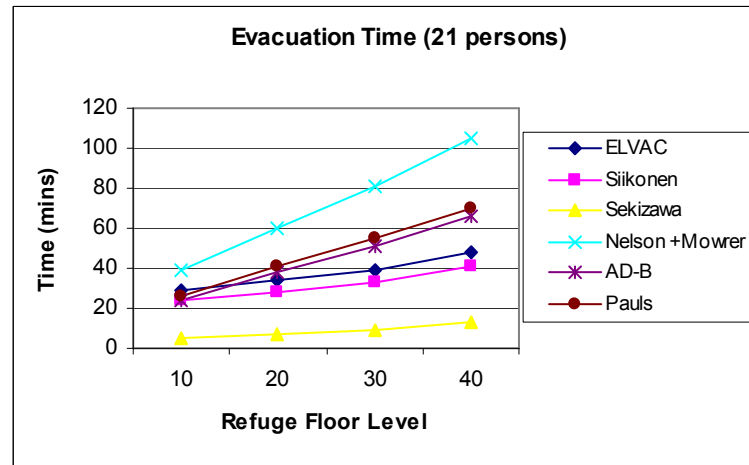
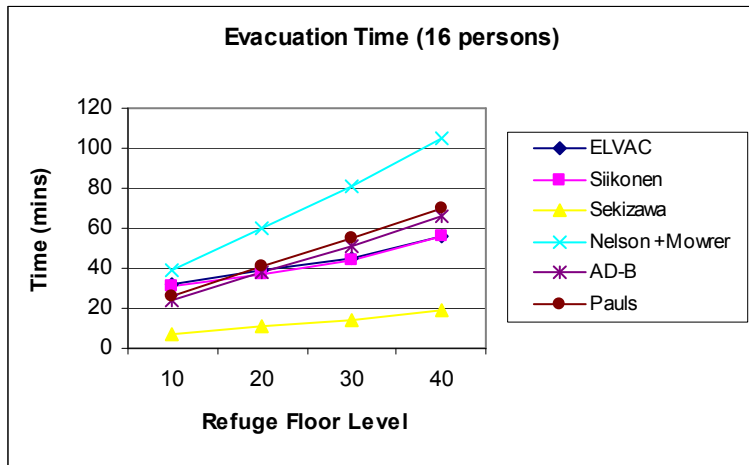


### 10 Storey Interval – Variable Acceleration

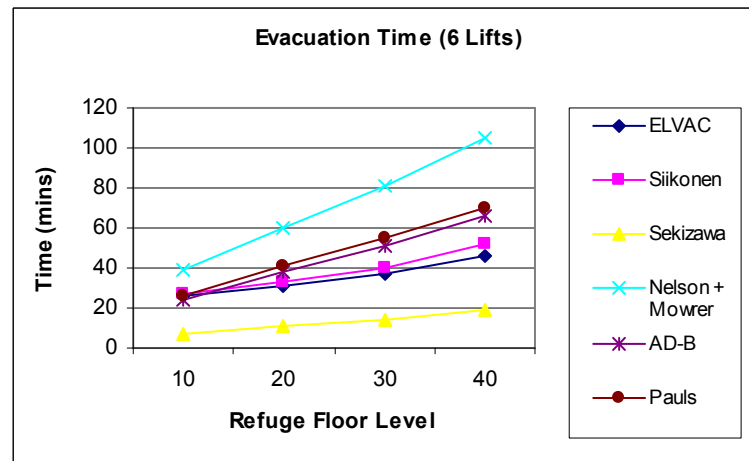
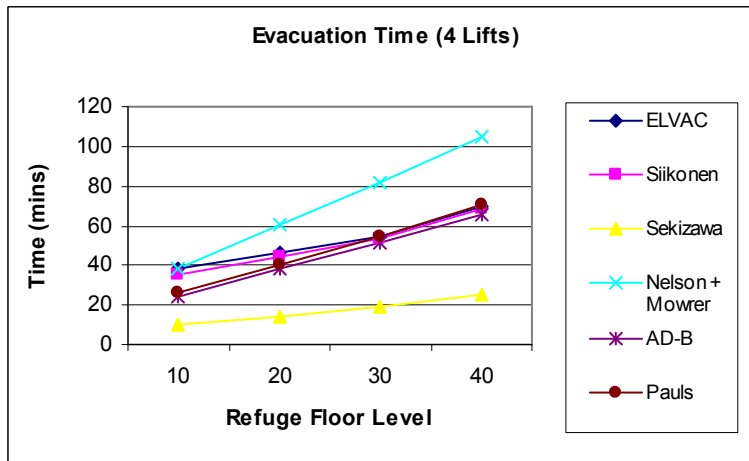


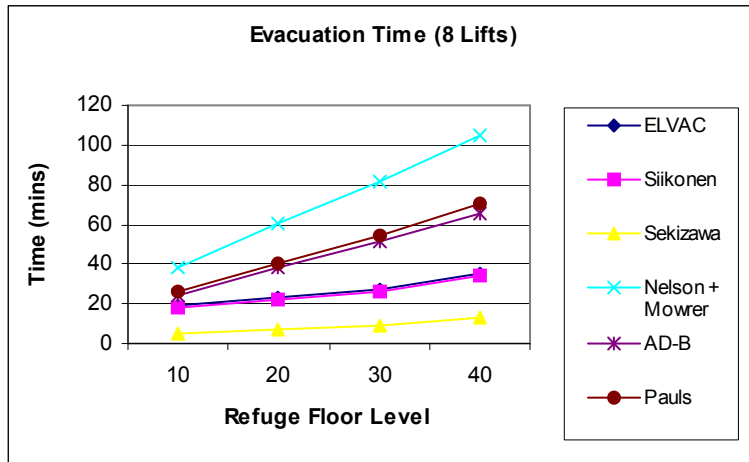
### 10 Storey Interval – Variable Capacity



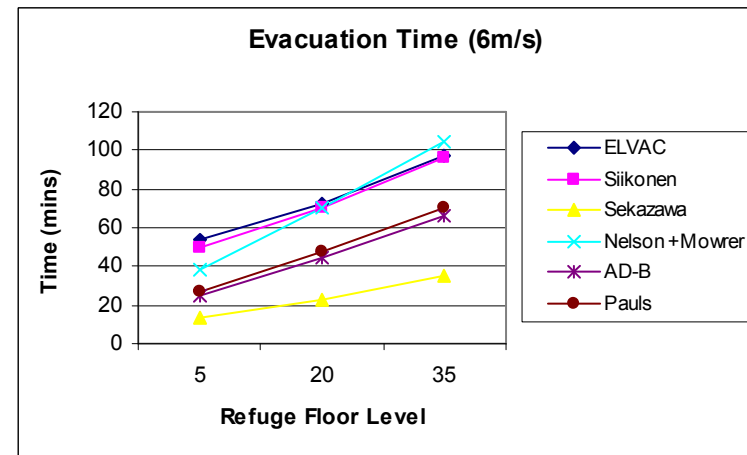
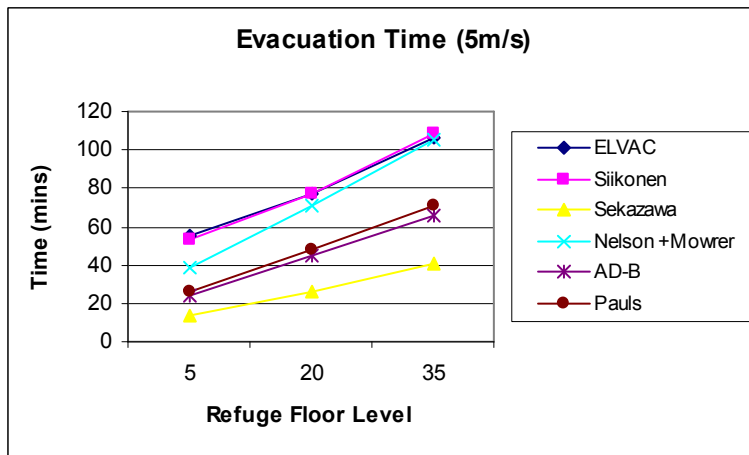


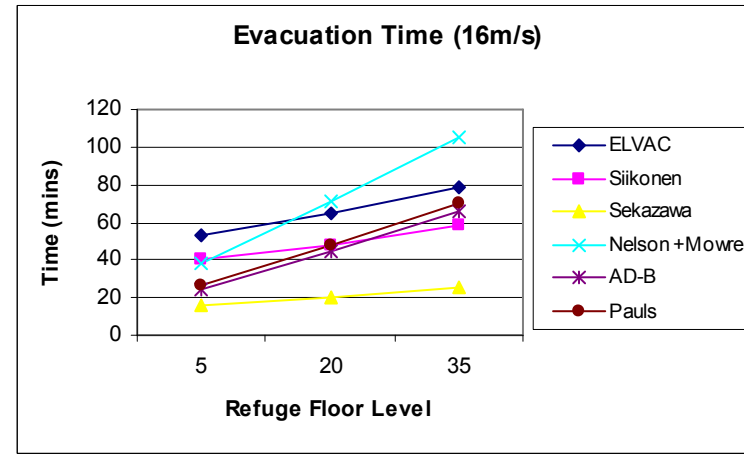
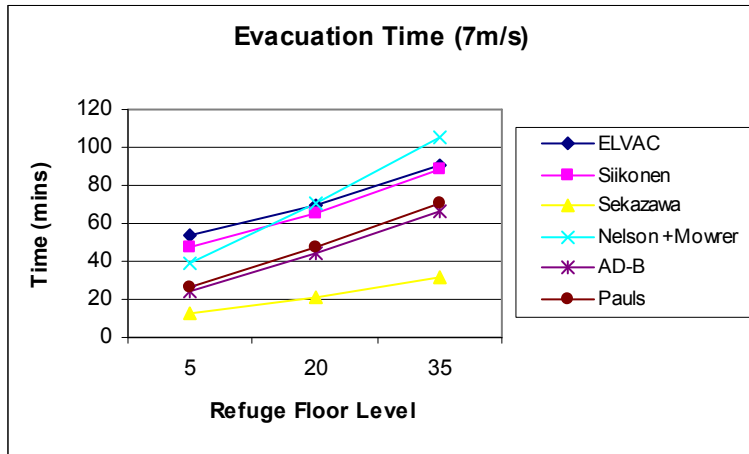
## Variable Lifts



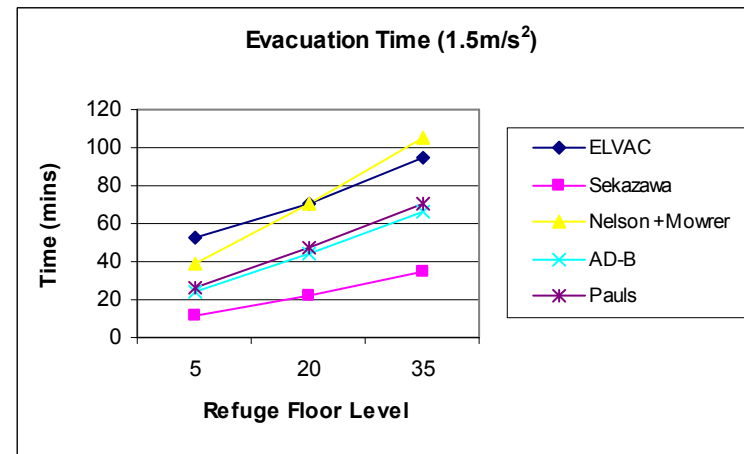
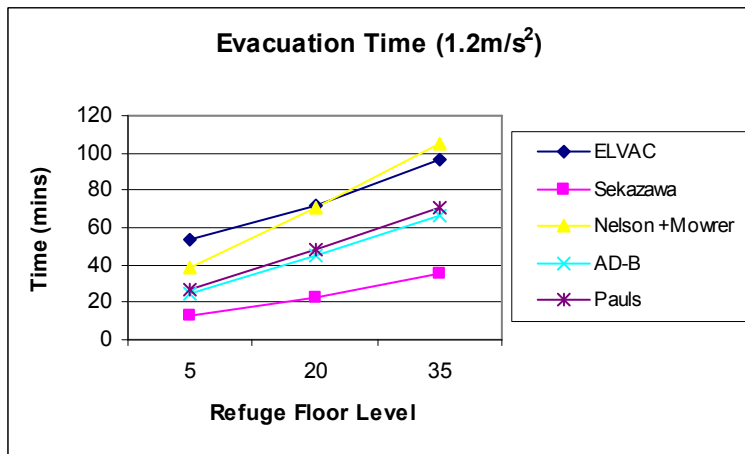


### 15 Storey Interval – Variable Speed

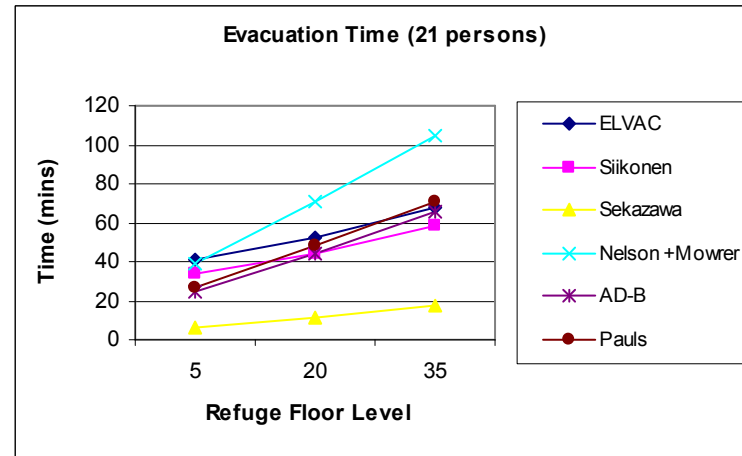
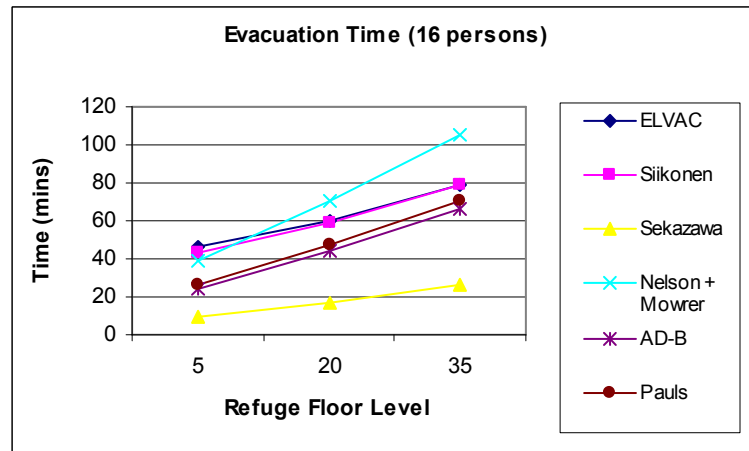
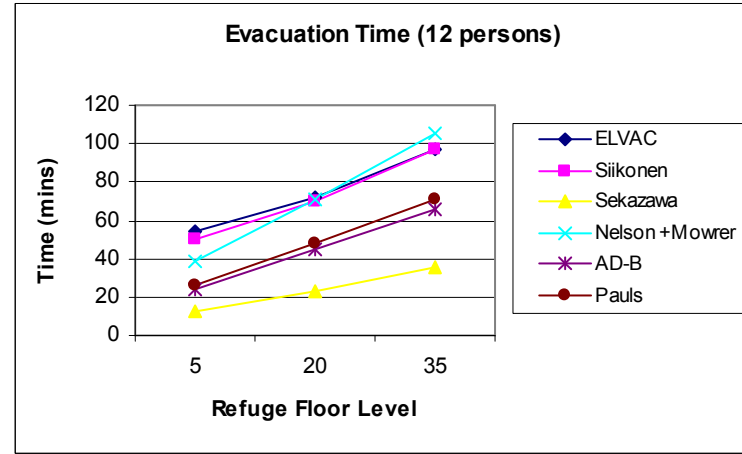
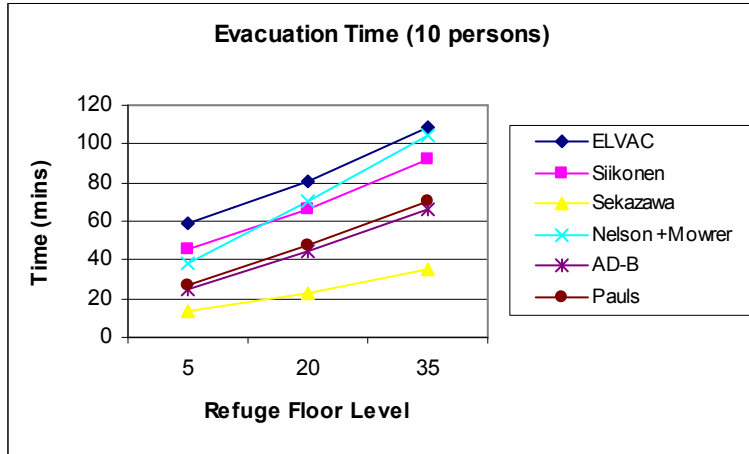




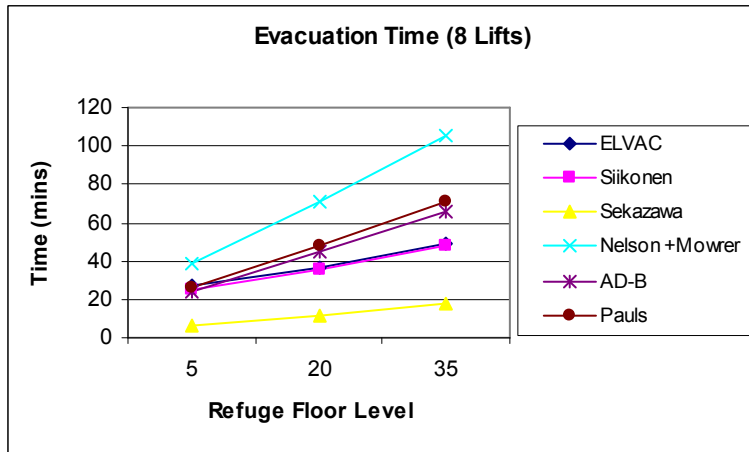
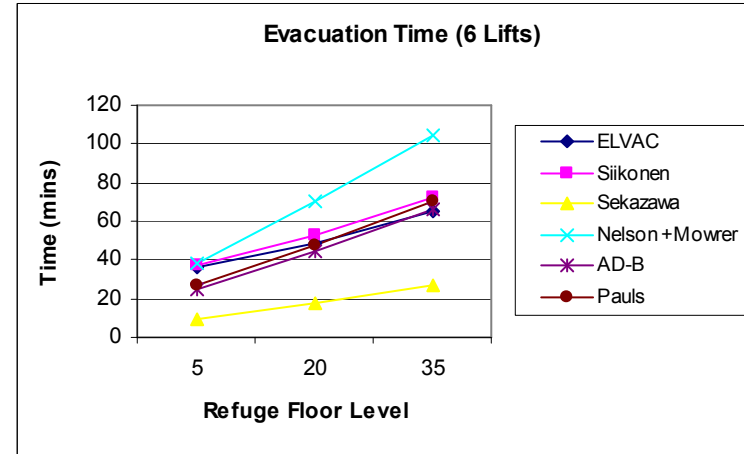
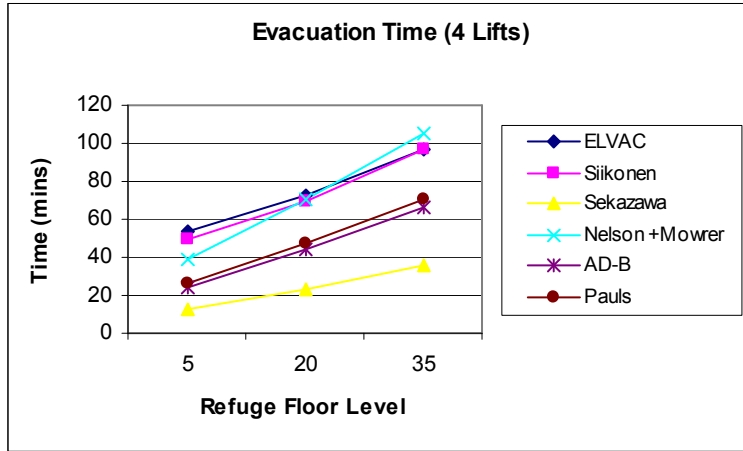
### 15 Storey Interval – Variable Acceleration



### 15 Storey Interval – Variable Capacity

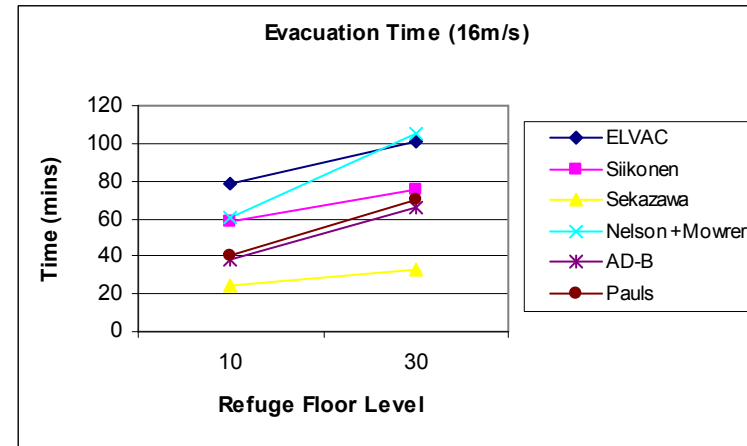
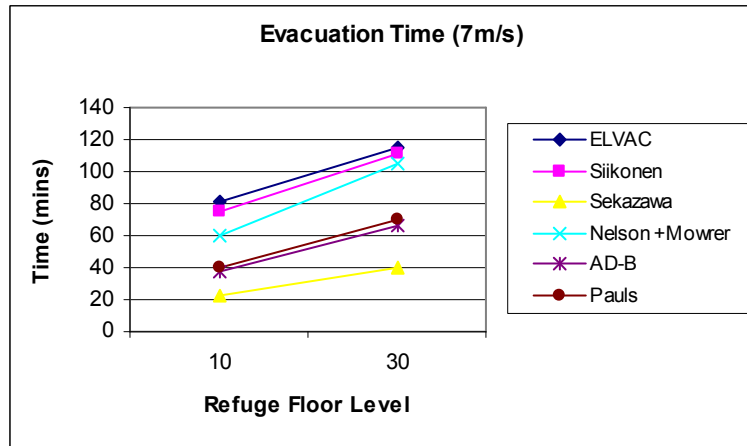
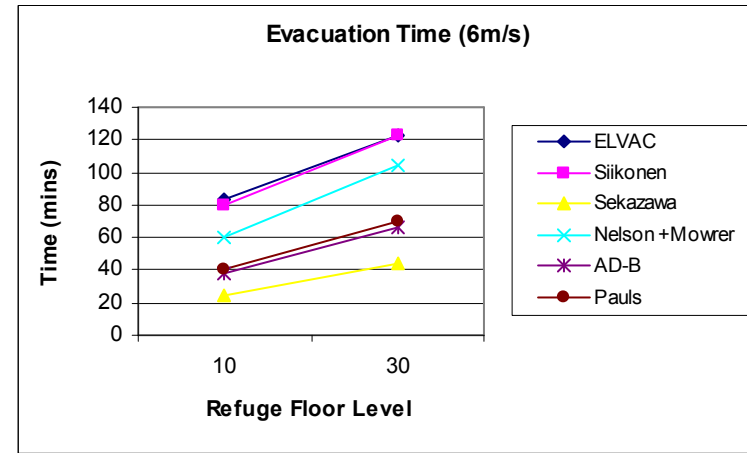
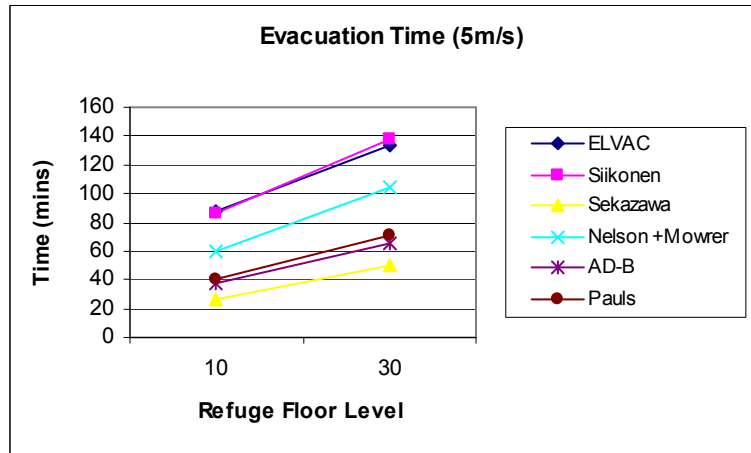


### 15 Storey Interval – Variable Lifts

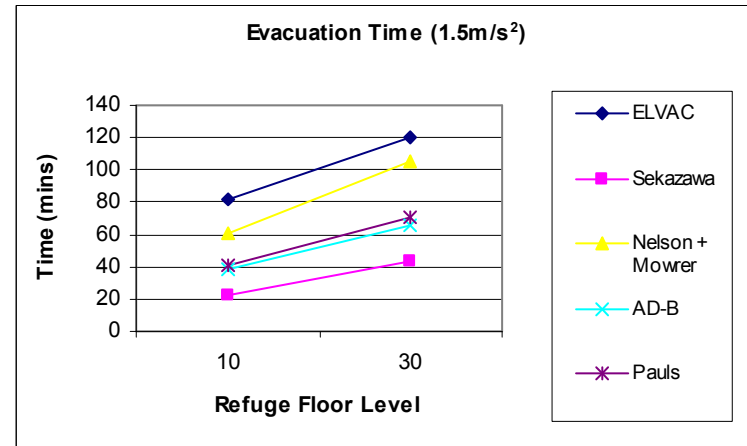
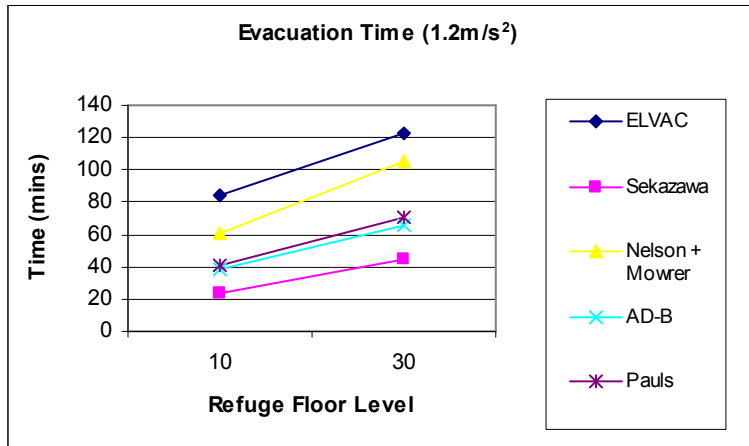




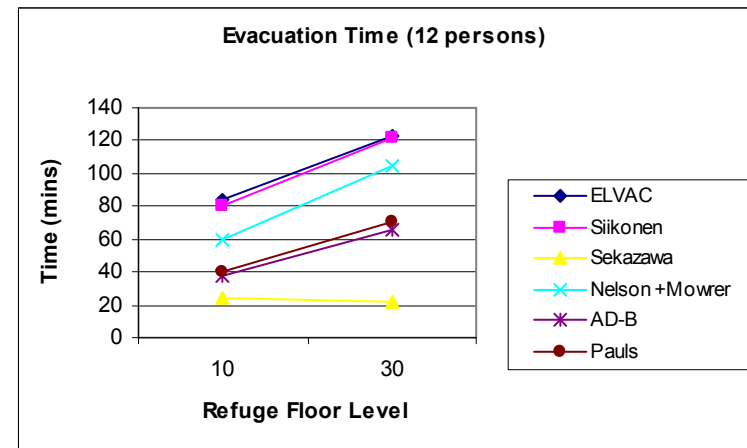
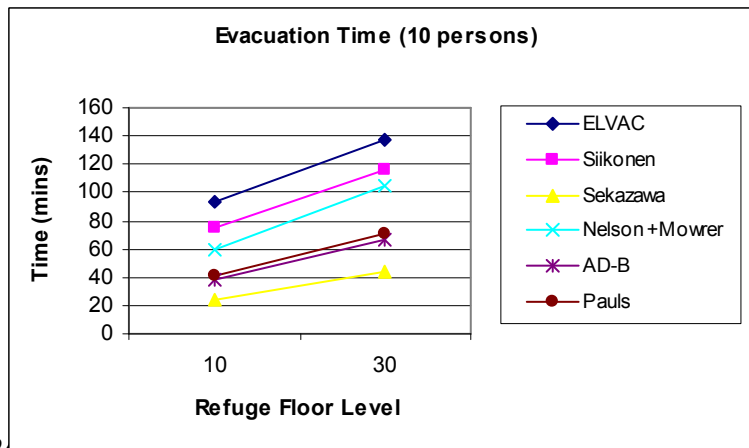
## 20 Storey Interval – Variable Speed

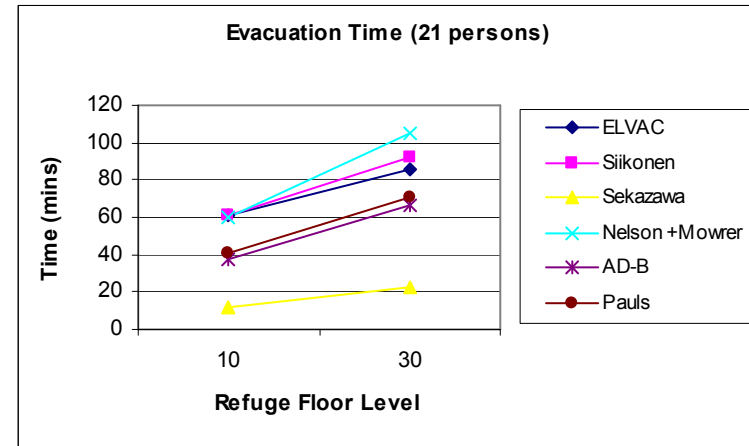
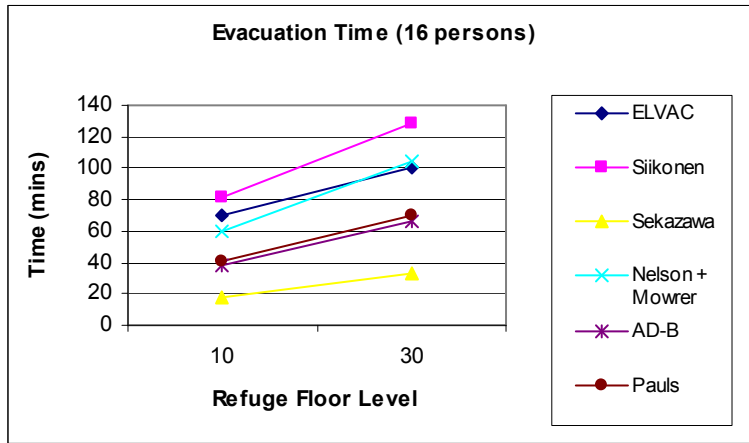


### 20 Storey Interval – Variable Speed

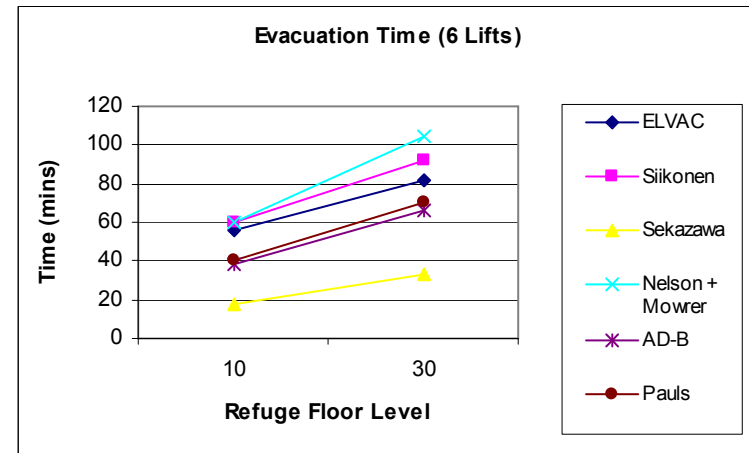
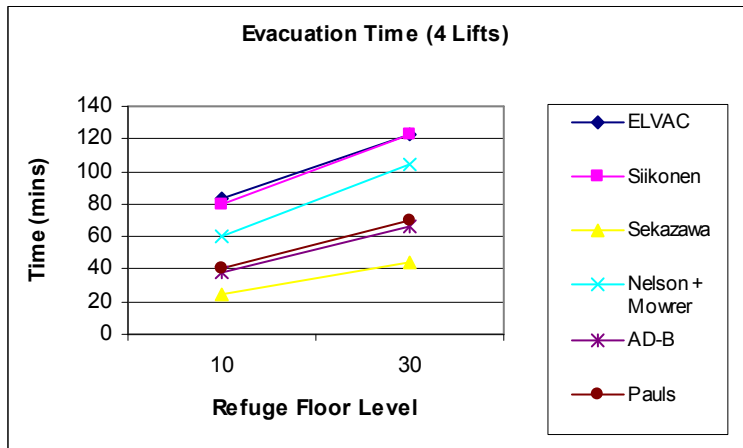


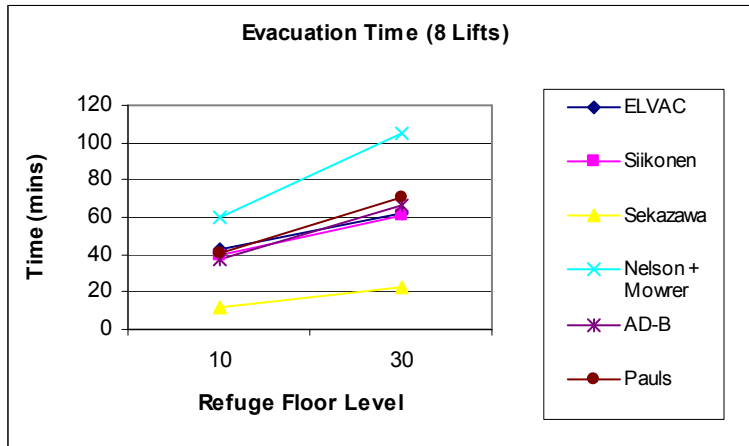
### 20 Storey Interval – Variable Capacity



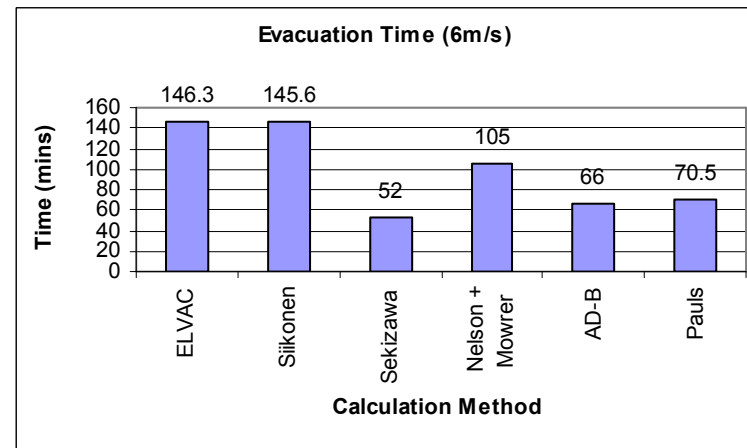
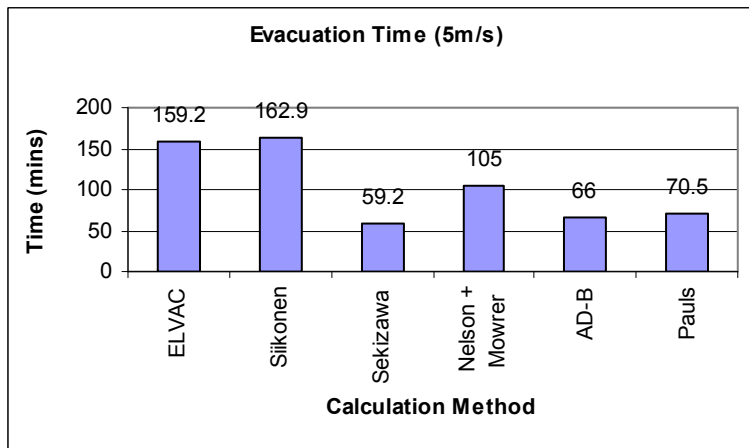


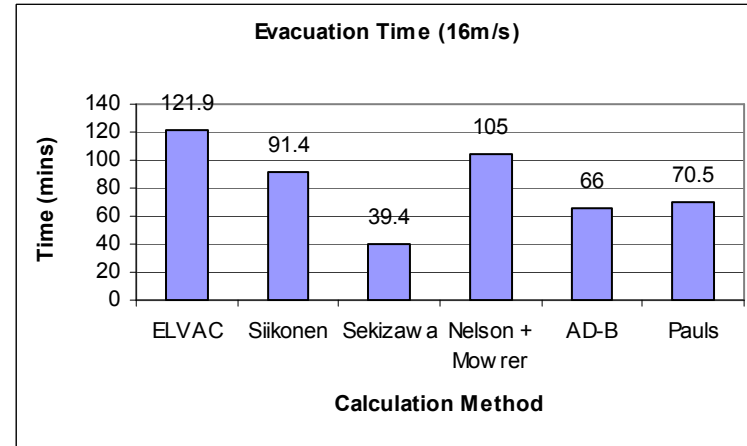
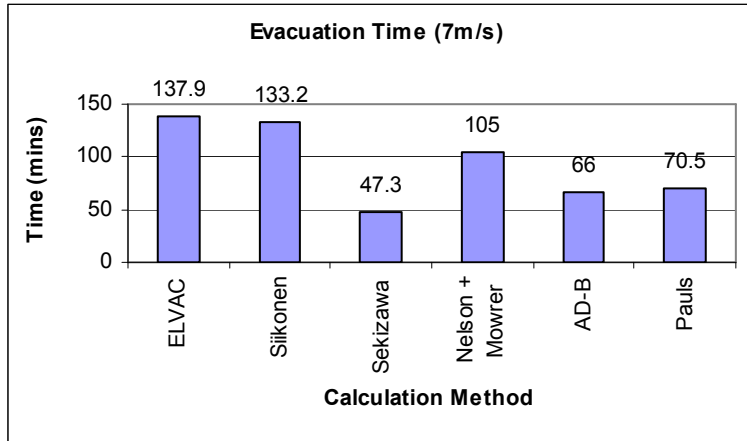
## 20 Storey Interval – Variable Capacity



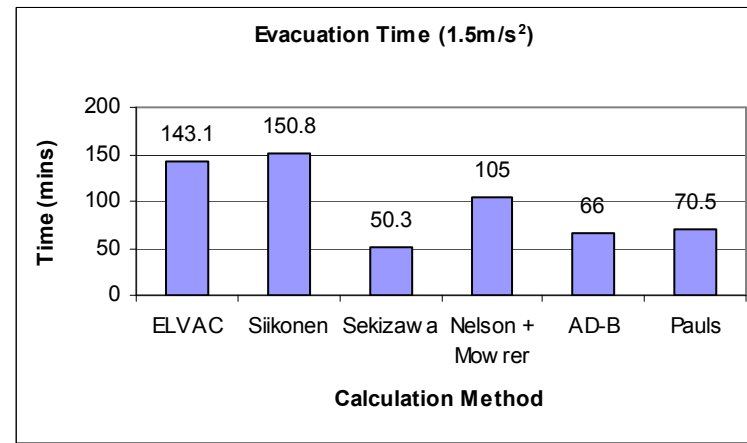
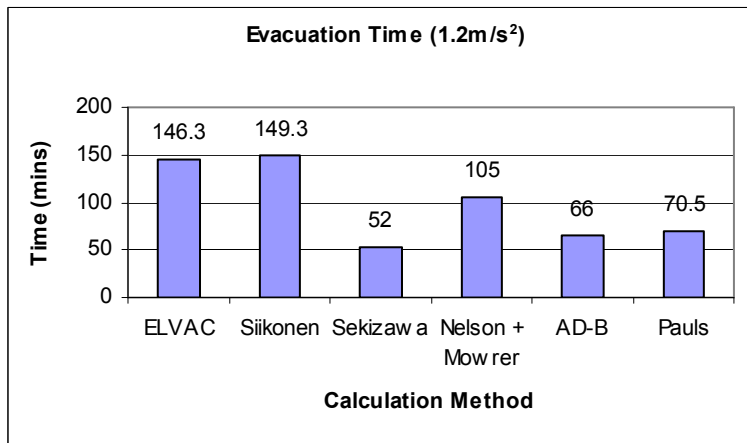


### 25 Storey Interval – Variable Speed

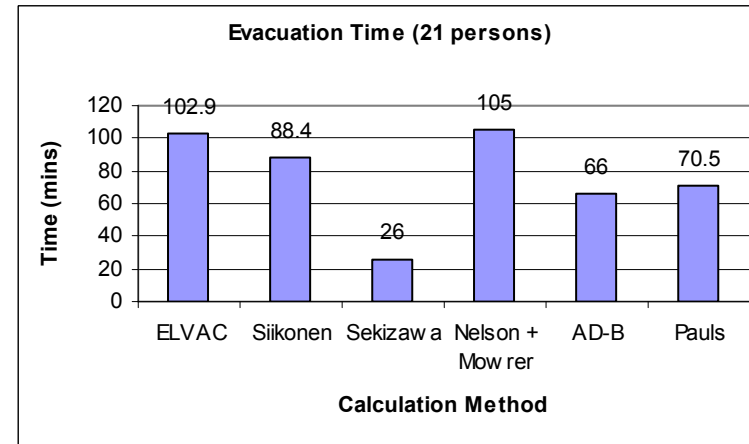
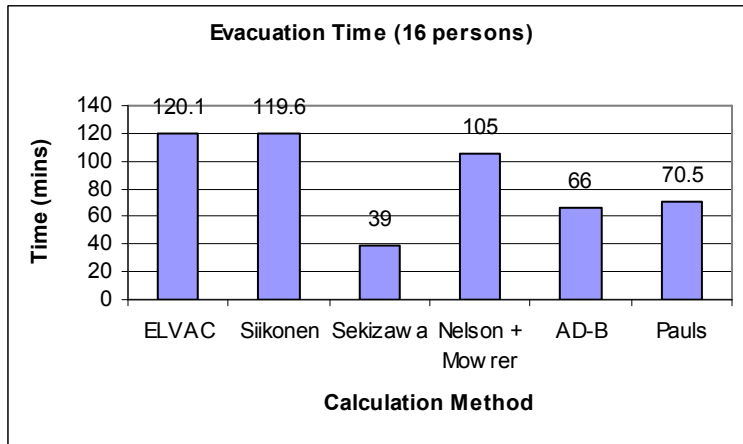
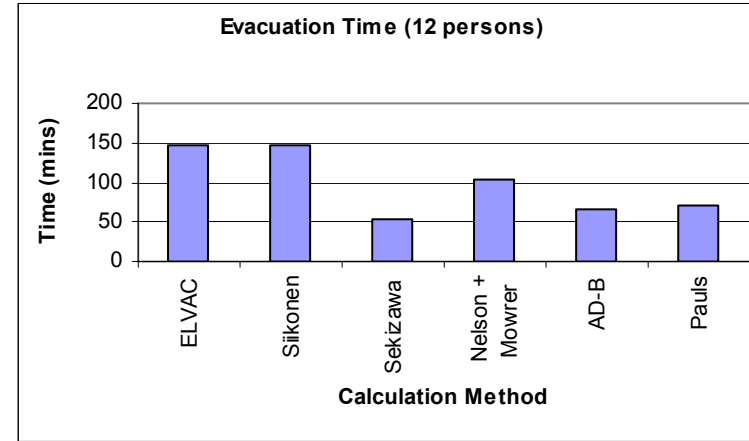
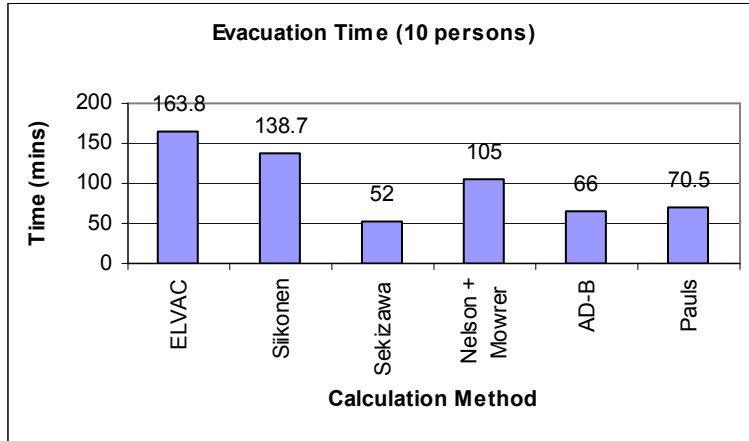




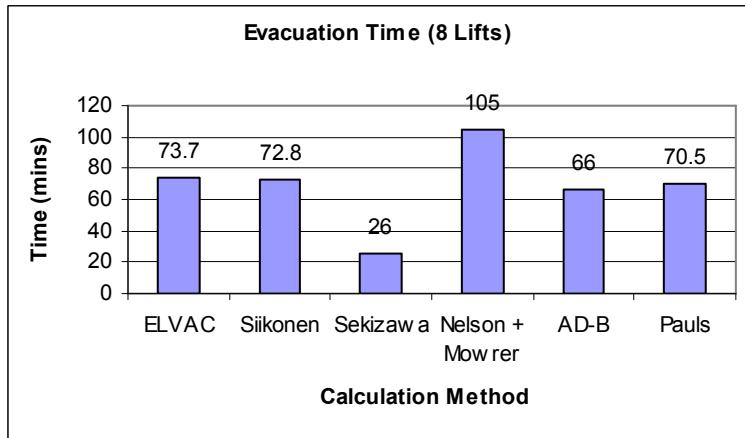
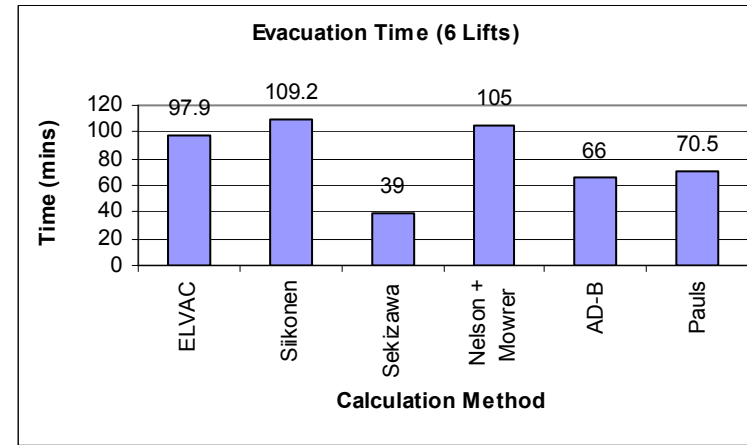
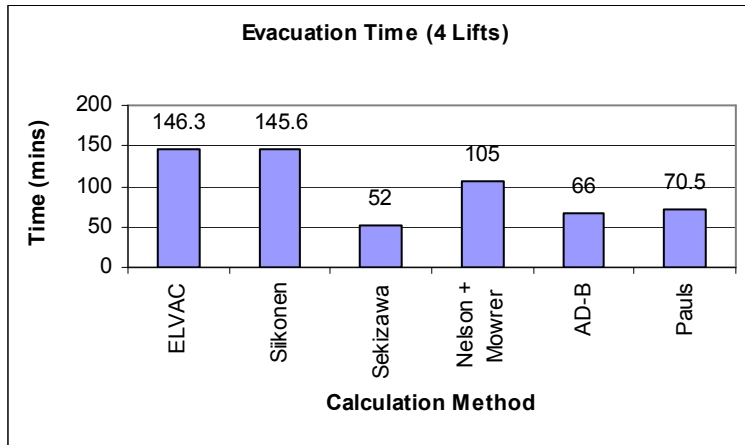
**25 Storey Interval – Variable Acceleration**



### 25 Storey Interval – Variable Capacity



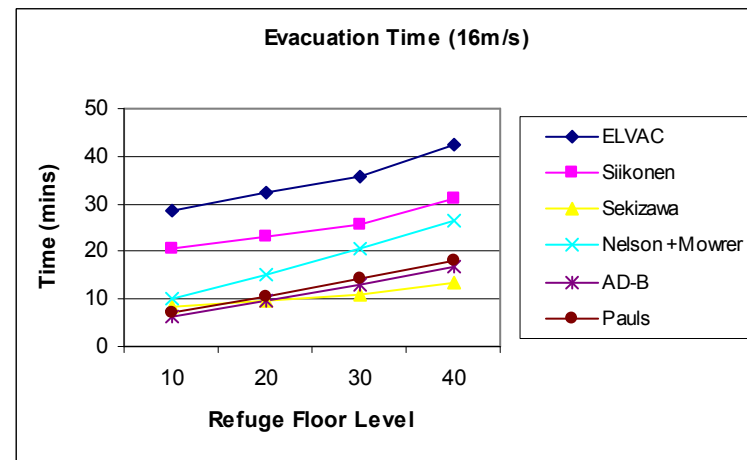
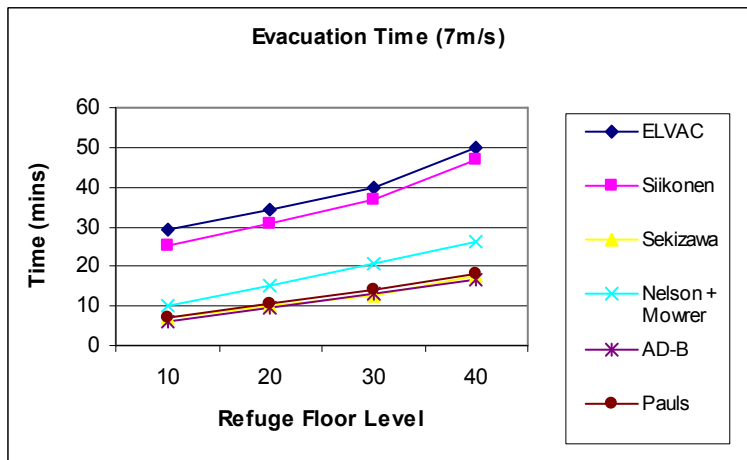
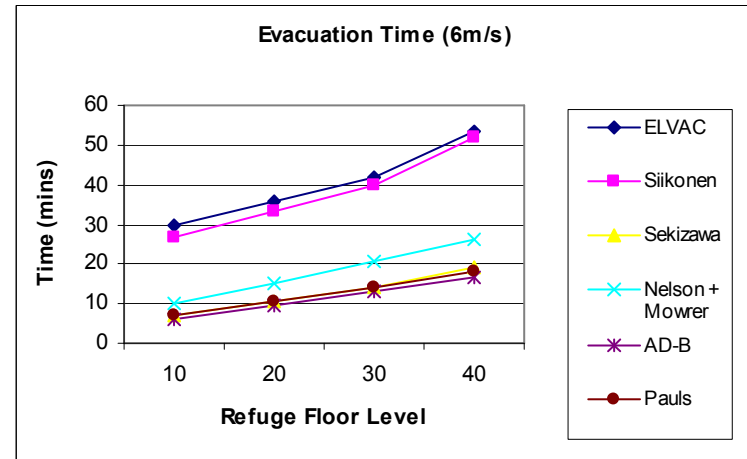
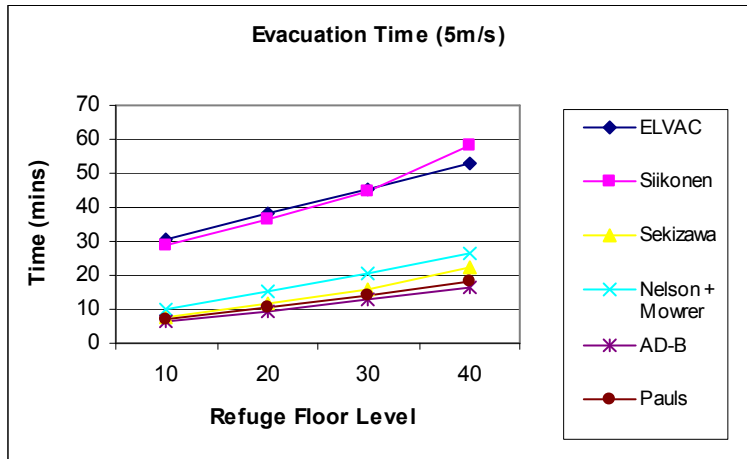
### 25 Storey Interval – Variable Lifts



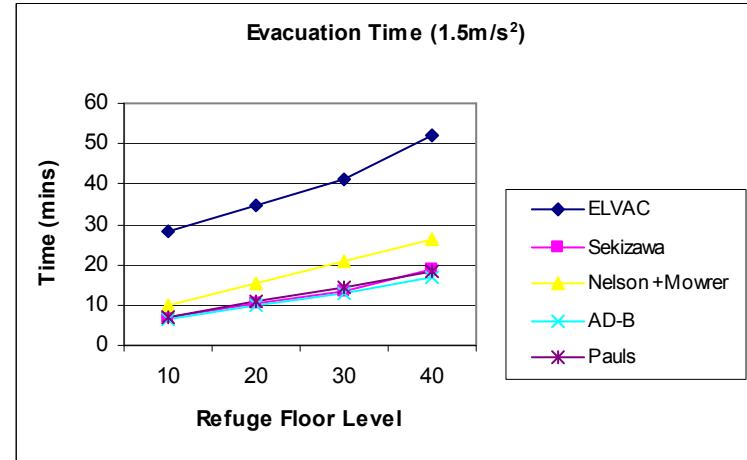
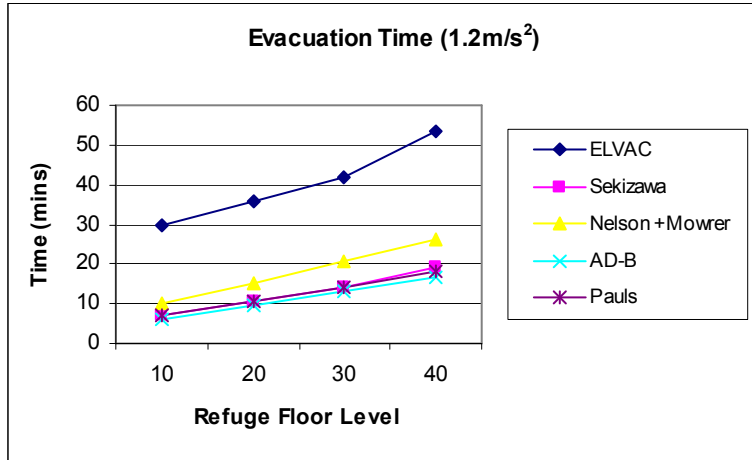
**APPENDIX E – EVACUATION FROM EVACUATION ZONE (75% LIFT USAGE)**



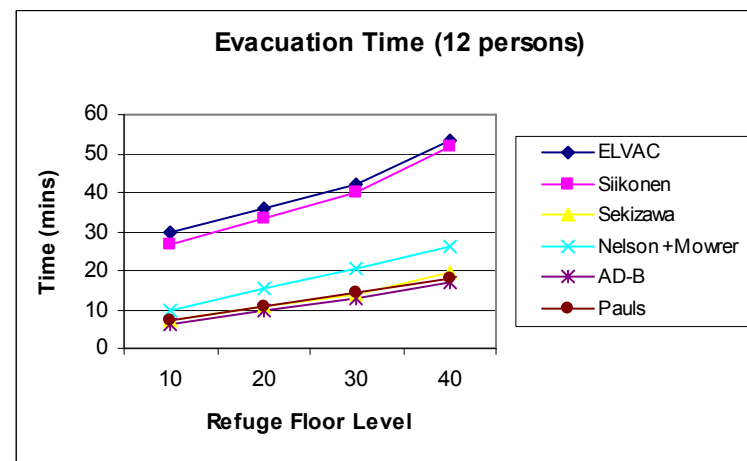
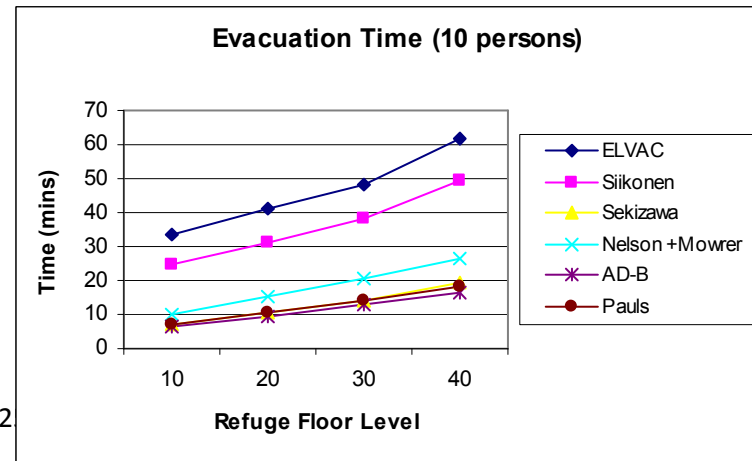
### 10 Storey Interval – Variable Speed

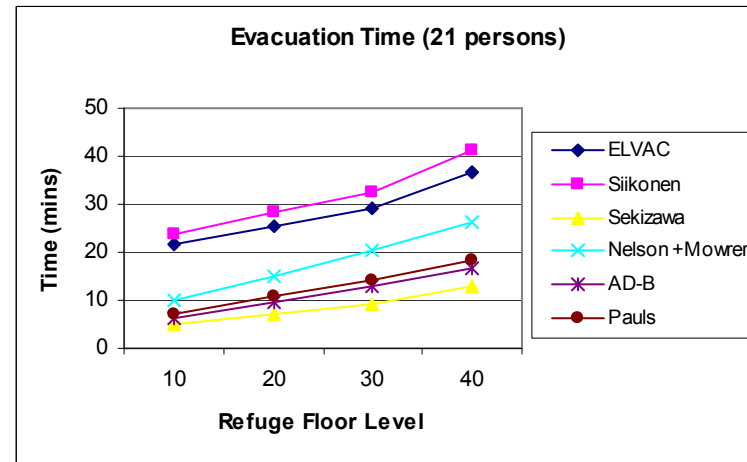
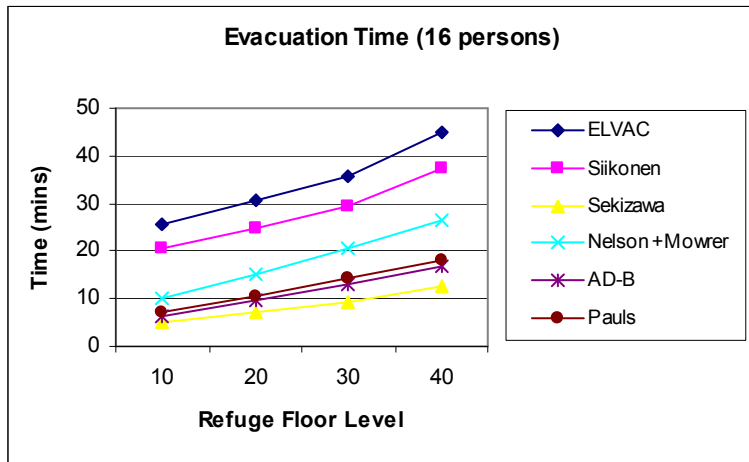


### 10 Storey Interval – Variable Acceleration

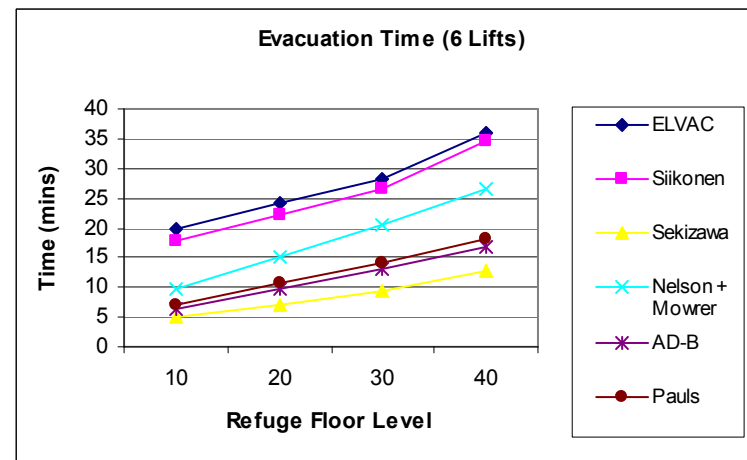
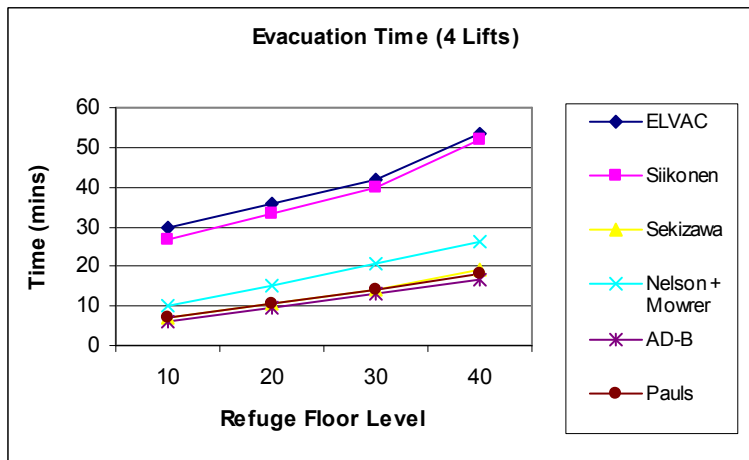


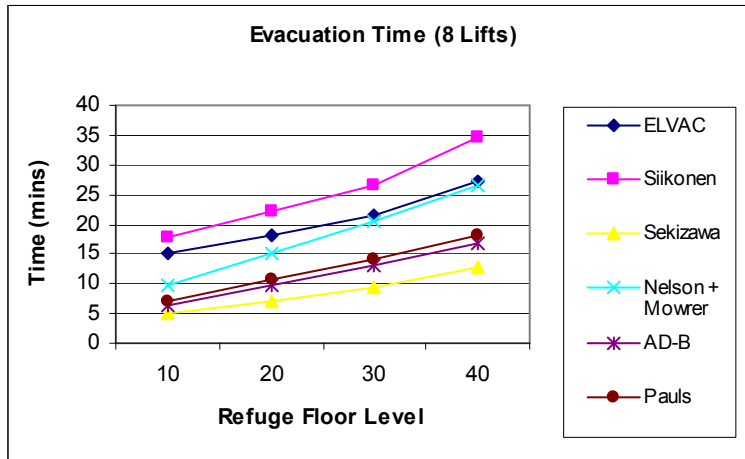
### 10 Storey Interval – Variable Capacity



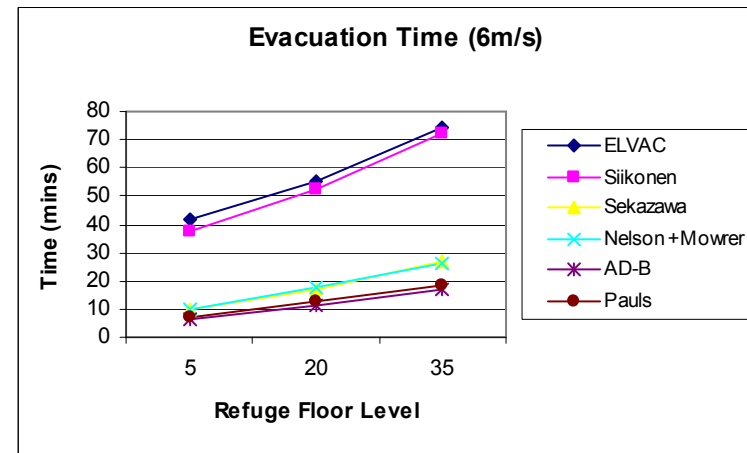
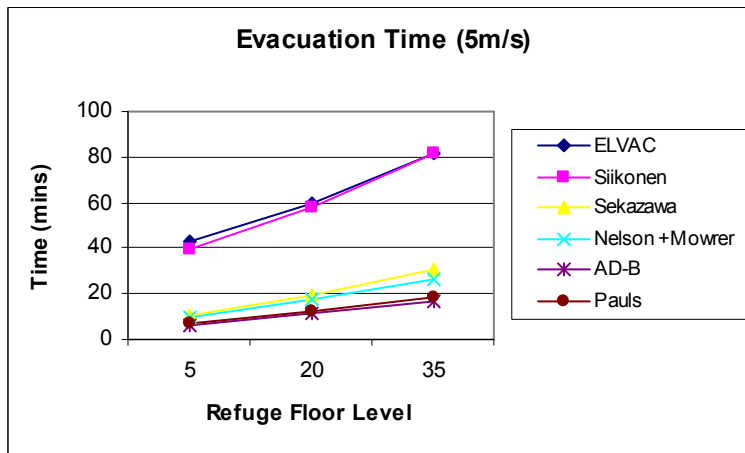


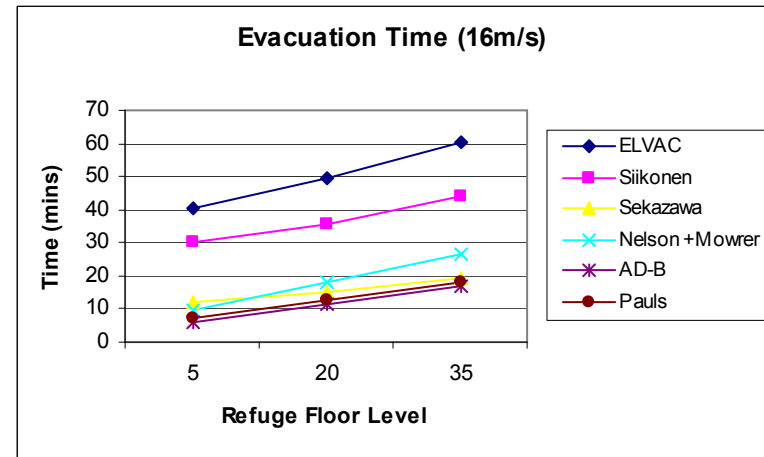
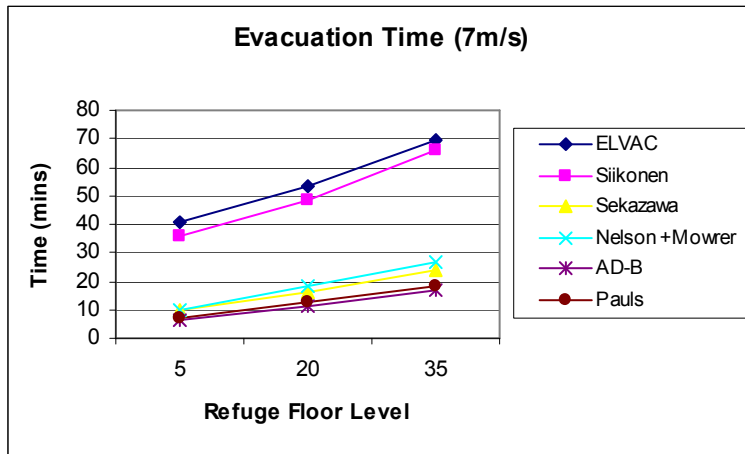
## 10 Storey Interval – Variable Lifts



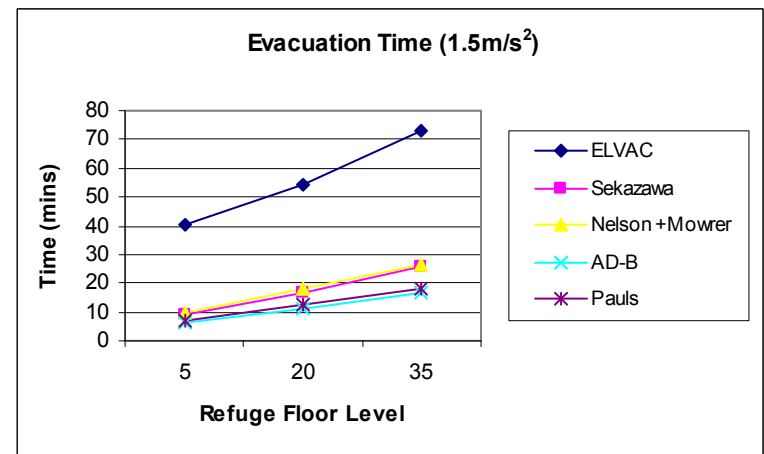
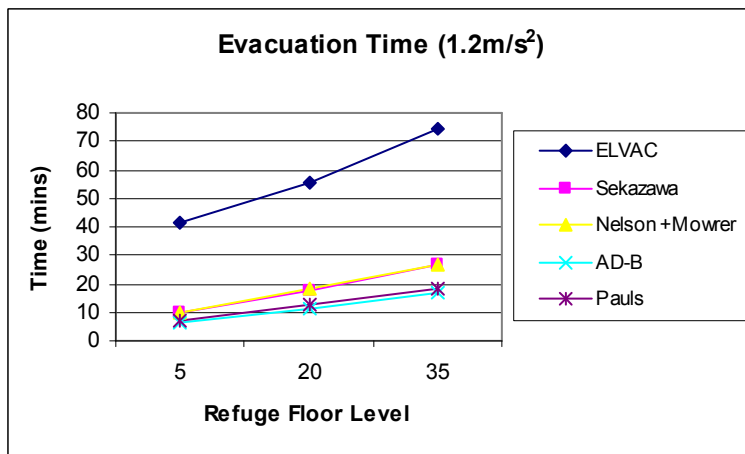


## 15 Storey Interval – Variable Speed

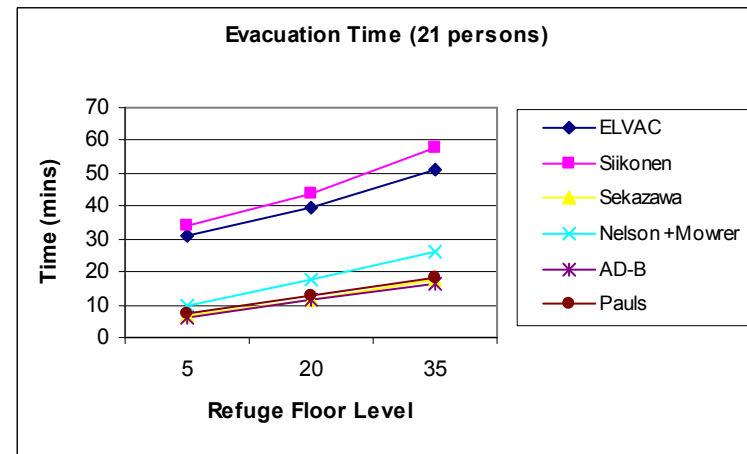
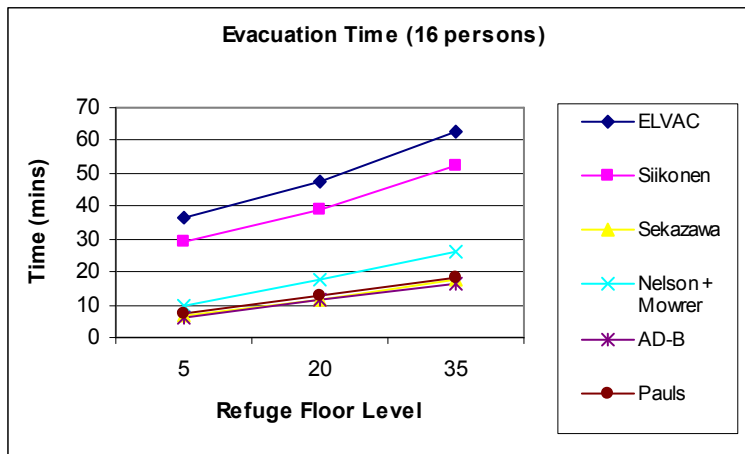
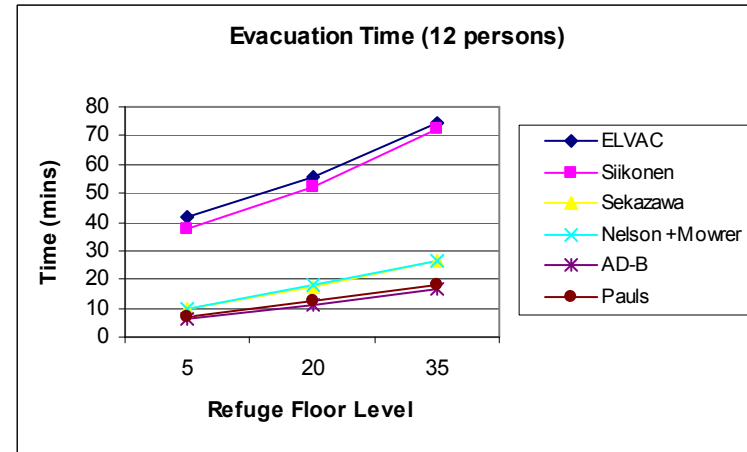
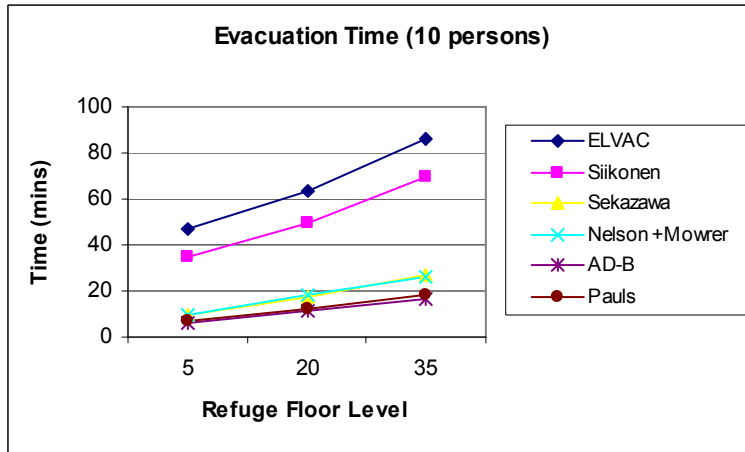




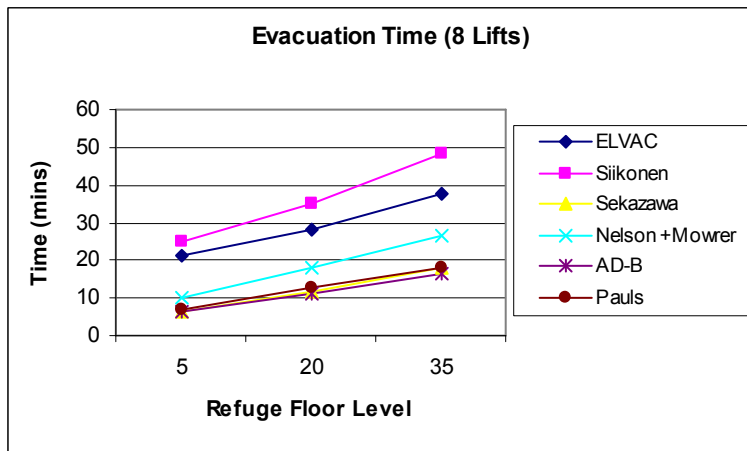
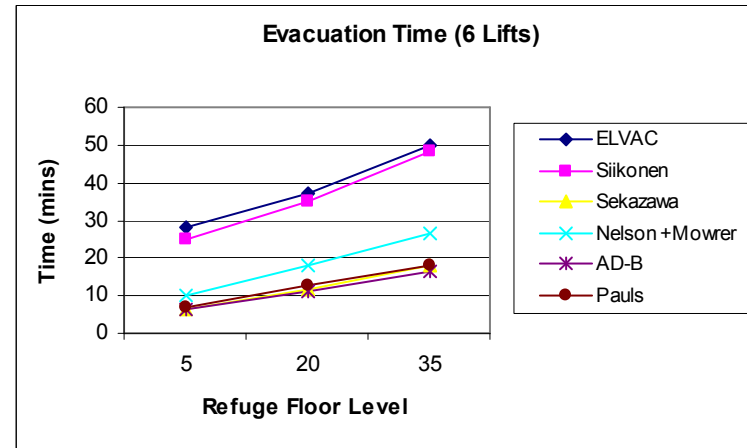
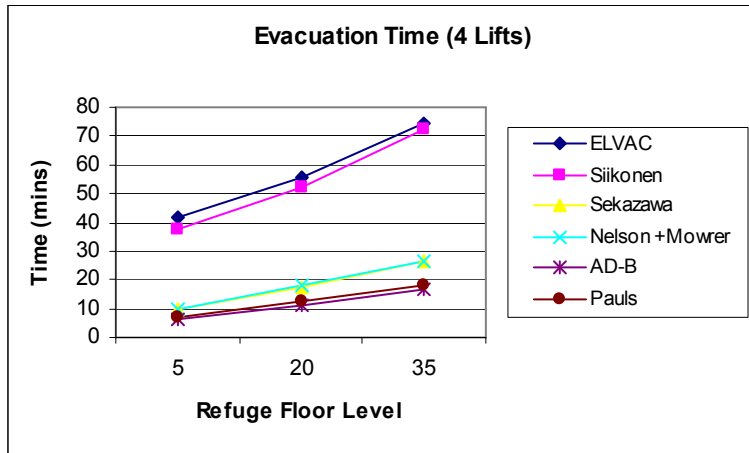
## 15 Storey Interval – Variable Acceleration



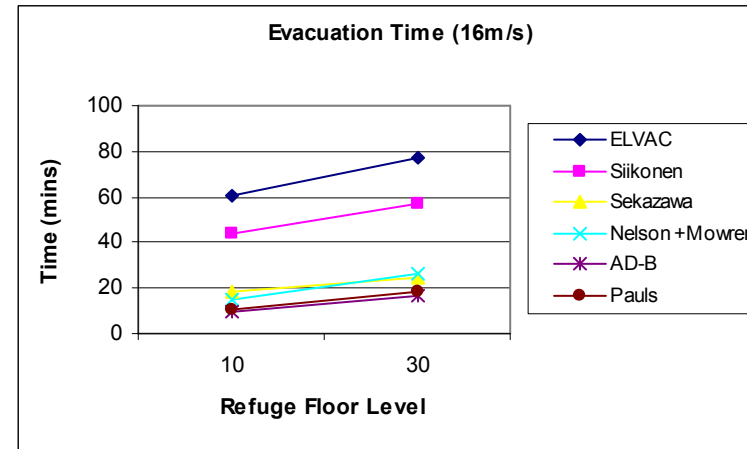
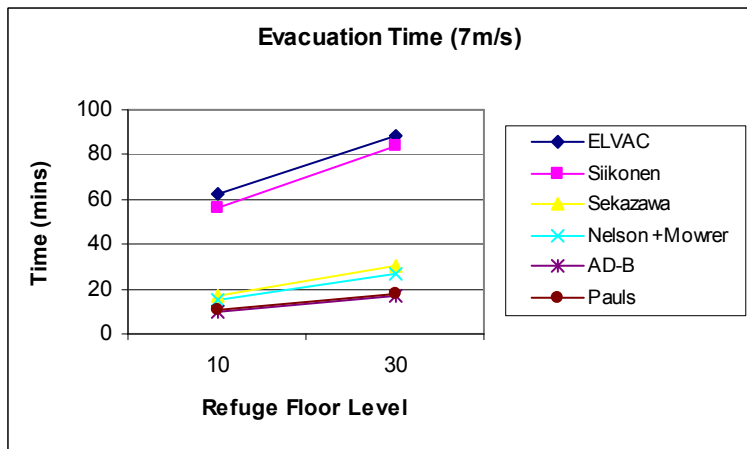
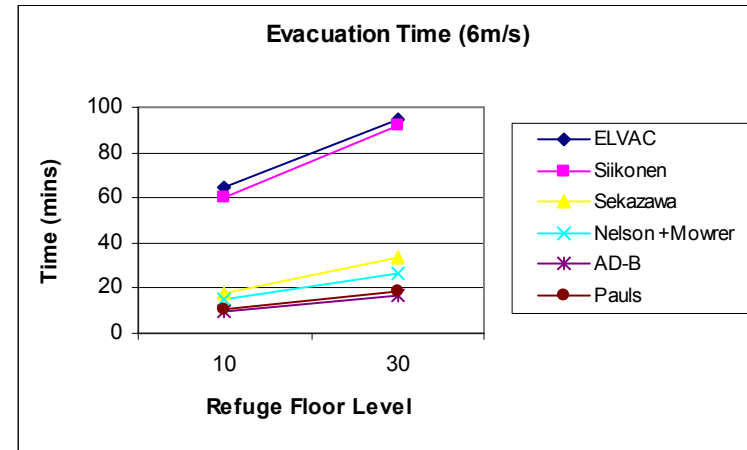
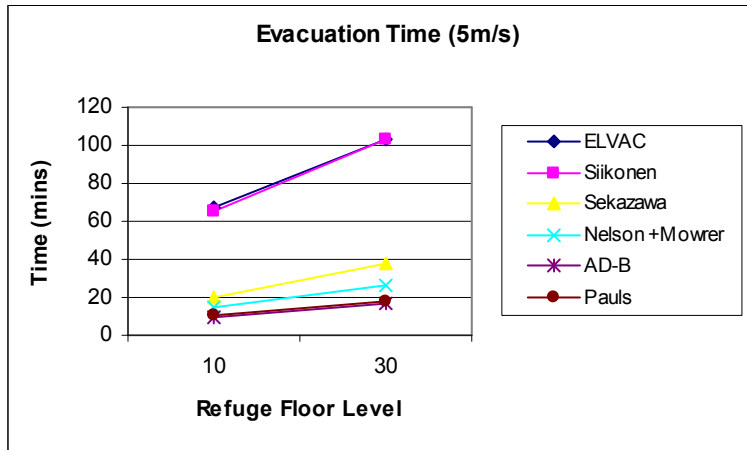
### 15 Storey Interval – Variable Capacity



### 15 Storey Interval – Variable Lifts

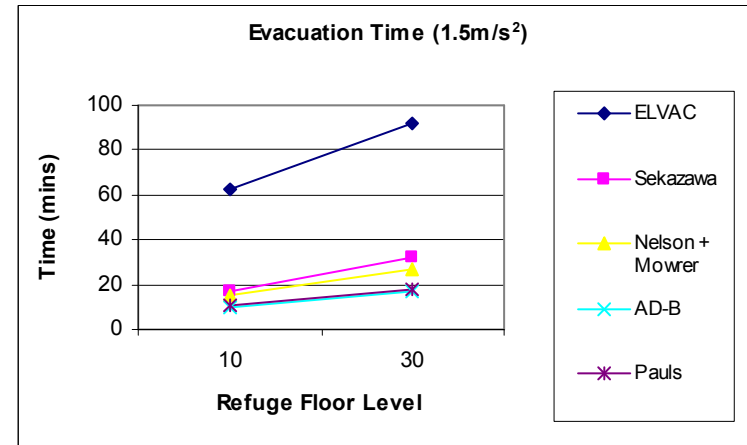
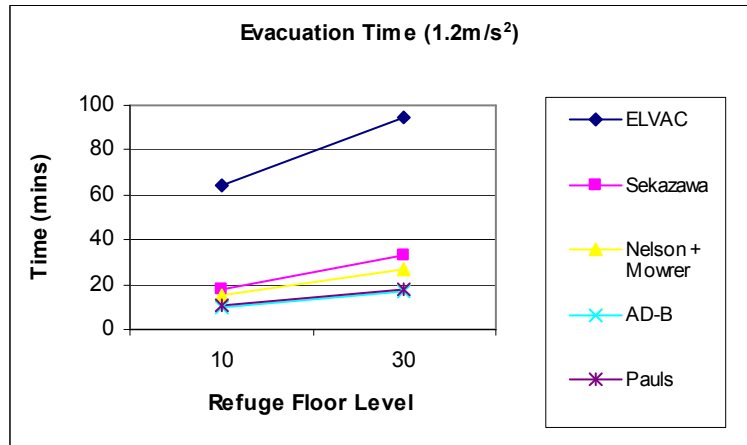


## 20 Storey Interval – Variable Speed

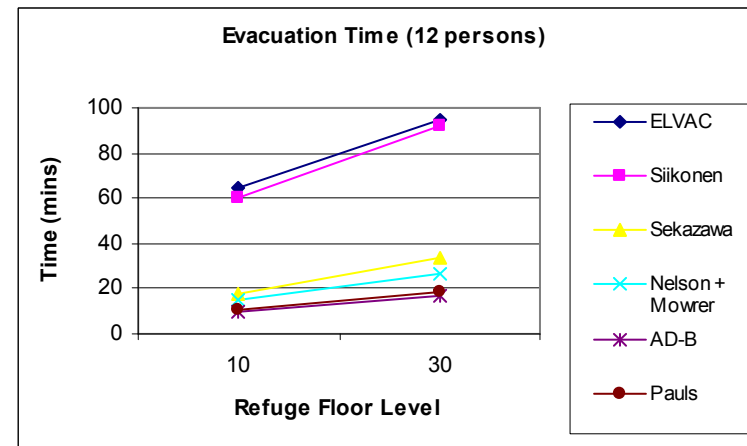
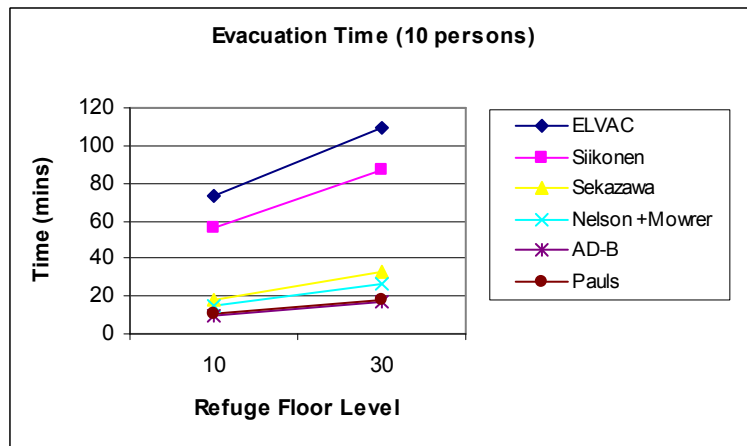


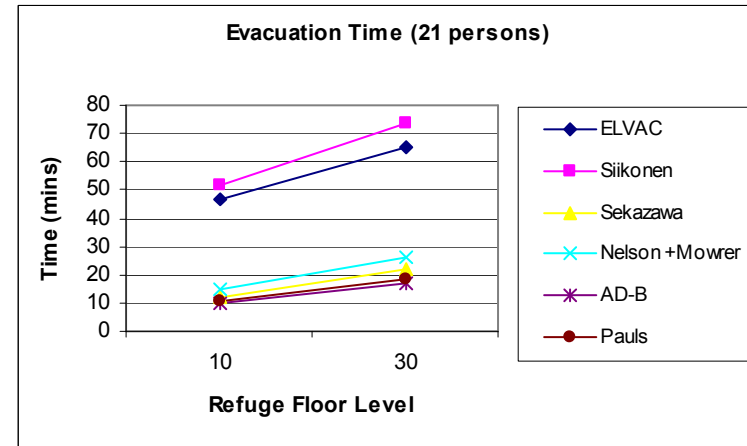
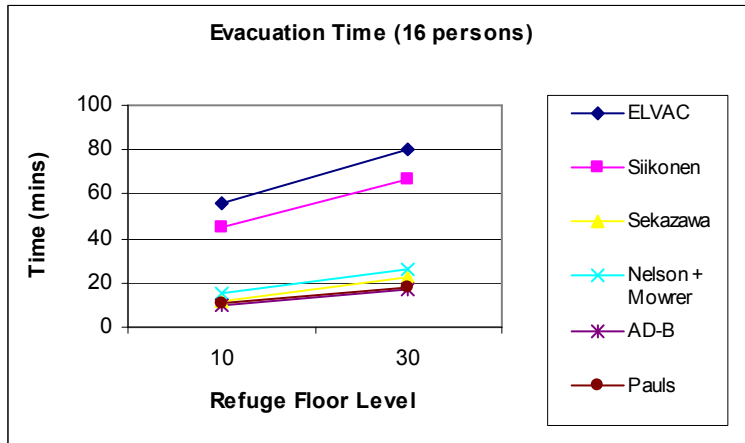


### 20 Storey Interval – Variable Acceleration

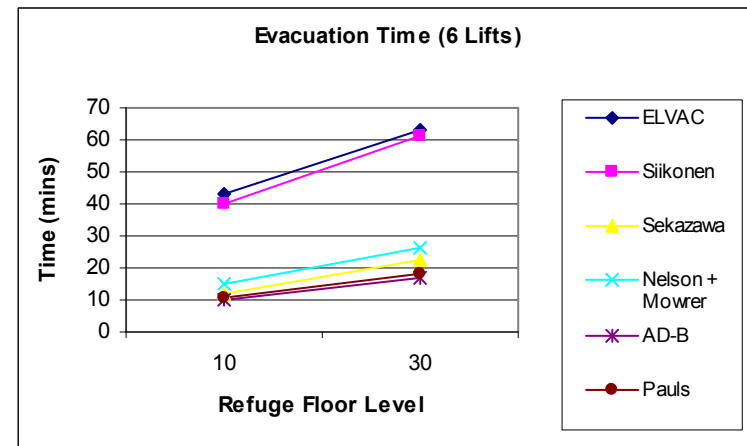
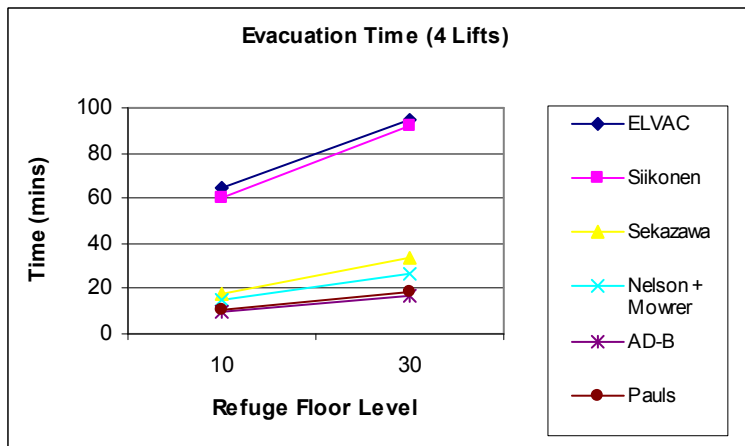


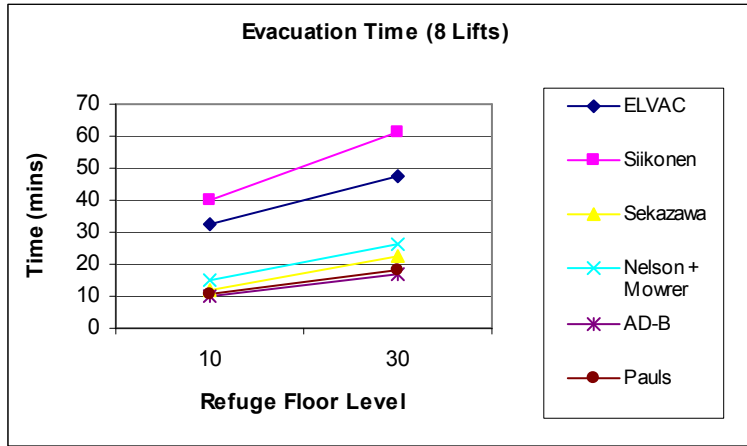
### 20 Storey Interval – Variable Capacity



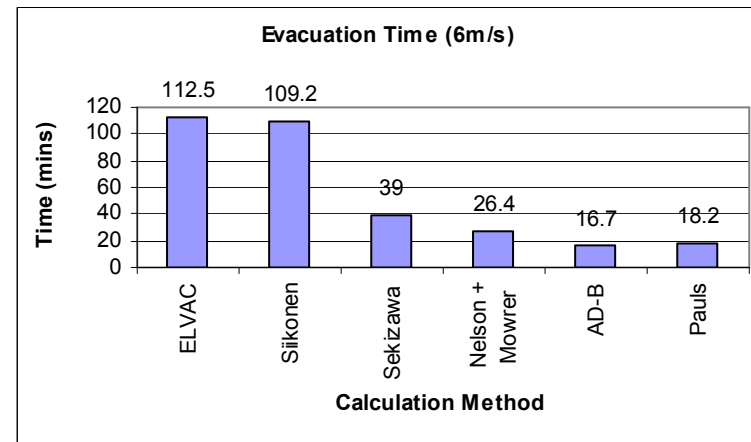
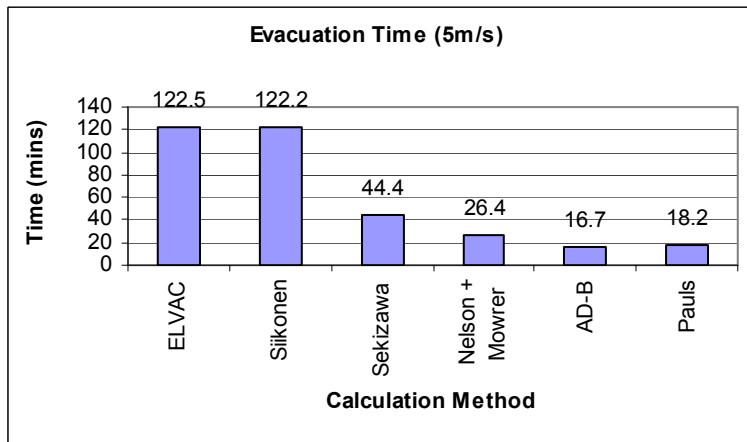


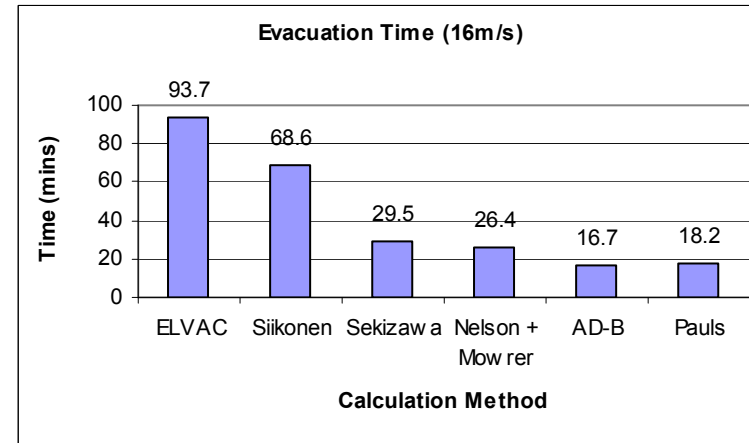
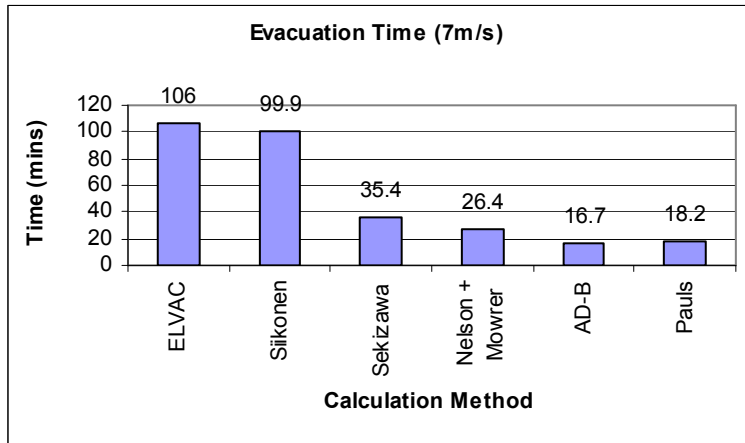
## 20 Storey Interval – Variable Lifts



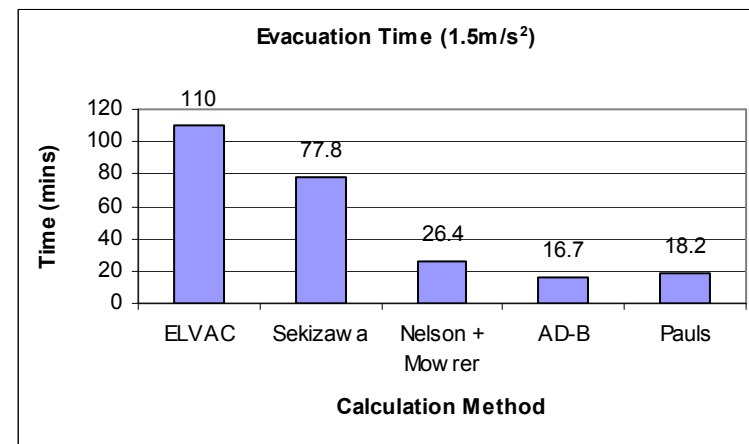
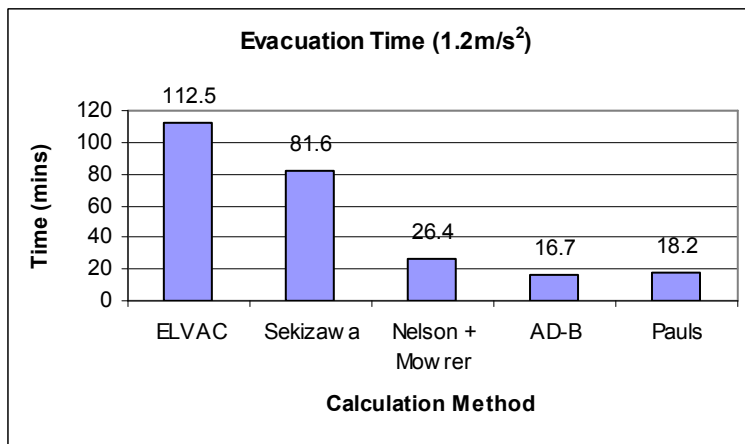


### 25 Storey Interval – Variable Speed

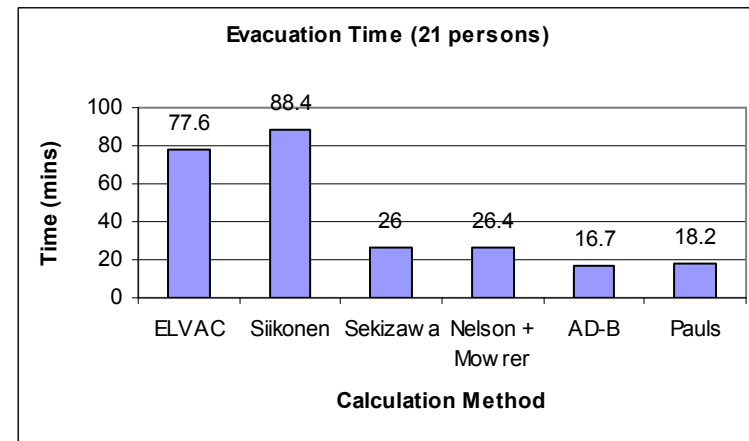
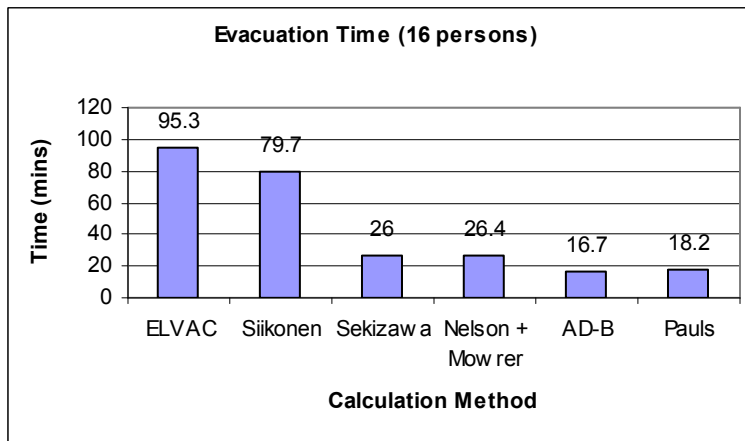
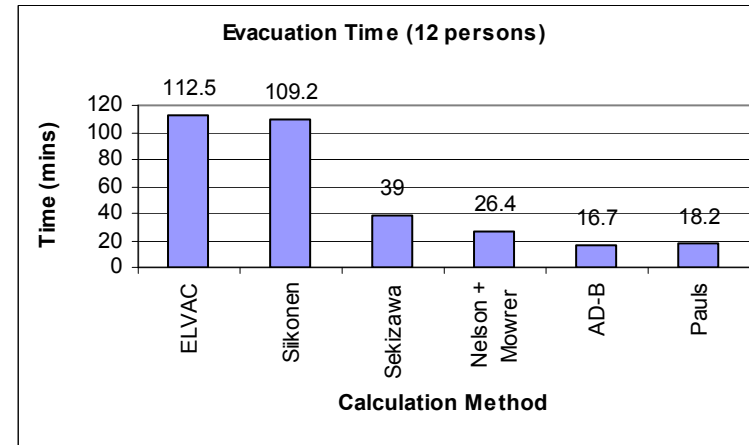
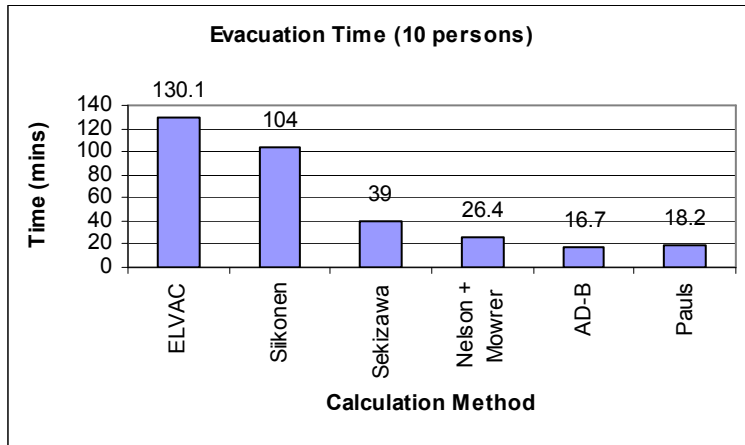




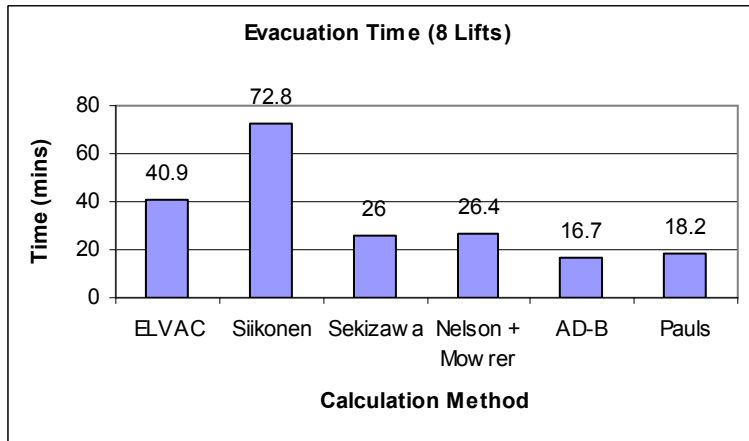
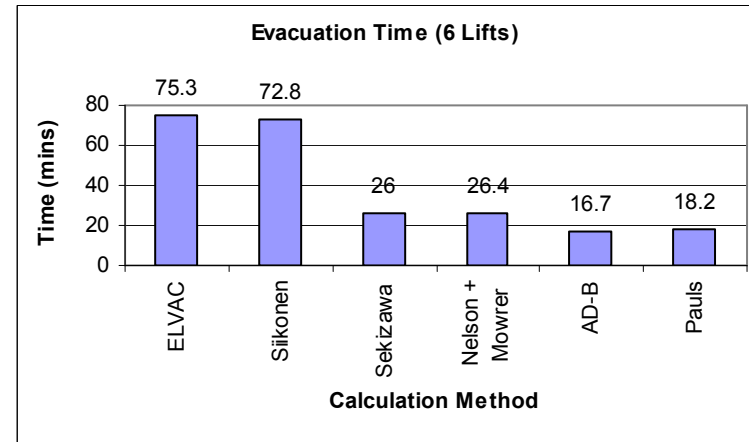
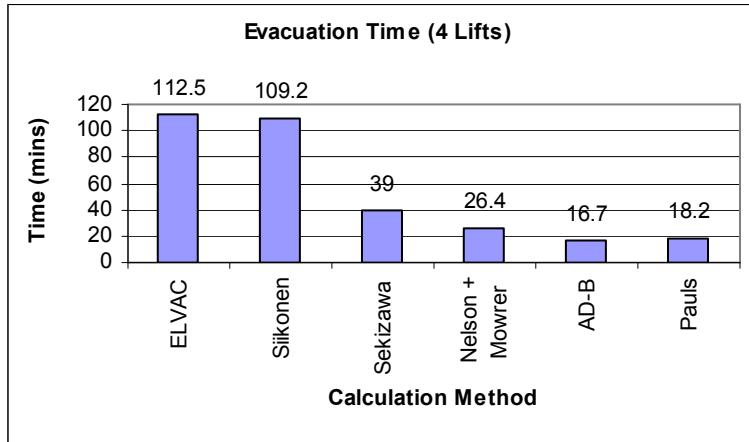
**25 Storey Interval – Variable Acceleration**



## 25 Storey Interval – Variable Capacity

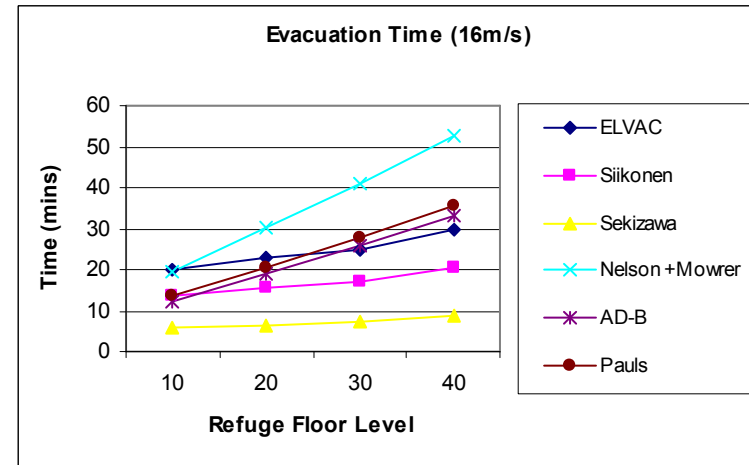
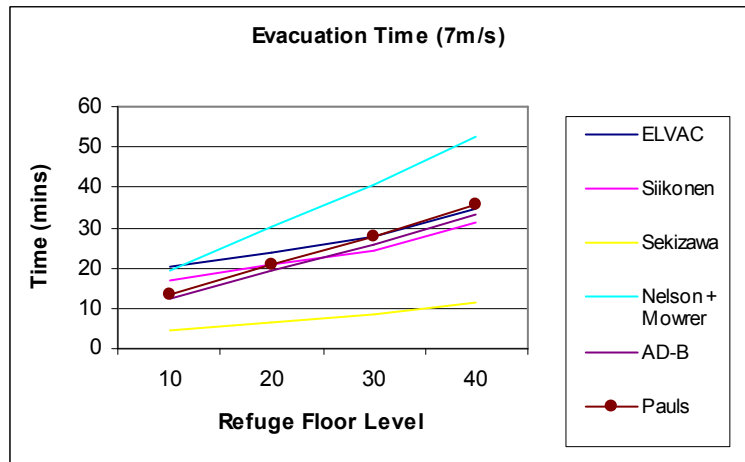
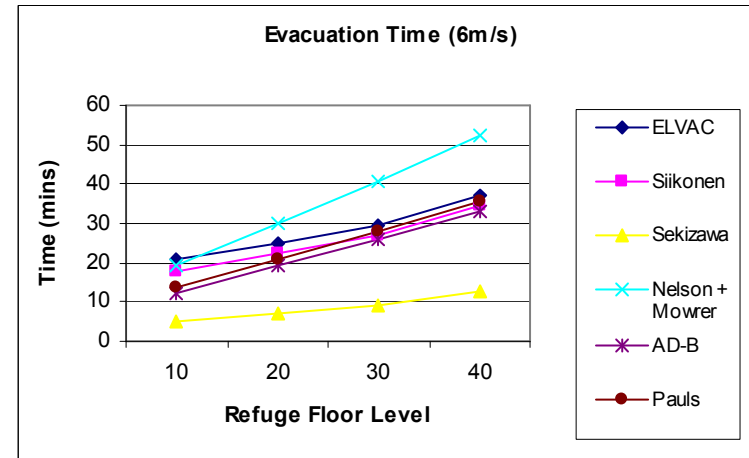
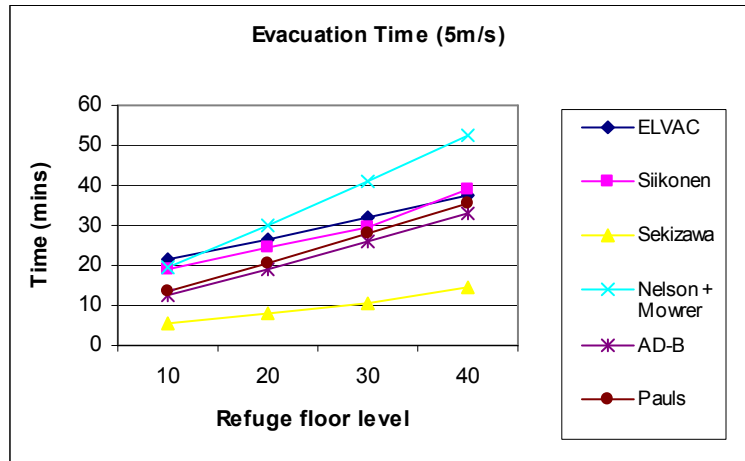


### 25 Storey Interval – Variable Lifts



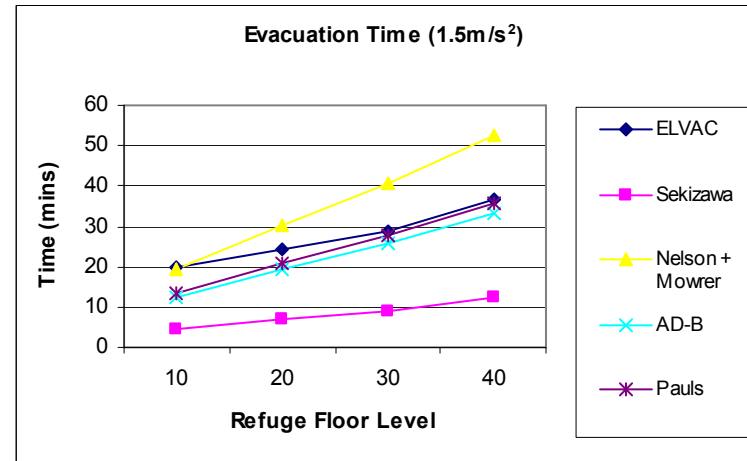
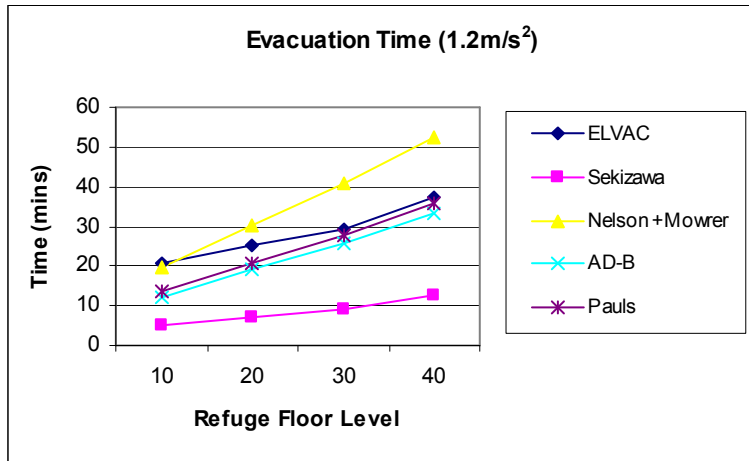
**APPENDIX F - EVACUATION FROM EVACUATION ZONE (50% LIFT USAGE)**

### 10 Storey Interval – Variable Speed

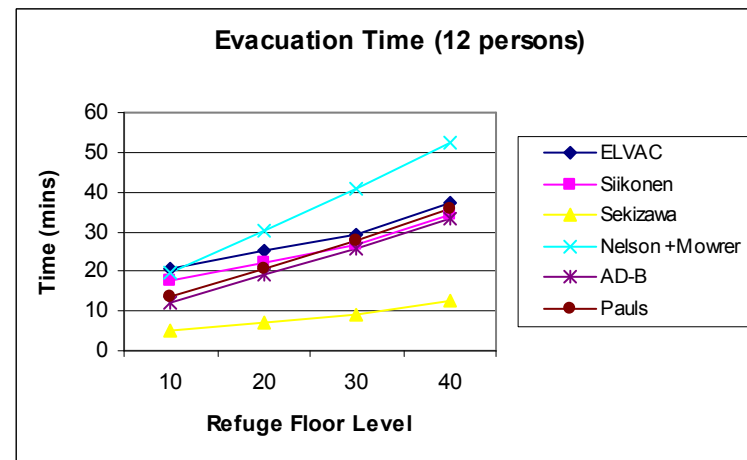
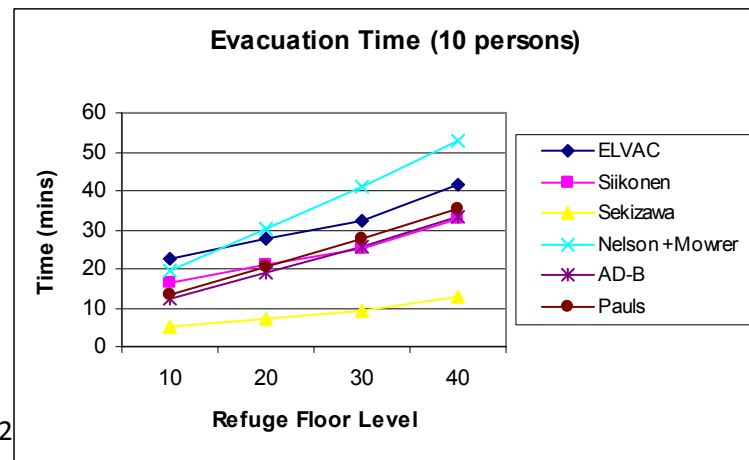


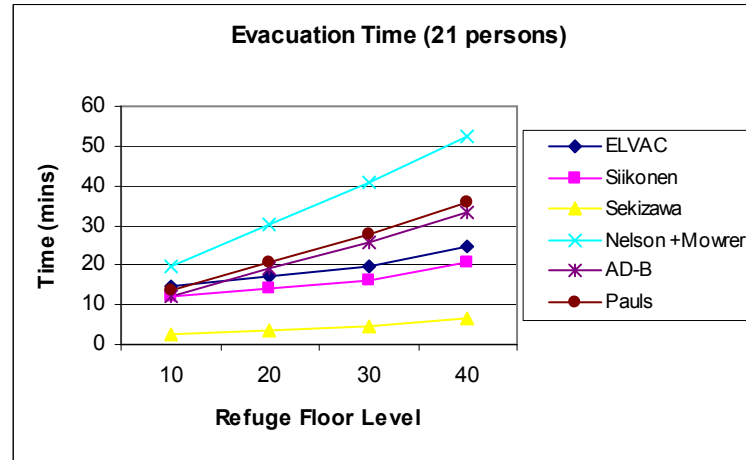
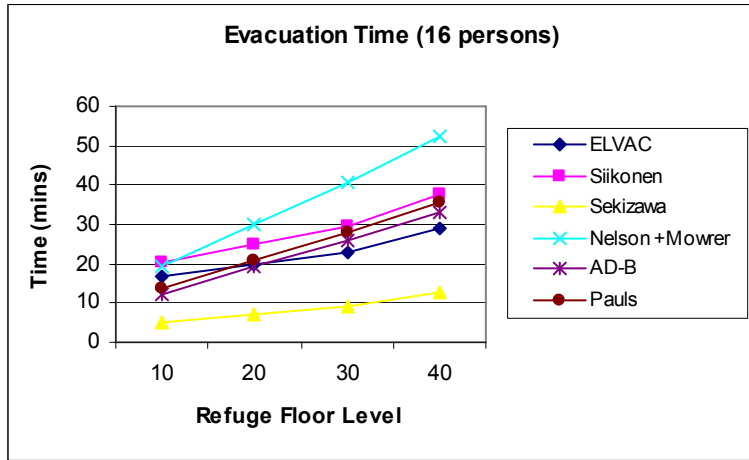


### 10 Storey Interval – Variable Acceleration

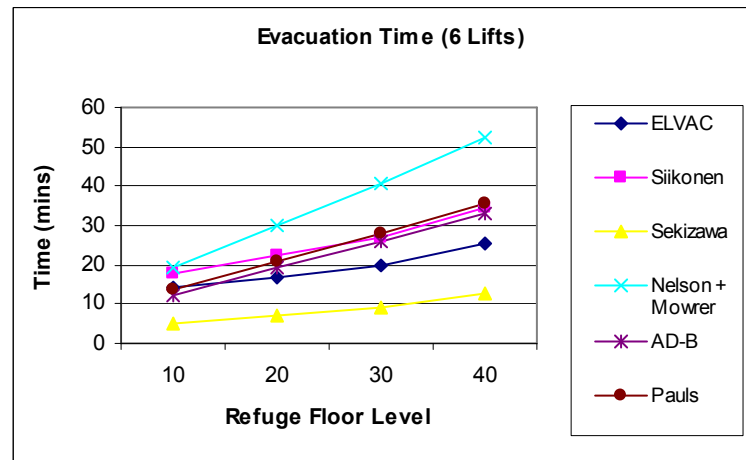
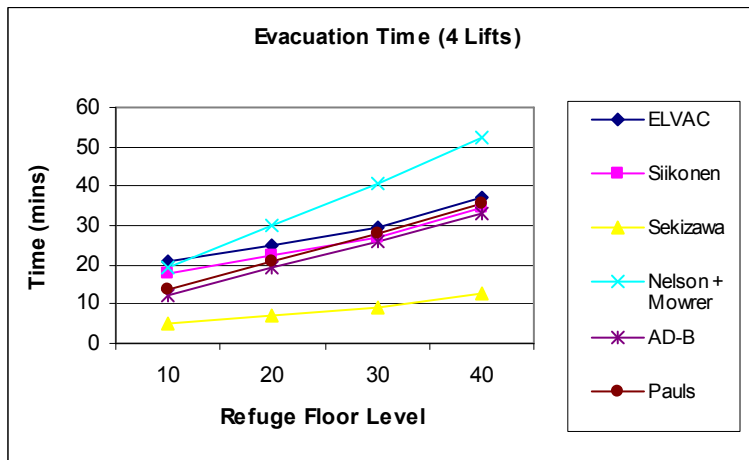


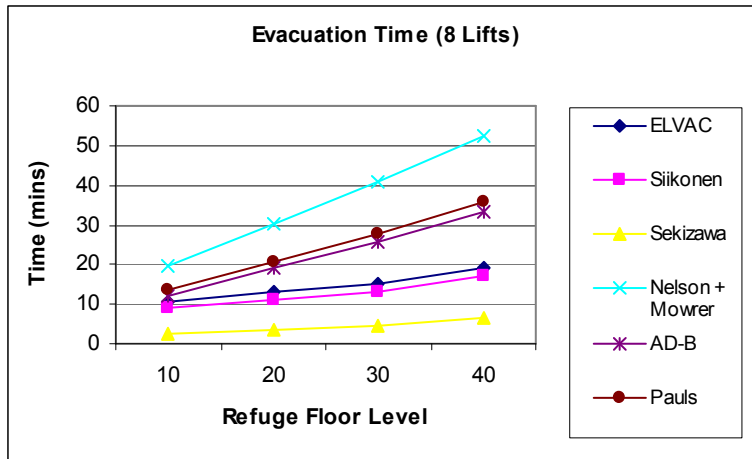
### 10 Storey Interval – Variable Capacity



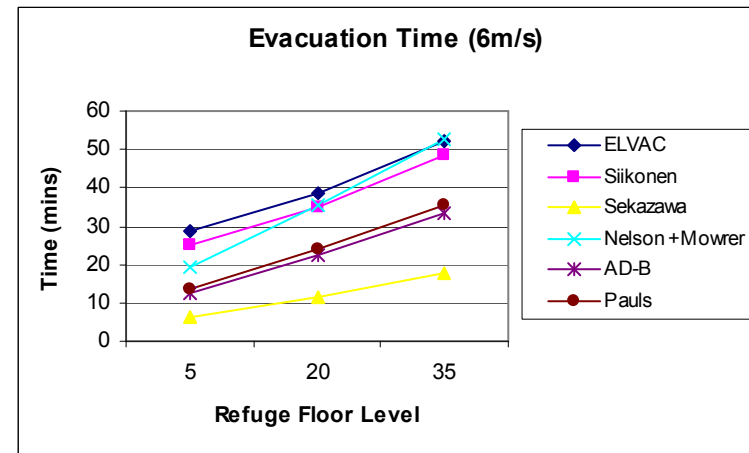
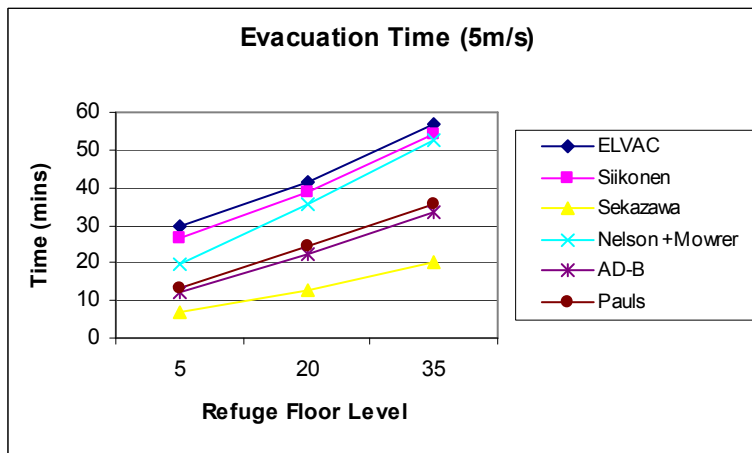


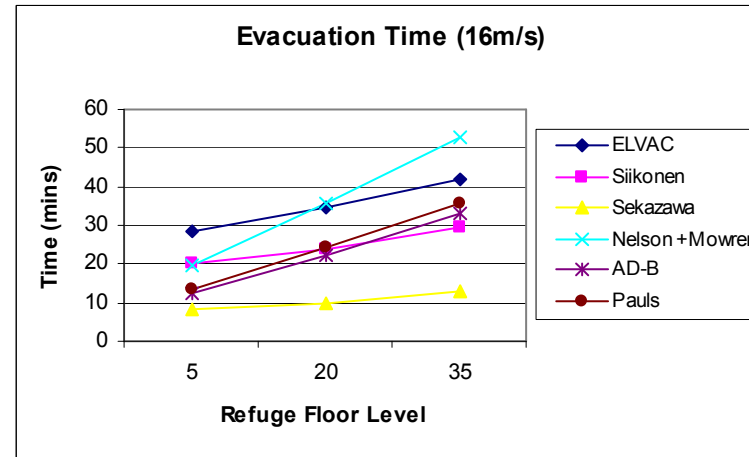
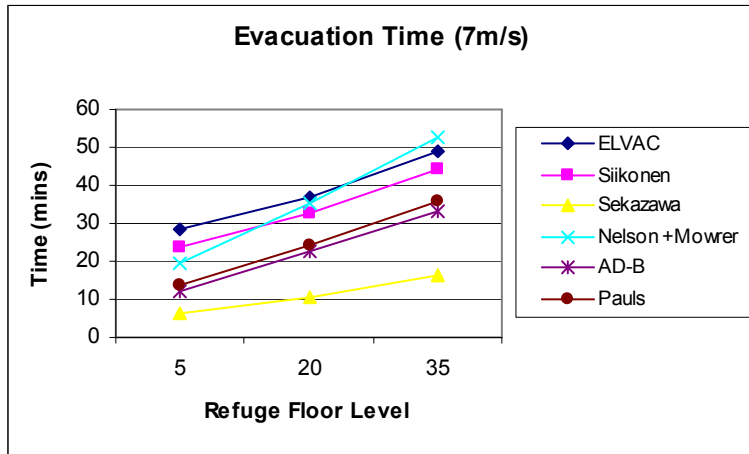
## 10 Storey Interval – Variable Lifts



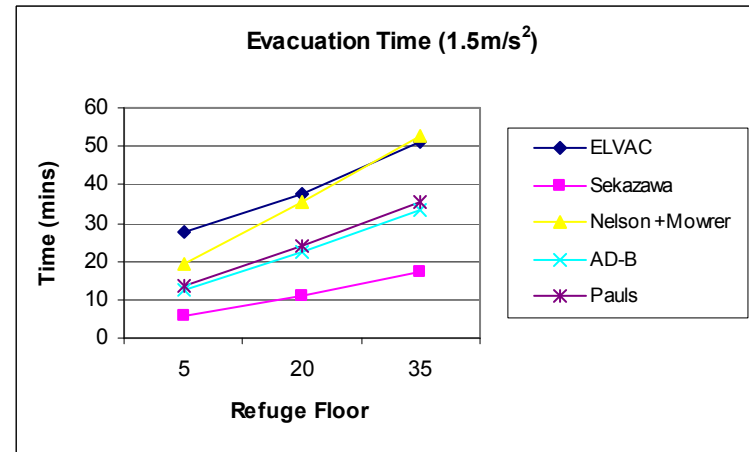
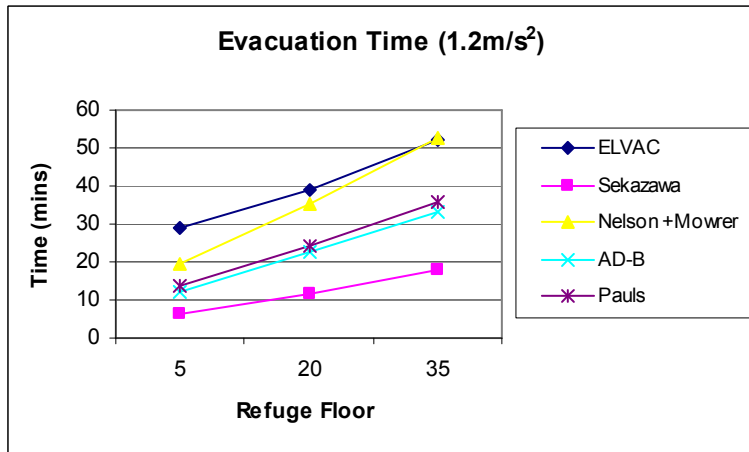


### 15 Storey Interval – Variable Speed

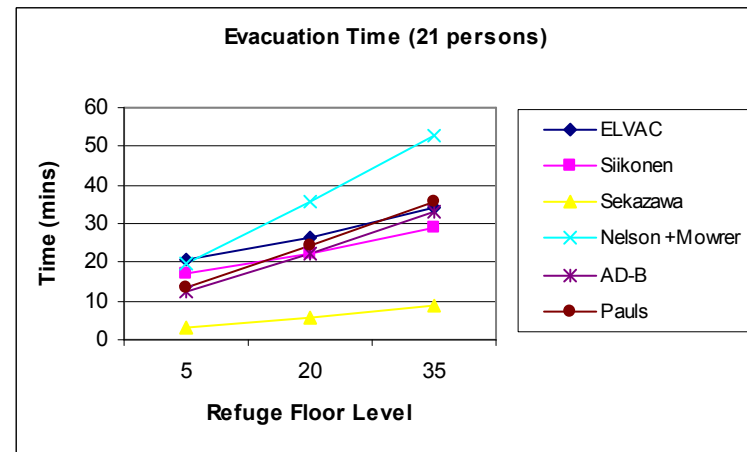
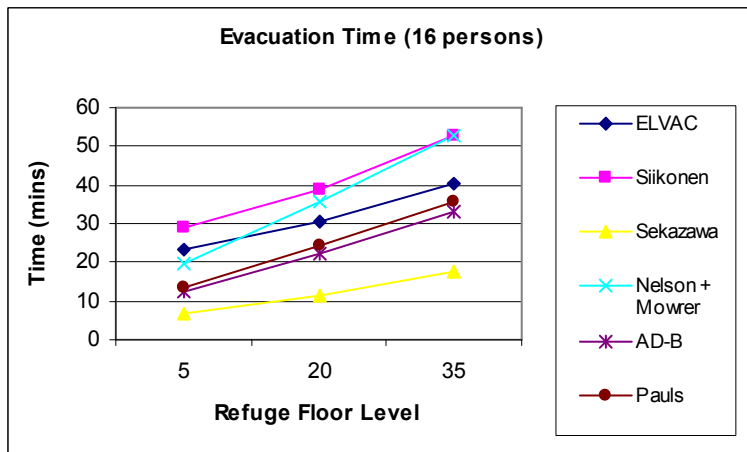
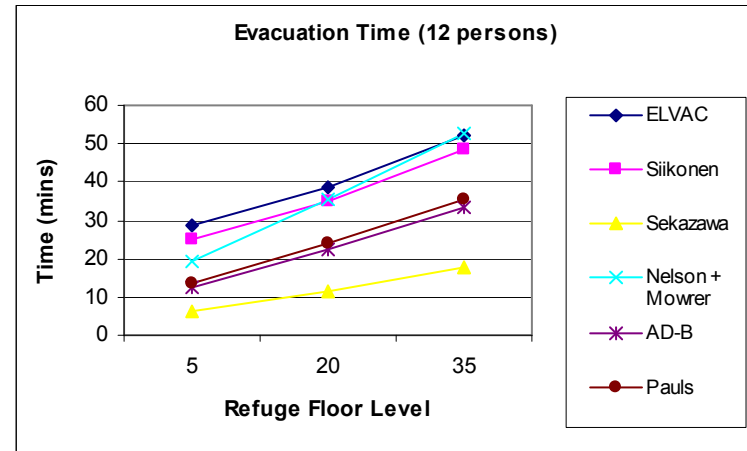
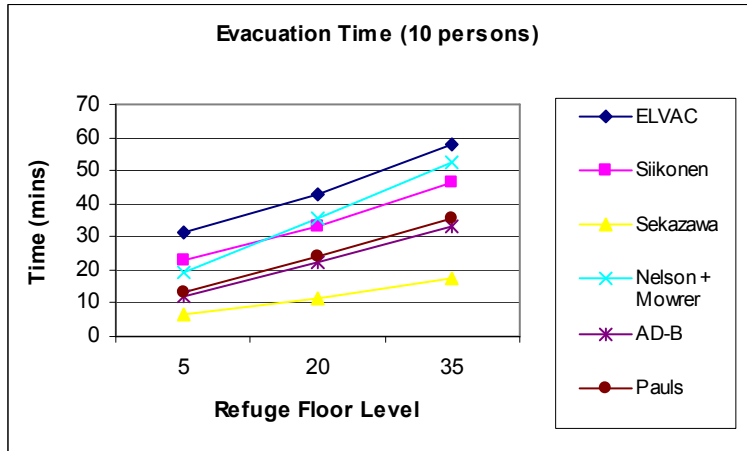




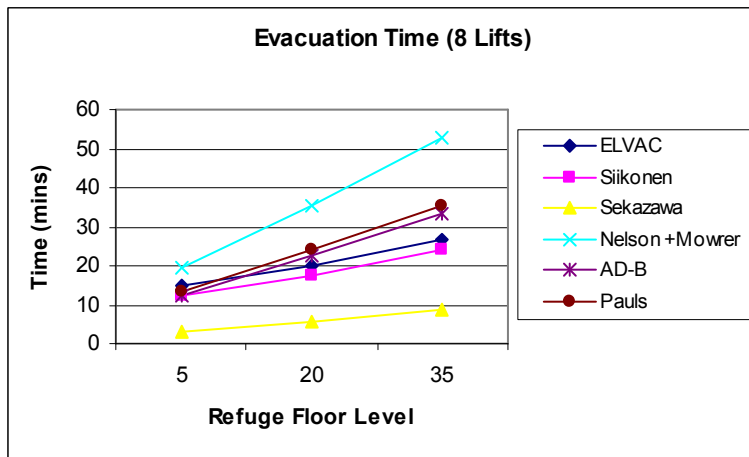
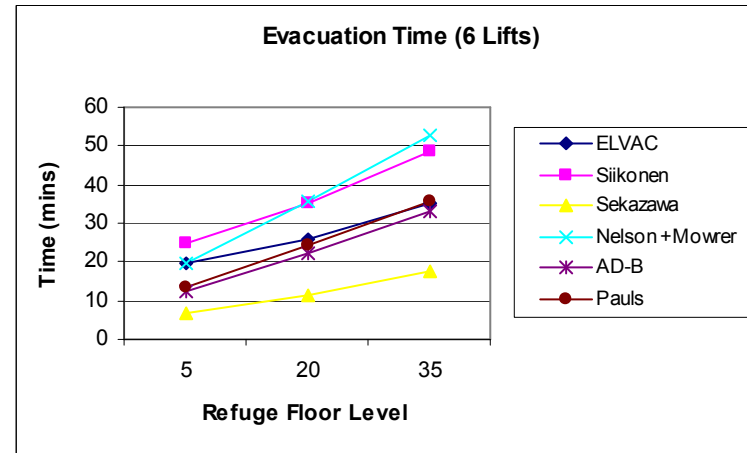
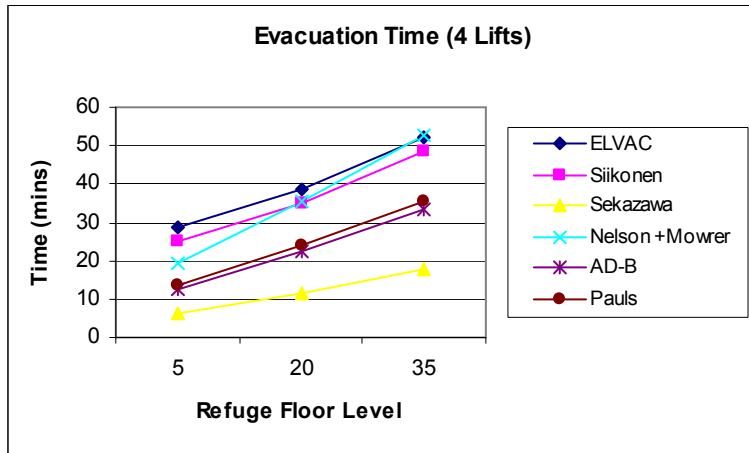
## 15 Storey Interval – Variable Acceleration



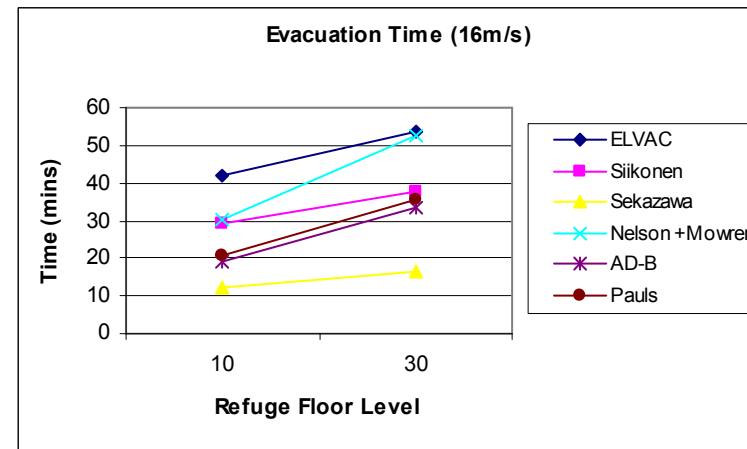
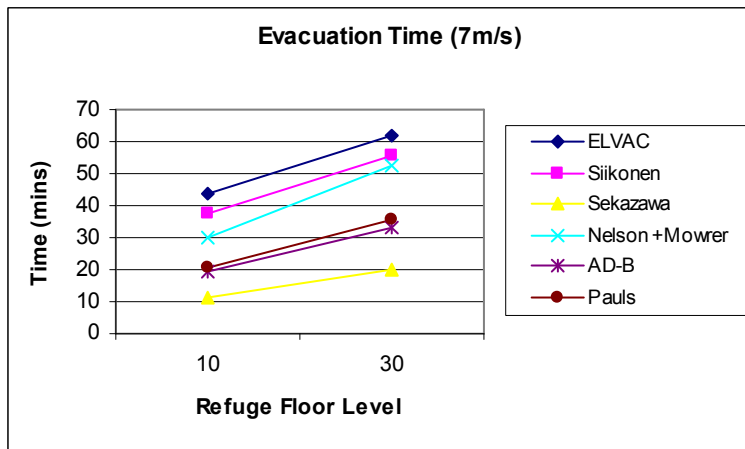
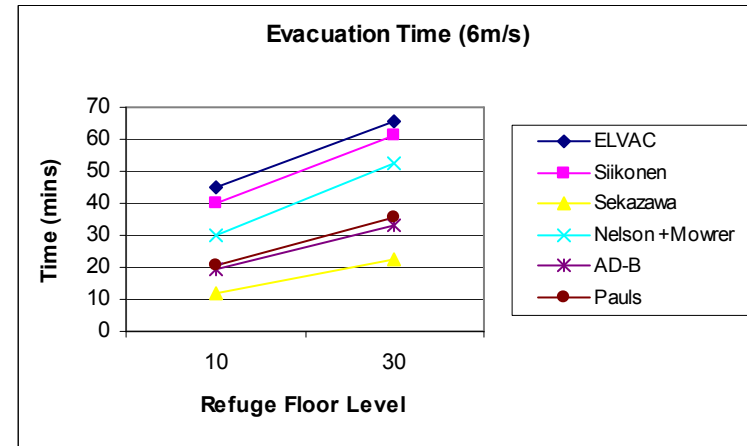
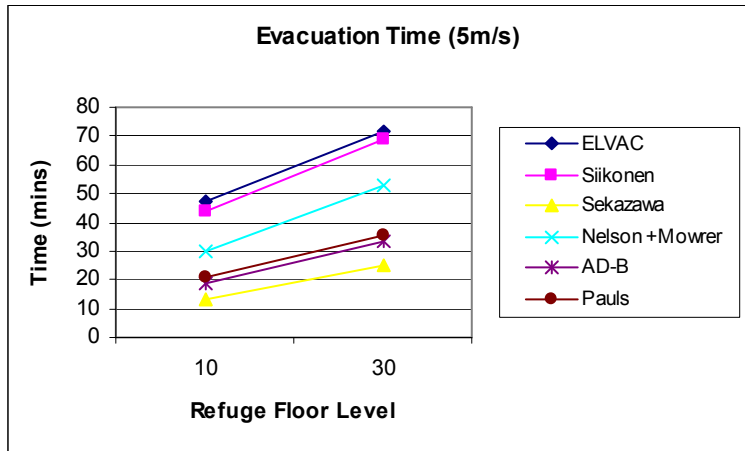
### 15 Storey Interval – Variable Capacity



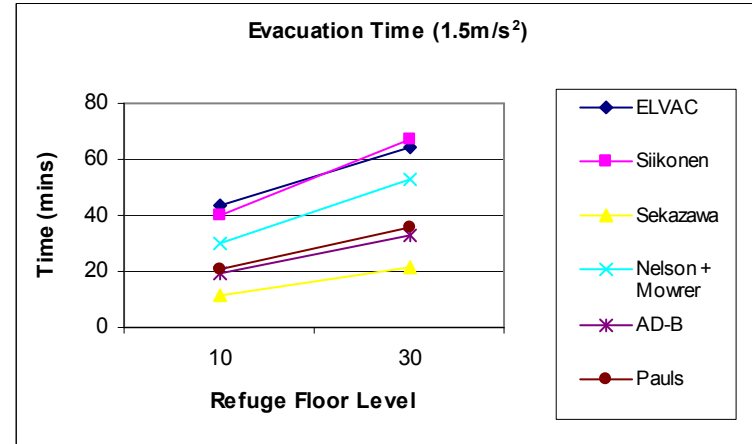
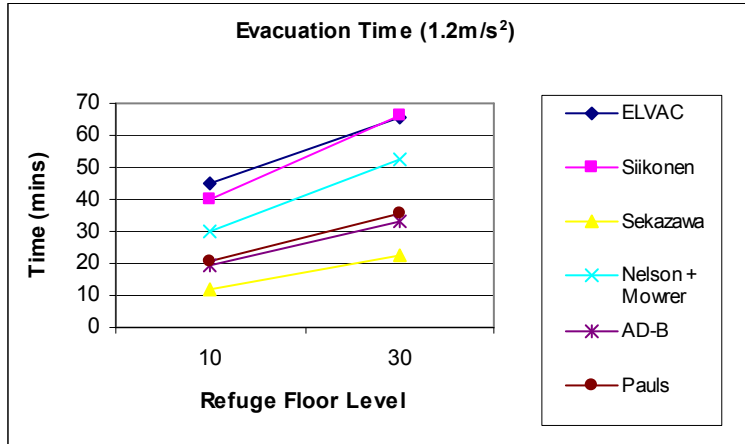
### 15 Storey Interval – Variable Lifts



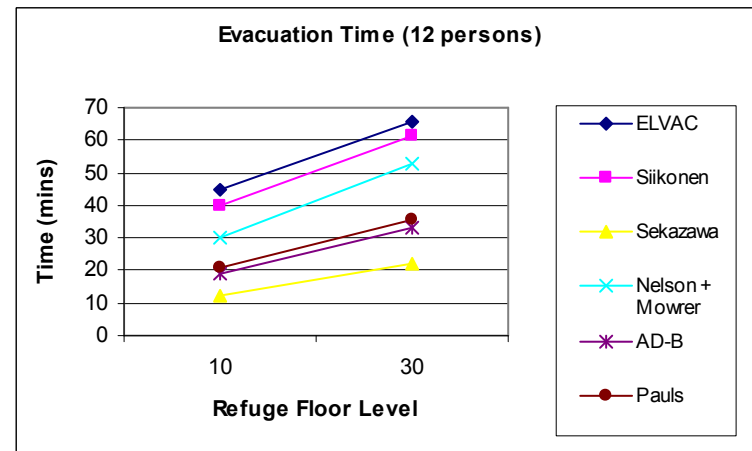
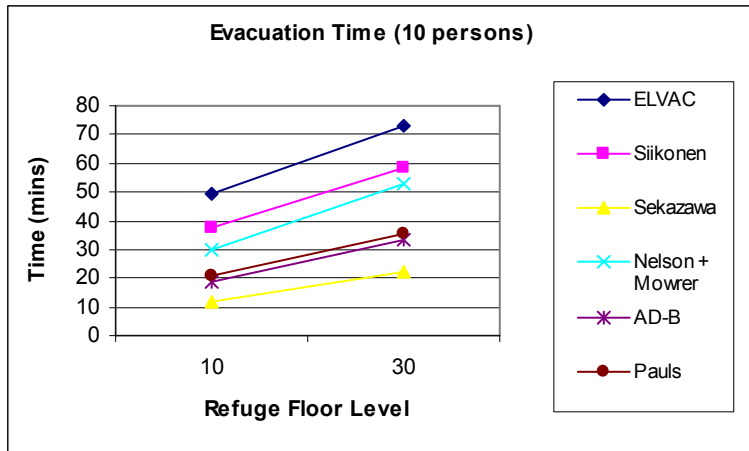
## 20 Storey Interval – Variable Speed



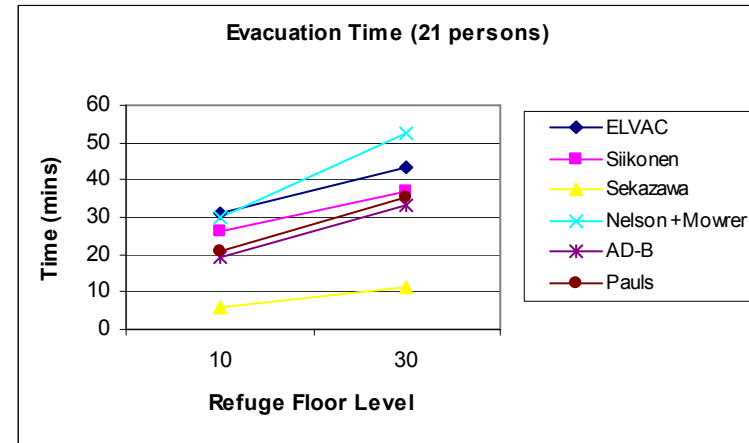
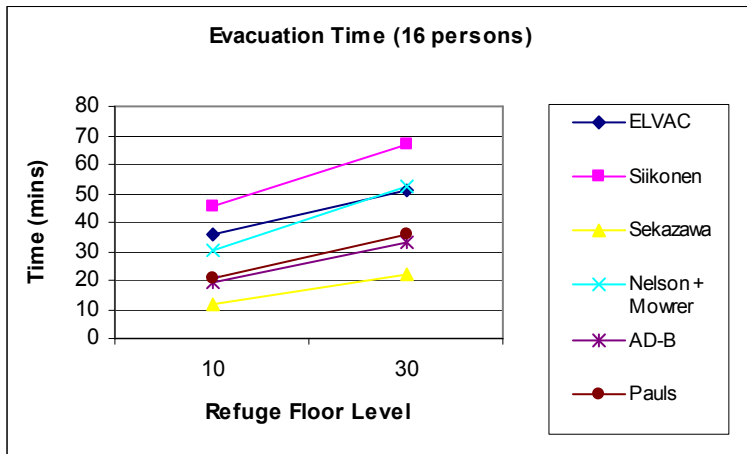
### 20 Storey Interval – Variable Acceleration



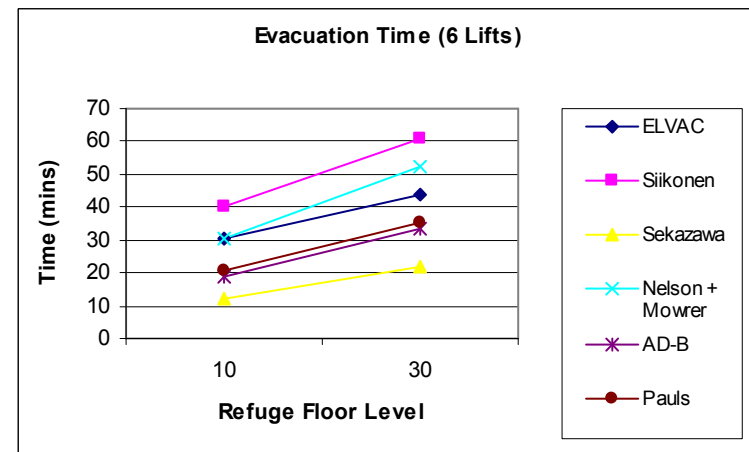
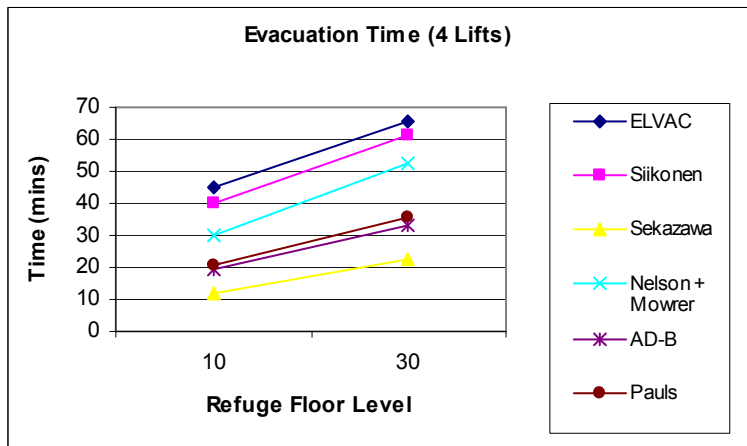
### 20 Storey Interval – Variable Capacity

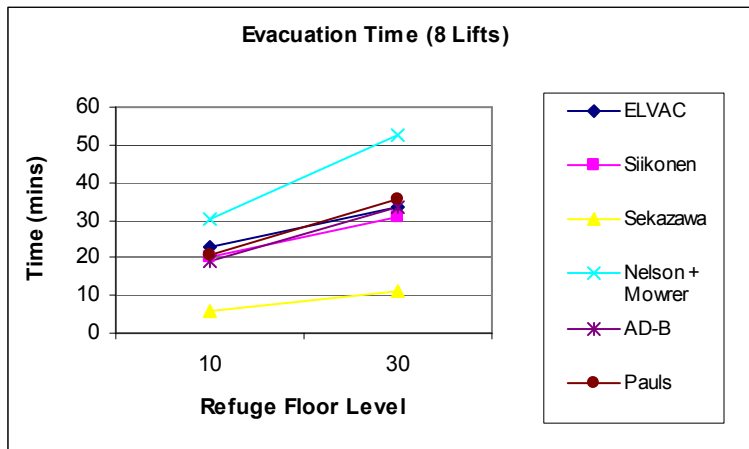




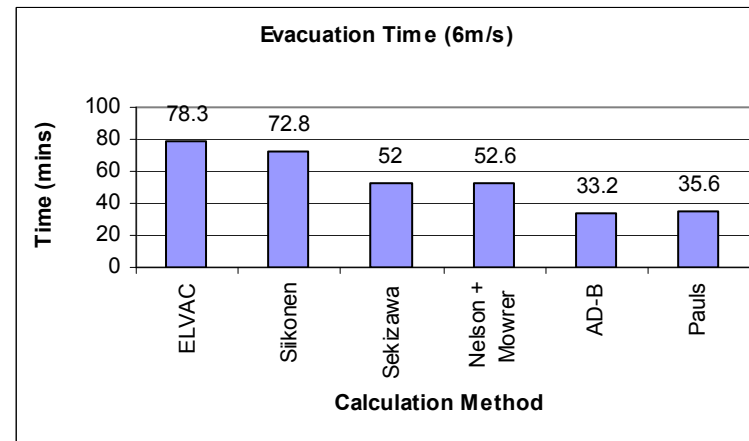
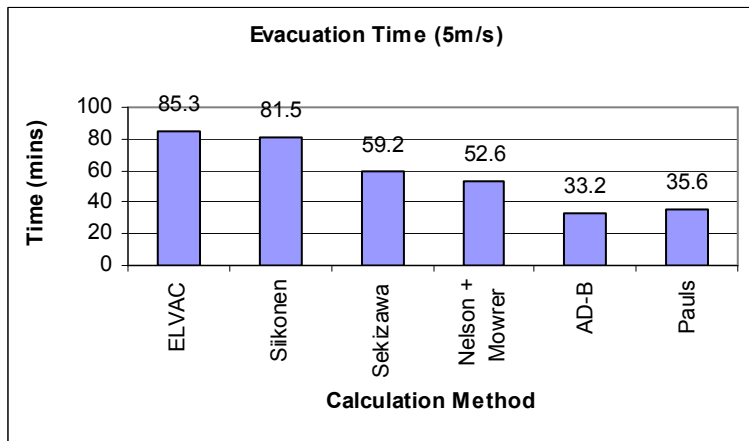


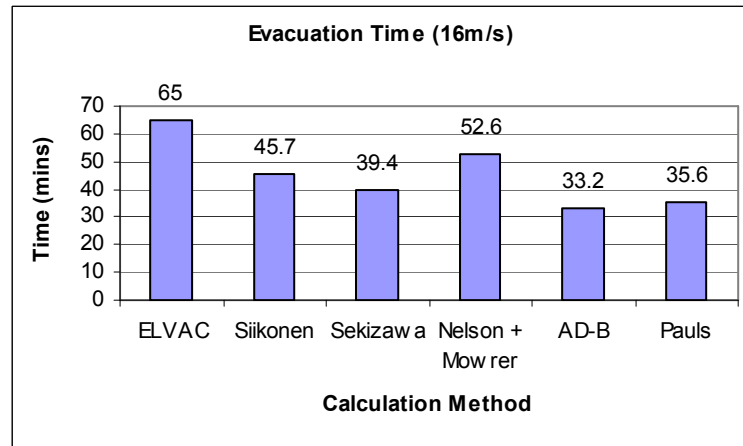
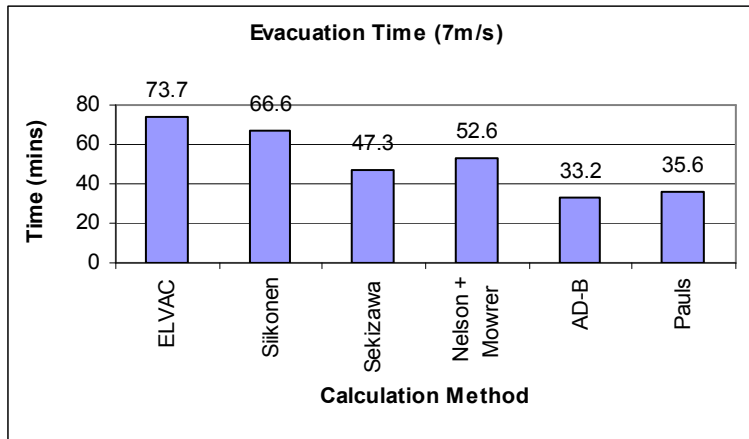
## 20 Storey Interval – Variable Lifts



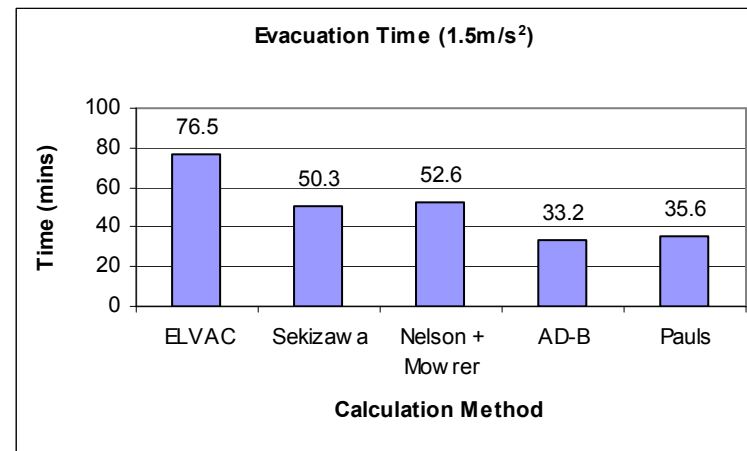
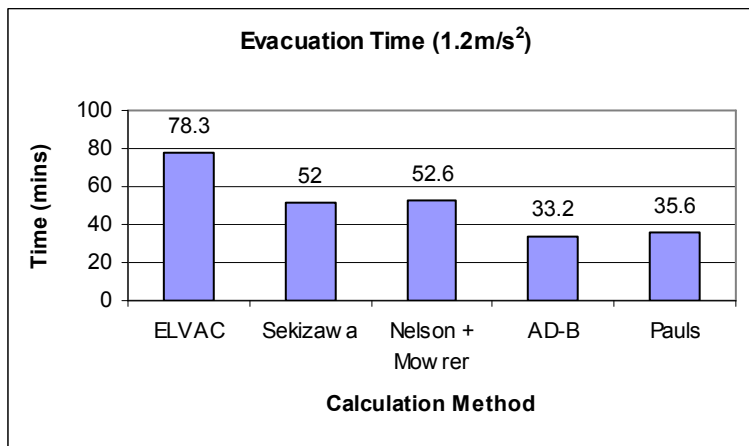


### 25 Storey Interval – Variable Speed

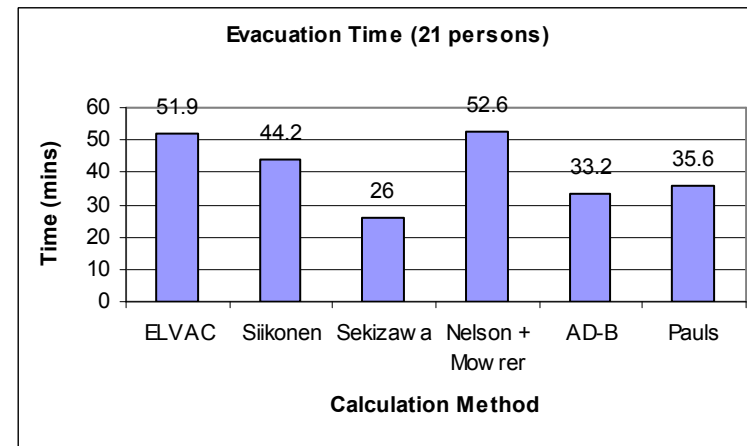
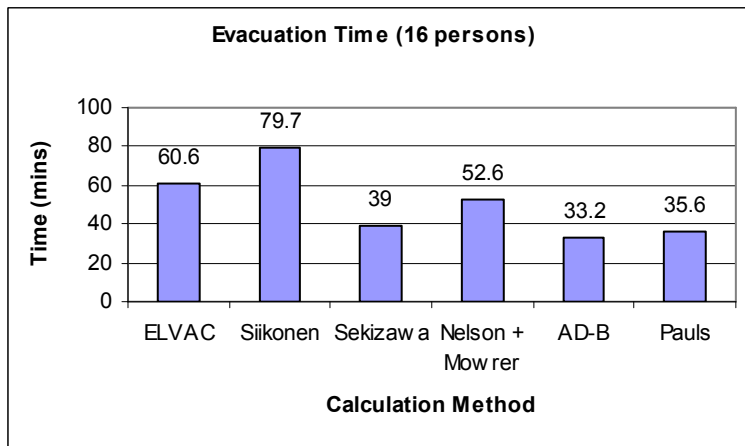
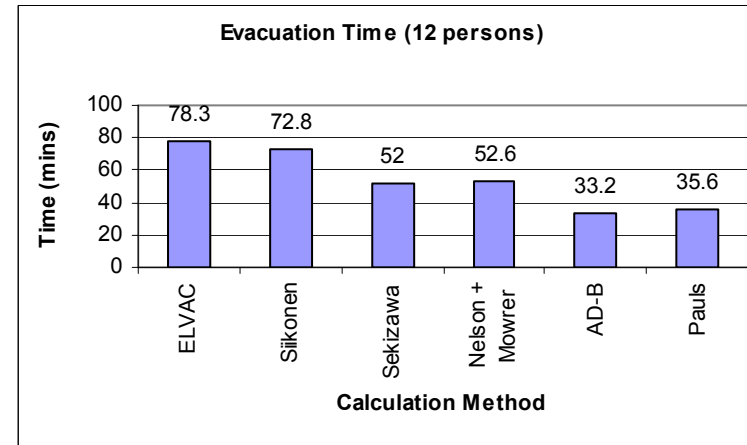
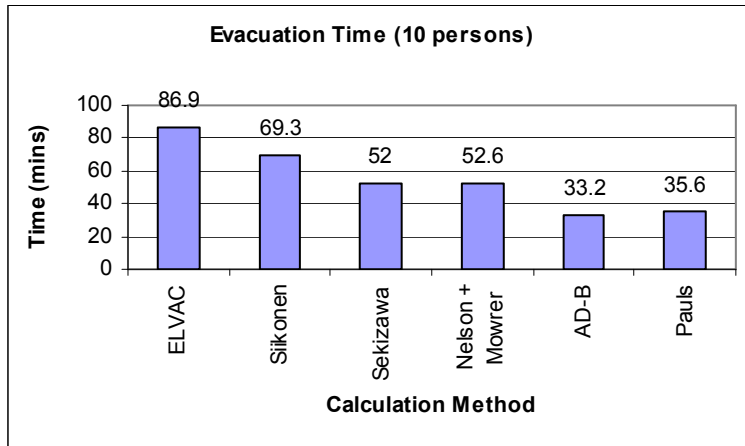




**25 Storey Interval – Variable Acceleration**



## 25 Storey Interval – Variable Capacity



**25 Storey Interval – Variable Lifts**

