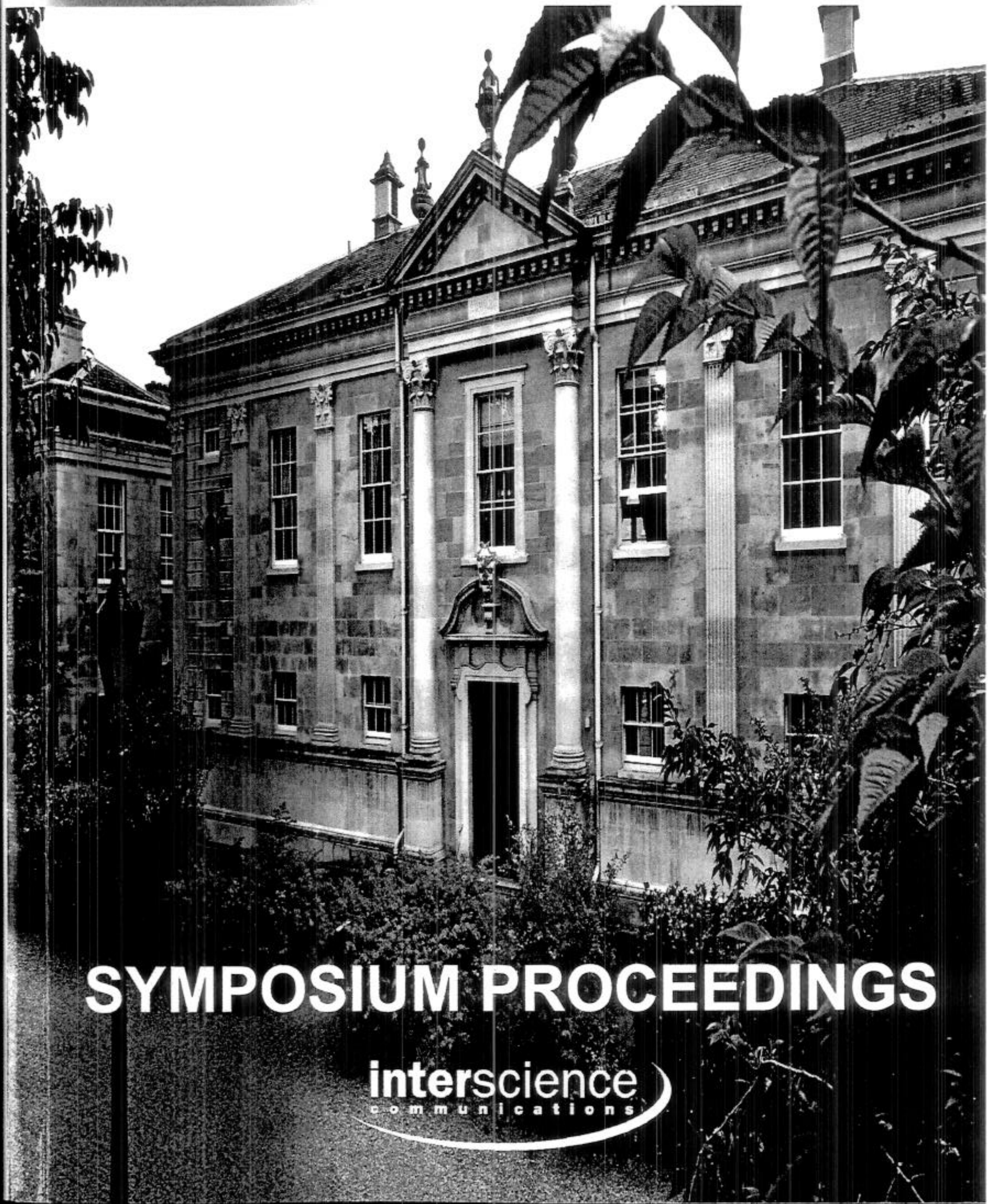
5th international Symposium

Human Behaviour in Fire 2012

Downing College, Cambridge, UK

19th - 21st September 2012



SYMPOSIUM PROCEEDINGS

interscience communications

Proceedings of the 5th International Symposium on Human Behaviour in Fire 2012

held at the Downing, Cambridge, UK
19-21 September 2012

A conference organised by:
Interscience Communications Ltd
West Yard House, Guildford Grove,
LONDON SE10 8JT, England

Human Behaviour in Fire 2012

ISBN 978-0-9556548-8-6

p619, 120 tables and 250 illustrations

ORGANISING COMMITTEE

INTRODUCTION

It gives me very great pleasure to welcome you all to this the 5th international symposium on Human Behaviour in Fire. Since the symposia's inception in 1998 we have directly influenced many changes and been prominent in the development of fire safety engineering. We see colleagues make career changes and sadly some are taken from us. All the more reason then to make the most of our time here together, to network and catch up with old friends and colleagues. Remember at this symposium there are no strangers here only friends waiting to be introduced.

The Programme Committee have selected a cross section of papers to stimulate the mind and hopefully the organisers will include some moments in the social programme to stimulate the senses! Some 43 technical papers and 14 poster papers are included along with Panel Discussions and Workshops on:-

- Life Safety Options for People with Disabilities - How far have we come? - Implications of Our Aging Society on Design and Management of Buildings
- Fundamentals of Egress Calculations for Life Safety Assessment
- Workshop on the Ethics of Behavioural Studies

As we approach the 5th symposium there many big issues to be addressed. For example, where exactly are we, in human behaviour terms, with respect to fire safety engineering and performance based design? Given our well established foundations what should be our focussing on for the next decade? These issues will be addressed at the symposium and your active partition in discussions surrounding them is eagerly anticipated.

I hope you will enjoy the next 3-4 days and like me, make the most of your time here in the fine surroundings of Downing College, Cambridge.

Prof. T Jim Shields

Symposium Chair

MODELLING HUMAN FACTORS AND EVACUATION LIFT DISPATCH STRATEGIES

Michael J. Kinsey, Edwin R. Galea and Peter J. Lawrence
Fire Safety Engineering Group,
University of Greenwich,
30 Park Row, Greenwich, London, SE10 9LS, UK

ABSTRACT

This paper presents an overview of a series of evacuation simulations utilising different lift dispatch strategies using an empirical based enhanced agent-lift model developed within the buildingEXODUS software. A brief description of the enhanced agent-lift model is presented. The evacuation scenarios investigated are based on a hypothetical 50 floor building with four staircases and a population of 7,840 agents. While past studies have measured the influence of such evacuation lift dispatch strategies assuming compliant/homogenous agent behaviour, this study extends that work by highlighting the potential influence of human factors upon such evacuation lift dispatch strategies. The study suggests that evacuation lift human factors can considerably decrease evacuation performance and highlights the need for consideration within evacuation strategies based on lifts.

INTRODUCTION

This proliferation of high-rise buildings of increasing height throughout the world coupled with the World Trade Center 911 attacks[1], has cast doubt over the capability of such buildings to provide adequate simultaneous full building evacuation using stairs alone. In many high-rise buildings the emergency stairwell widths are only designed to accommodate simultaneous evacuation from a select number of floors[2] (i.e. not designed for full simultaneous evacuation). Furthermore, modelling analysis has suggested that for a given building configuration, there is a maximum number of floors above which it is not practical to evacuate a high-rise building by stairs alone[3]. Subsequently, the use of lifts during evacuations, whilst not a new concept for the transport of disabled occupants and fire fighter access[4], has become a serious consideration over the last decade for the general population[5]. Several building codes and standards have now begun to consider and include the provision for lift usage for the general population during evacuations[4,6-8]. The increased interest in evacuation lifts requires the examination of the potential merits of evacuation lift strategies and associated human factors. Both of these factors can be explored through computer simulation[5].

Past simulation studies using such models and/or analytical calculations have demonstrated how a single lift dispatch strategy could potentially influence an evacuation compared to a stair only evacuation given a hypothetical scenario[5, 9-13]. As expected, results from such studies suggest that the combined use of lifts and stairs is recommended in order to reduce total evacuation times by increasing the vertical throughput within a building. It appears a common result in the majority of those studies, assuming optimum use of lifts and stairs, that the total evacuation time can be reduced by as much as 50%. The impact of evacuation lift human factors on such results has been neglected in such studies and indeed the primary purpose of such investigations appears to be for the demonstration of the potential impact of using lifts during an evacuation. Only a small number of studies have collected data related to human factors associated with lift usage during emergency situations[14-17].

However, to date no dedicated lift model or evacuation model represents empirical based lift human factors during evacuations.

In this paper an enhanced agent-lift model implemented within the buildingEXODUS evacuation software is presented which incorporates lift human factors based on data collected via an online survey[14,18]. The model has been used to demonstrate the potential influence of human factors upon a series of evacuation lift dispatch strategies.

ENHANCED AGENT-LIFT MODEL

The core software used in the study is buildingEXODUS V4.06. The basis of the software has frequently been described in other publications[19, 20] and so will not be described again here. Suffice it to say that buildingEXODUS is an agent based model used for the simulation of both evacuation and circulation.

The agent-lift model within buildingEXODUS[5,10] involves three core agent behaviours: (1) lift bank selection; (2) lift waiting area selection and wait duration; and (3) lift car selection and entry. The initial version of agent-lift model was considered to represent compliant/homogenous and non-adaptive behaviour. During the development of the initial lift model it was necessary to implement this simplified agent-lift model due to the lack of available human factors data describing how people would actually behave when attempting to use lifts in emergency evacuation situations. To address this issue and attempt to gain a better understanding of evacuation lift human factors, an online survey was carried out asking participants how they would behave with regards to lift usage within a hypothetical evacuation situation[14, 18]. Datasets from the survey formed the empirical basis for the enhanced agent-lift model[14, 18, 21]. Analysis of the datasets suggest that approximately half of all occupants would consider using a lift during an evacuation, with occupants choosing to actually use a lift varying with floor height, levels of crowding in the lift waiting area and lift wait time. In this analysis we have assumed that all agents will consider using a lift during an evacuation. This is intended to represents the increased acceptance of occupants to consider using a lift through having sufficient training. Consequently the results should be considered conservative. Note, that while agents will consider using a lift, this does not mean that they will in fact use the lift and may decide to use the stairs.

The algorithm used to determine whether or not an agent will decide to use the lift or the stair is complex and based on a number of factors, all of which are derived from an international survey conducted by the authors[18]. The first factor considered is the floor on which the agent is initially positioned. There is a probability that the agent will decide to use a lift which increases with floor number i.e. the higher the floor that the agent is initially located on, the higher the probability that they will decide to use a lift. Each agent is assigned a lift waiting area congestion threshold (LCT). If the agent enters the lift waiting area and the population density in the area is greater than or equal to their LCT the agent will immediately redirect to the stair. The LCT distribution, which is floor dependent is based on the data collected in the survey[18]. If the population density is less than their LCT the agent will wait for a lift. The agent is assigned a lift waiting time i.e. the maximum time the agent is prepared to wait for a lift, which is floor dependent and based on the data collected in the survey[18]. The lift waiting time is a function which increases with floor number. While the agent is waiting for the lift, if the LCT is reached there is a time dependent probability that the agent will continue to wait for the lift for the assigned lift waiting time. The probability of redirecting to the stair due to congestion decreases as the wait time increases. This means that agents who have waited in the lift waiting area for a longer period of time will have an increased chance of maintaining their initial choice to use the lift if their LCT is reached or exceeded. Agents whose LCT is reached after being in the lift waiting area for a short period of time will have an increased probability of redirecting to the stairs; representing a decreased level of commitment to their initial choice to use a lift.

If the agent has not boarded a lift by the time their lift wait time has expired they will redirect to the stairs. Irrespective of an agent redirecting to the stairs either due to congestion or lift wait time

expiration, providing the agent is still inside the lift waiting area they are still able to board a lift should one arrive and have sufficient space inside. This allows agents that have redirected to the stairs but still inside the lift waiting area to board a lift should it become available i.e. they will not walk past an open lift if they are able to board it.

THE SIMULATIONS

A series of 11 full building evacuation scenarios have been performed using the enhanced agent-lift model using a hypothetical building. Results of identical scenarios using the initial agent-lift model where agent behaviour was compliant, homogenous and not based on empirical data can be found in[5]. The configuration of the software used for each scenario and the nature of each scenario is briefly described in the following sections.

Geometry

The building has 50 floors with a floor to floor height of 3m (the total height of the building was 150m in height), with four stairwell cores and four lift banks each containing eight lifts. With the exception of the ground floor all levels in the building have the same layout and configuration. In certain scenarios specific floors were designated as sky lobbies where agents from multiple floors moved to in order to use a lift during their evacuation. In such buildings, it is common to find that sky lobbies are intended to be refugee areas with sufficient occupant capacity and fire/smoke/water protective measures in place to protect the enclosed population. However, the influence of such configuration factors upon evacuation dynamics is considered beyond the scope of the study.

Each stair within the building allowed two agents to stand abreast side-by-side with agents preferring to stagger their locations (i.e. prefer not to stand side-by-side) and maintain at least one tread spacing between themselves and the agent in front. Each stair is dog-legged design with a mid-floor landing (1m x 3.2m) connecting the two legs; each leg being 1.5m in width and 4.6m in horizontal length allowing a maximum of 16 agents to simultaneously occupy each leg of the stairs at a time. Within the building all of the lifts have the capacity to service all floors. It is recognised that many high-rise buildings include vertical partitioning of lifts, where lifts are restricted to service a given range of floors. However, the purpose of allowing all lifts and stairs to service all floors was to allow for flexibility in exploring a variety of different evacuation procedures without being inhibited by physical vertical partitioning/zoning of the lift shafts, which is typically dictated by ingress performance requirements. Due to the hypothetical nature of the building, aside from the external walls and the stair/lift cores, no furniture or internal obstructions were represented within the building geometry.

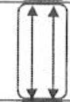
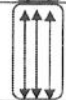
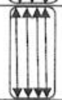
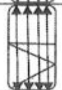
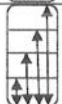
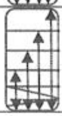
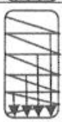
Population

The building population comprised 7,840 agents. With the exception of the ground floor, there were 160 agents located on each floor. Agents were modelled as non-connected individuals and were not constrained by groups. The population used the default population attributes within buildingEXODUS[19] and consisted of people with different movement capabilities reflecting the variety of the different ages, genders and abilities. All agents were assumed to react instantly at the beginning of each scenario so response time is not considered a parameter within this analysis.

Agent-Lift Interaction

At the beginning of each scenario agents were assigned to either use a lift or stairs based on a probability distribution according to the floor each agent started on. Of agents that were assigned to use a lift, they choose to use a lift bank which was not already over-subscribed by other agents i.e. approximately an equal number of agents used each lift bank on each floor. Likewise, stair users were assigned which stair to use based on the same system. This concept of equal core load balancing was considered appropriate as unequal use of lift banks or stairwells has the potential to significantly increase total evacuation time and levels of congestion. While this type of sub-optimal behaviour is likely to occur in actual situations, exploring such behaviour is not considered relevant to this analysis and so is not included.

Table 1: Overview of evacuation scenarios

Scenario	Diagram	Description
1		Stairs only (4 stairs)
2		8 lifts (1 lift bank)
3		16 lifts (2 lift banks)
4		24 lifts (3 lift banks)
5		32 lifts (4 lift banks)
6		32 lifts, with the lower half of the building (floors 0-25) population using the stairs and the upper half (26-49) using the lifts to shuttle to the ground floor.
7		32 lifts, with the lower-half of the building (floors 0-25) population using the stairs and the upper half (26-49) using the lifts to shuttle to the middle floor (floor 25) from the agents floor of origin, then continue their evacuation via the stairs.
8		32 lifts, with the lower-half of the building (floors 0-25) population using the stairs and the upper half (26-49) initially using the stairs to walk to a sky lobby on floor 26 where agents would be shuttled via lifts to the ground floor.
9		32 lifts, 4 shuttle zones - each lift bank servicing a series of 12 floors of agents, with each zone being evacuated from the top-down of the zone to the ground floor.
10		32 lifts, 4 shuttle zones + 1 Stair zone - each lift bank servicing a series of 10 floors of agents, with each zone being evacuated from the top-down of the zone to the ground floor. Agents below floor 10 only use the stairs to evacuate.
11		32 lifts, 4 Sky lobbies – there is a sky lobby every 10 floors in the building (4 sky lobbies in total) with each lift bank servicing one of the sky lobbies. Agents travel down the stairs to the next sky lobby below where the lifts shuttle them to the ground floor. Agents below floor 10 only use the stairs to evacuate.

Of agents that were assigned to use a lift they were also assigned a lift wait area congestion threshold value based on a probability distribution according to the floor each agent started on. When those agents enter into the chosen lift waiting area, providing they do not redirect to the stairs due to the

levels of congestion, are initially assigned a wait location along with a lift wait time derived from a lift wait time distribution, again according to the floor each agent started on.

The lift stair probability value, congestion threshold value and lift wait time values assigned to agents were derived from probability distributions based on the survey data. Certain sky lobby scenarios required agent's to initially traverse a number of floors via the stairs before using a lift. It was considered appropriate to assign the agents respective lift behaviour values from the datasets according to the floor the agents initially started on as opposed to the floor they had the option to board the lift i.e. the sky lobbies. Due to the trends in the datasets, this meant that agent's initially higher above the sky lobby would likely have a higher chance of electing to use a lift, have a higher tolerance to congestion levels and be prepared to wait a longer amount of time for a lift than those agents typically closer to the sky lobby floor.

Lift Attributes

The defining attributes for the lift kinematics and physical characteristics were based on the Chartered Institution for Building Service Engineers (CIBSE) Guide D: Transportation Systems in buildings[22]. Each lift had a maximum capacity of 13 agents, a maximum speed of 6 m/s, acceleration rate of 1.2m/s² and a jerk rate of 1.8 m/s³. In addition each lift had a door opening time of 0.8s, door closing time of 3.0 seconds, a dwell delay of 3.0 seconds and a motor delay time of 0.5 seconds. Using these parameters approximately 31.5s are required for a car to travel from the ground floor to the top floor and fully open its doors. At the beginning of each simulation each lift started at the ground floor. For each lift simulation not involving stairs, where lifts serviced multiple floors (i.e. non-sky lobby scenarios), a top-down-shuttle evacuation strategy was employed by each of the lifts whereby all the lifts evacuate the agents on the top floor first and shuttle them to the ground floor. This process is repeated until all people evacuated that floor. The lifts then proceed to the floor below this and the process is repeated until all of the floors in the sequence have taken all agents on those floors to the exit floor.

Scenarios

In each of the 11 full building evacuation scenarios, different combinations of lifts and stairs were used. In each case, the priority for the lifts was to service the upper floors first, sequentially working down to the lower floors. Several scenarios examined the use of shuttle lifts and sky lobby arrangements. The full list of scenarios is summarised in Table 1.

The different frequency of lifts used in certain scenarios is intended to explore the impact of lift number in evacuation efficiency and to explore the affects of lift banks being rendered inoperable during an evacuation (e.g. due to fire, technical fault etc). For each scenario all lifts initially started on the ground floor.

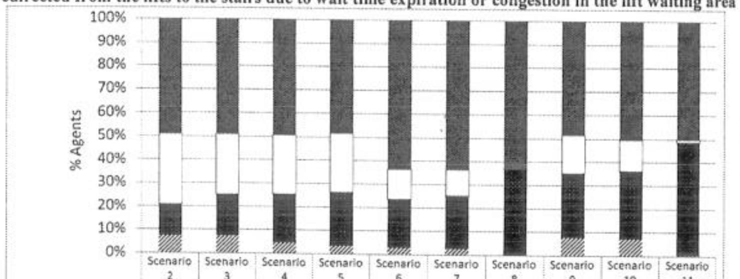
RESULTS AND DISCUSSION

A summary of results for the various simulations using the enhanced agent-lift model are presented in Table 2. In the 8 lift scenario (Scenario 2), the last agent to evacuate came from the stairs 14.3 min after the last lift user. From Figure 1 it can be seen that only 13.3% of agents actually used a lift. Indeed no agents on floor 10 and below used a lift to evacuate, while the largest proportion of lift users were located on the top ten floors of the building (see Figure 2). This indicates that the lift system was heavily under-utilised during the evacuation. This scenario cleared the top half of the building in 14.7 min representing a 26.6% decrease compared to the stair only scenario however; the building was cleared in 32.4 min representing an improvement of only 9.7% on the stair only case. The majority of agents who initially considered using a lift redirected to the stairs. Most of these agents (30.3%) were not prepared to wait longer to use a lift, though a small proportion (7.3%) redirected due to congestion in the lift waiting area (see Figure 1). Those who did redirect to the stairs waited on average 3.4 min in the lift waiting area. This was almost half as long as the average time that agents who used a lift waited (6.3 min) (see Table 3). Agents initially in the upper part of the building were serviced first by the lifts. In the lower part of the building there were only a small proportion of agents who considered using a lift. This explains why a lower proportion of agents redirected due to wait time expiration in both the upper and lower parts of the building (see Figure 2).

Table 2: Enhanced agent lift model simulation results - Summary

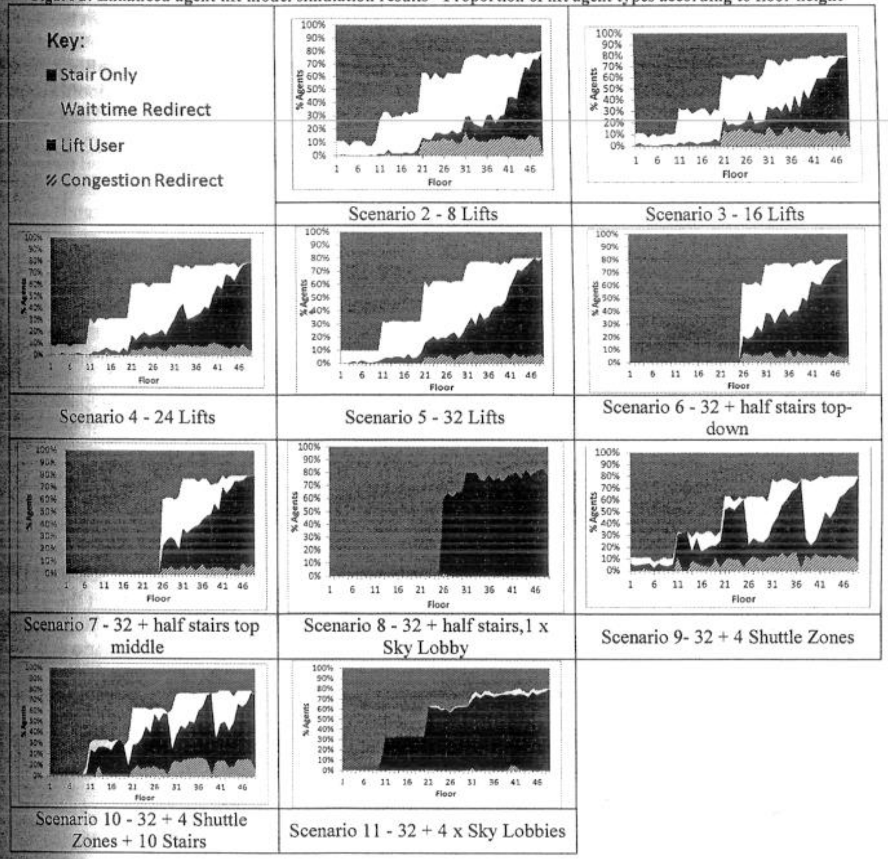
Scenario	Number of lifts	Evacuation time of last lift user (min)	Evacuation time of last stair user (min)	% Time saved (compared to stairs only)	Time to evacuate top half of building (floor ≥26) (min)	Avg PET (min)	Time taken to evacuate proportion of the population (min)		
							25%	50%	75%
1	0	-	35.9	-	20.3	17.6	9.3	17.5	25.8
2	8	18.1	32.4	9.7	14.9	14.4	7.4	13.6	21.3
3	16	14.8	31.0	13.6	13.1	13.3	6.4	14.2	20.1
4	24	12.4	29.6	17.5	13.2	12.5	5.7	11.2	19.0
5	32	12.0	29.1	18.9	10.9	12.0	5.2	10.9	18.3
6	32 + half stairs top-down	8.9	29.4	18.1	12.9	12.3	5.3	10.8	19.0
7	32 + half stairs top middle	35.7	35.7	0.6	22.0	17.6	9.4	17.6	25.9
8	32 + half stairs, 1 x Sky Lobby	18.5	24.9	30.6	17.4	10.9	6.1	10.9	15.4
9	32 + 4 Shuttle Zones	11.7	27.5	23.4	13.3	10.7	4.6	9.2	16.7
10	32 + 4 Shuttle Zones + 10 Stairs	11.3	26.6	25.9	13.5	10.5	4.6	8.7	16.3
11	32 + 4 x Sky Lobbies	14.0	24.0	33.1	16.5	8.2	4.4	7.4	11.3

Figure 1: Enhanced agent lift model simulation results - Overall Proportion of agent that used the stairs, lifts and redirected from the lifts to the stairs due to wait time expiration or congestion in the lift waiting area



	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11
■ Stair Only	49.0%	49.0%	49.3%	48.5%	63.6%	63.6%	63.1%	48.5%	50.3%	50.1%
□ Wait time Redirect	30.3%	26.1%	25.3%	25.3%	12.9%	11.2%	0.01%	16.4%	13.4%	1.4%
■ Lift User	13.3%	17.7%	20.9%	22.8%	20.7%	22.6%	36.8%	27.7%	29.2%	48.1%
▨ Congestion Redirect	7.3%	7.3%	4.5%	3.5%	2.8%	2.6%	0.1%	7.5%	7.1%	0.4%

Figure 2: Enhanced agent lift model simulation results - Proportion of lift agent types according to floor height



When further lift banks were included (Scenarios 3-5) only a marginal decrease in TET compared to the stair only scenario was produced. In these scenarios, the decrease in TET ranged from 9.7%-17.5% compared to the stair only scenario. The time to evacuate the top half of the building was 26.6%-46.3% (5.4 min-9.4 min) shorter than the stair only scenario. Of all the scenarios examined, Scenario 5 produced the shortest overall time to empty the upper half of the building, which is almost 50% faster than the stair only case.

Even though the number of available lifts increased in each scenario, up to a maximum of 400% in Scenario 4, the proportion of agents that used a lift only increased by 17.7%-22.8% (see Figure 1). This is because agents are not prepared to wait long periods of time for the lift to service the majority of floors. This is supported by Figure 2 which shows that a large number of agents redirect due to long wait times. Further to this, as the number of lifts increased, only a marginal decrease in the agent lift wait time (LWT) was recorded (see Table 3). This suggests that irrespective of the number of lifts available, using a top-down evacuation strategy for the entire building is not very effective as agents will incur excessive wait times and so are likely to redirect to the stairs.

Table 3: Enhanced agent lift model simulation results - Average LWT of all agents that considered using a lift; lift users and non-lift users (agents who initially chose to use a lift but then redirected to the stairs)

Scenario	Number of lifts	Avg Lift User LWT (min)	Avg Non Lift User LWT (min)	Avg Overall LWT (min)
2	8	6.3	3.4	4.2
3	16	4.7	2.8	3.5
4	24	4.1	2.8	3.3
5	32	3.8	2.7	3.2
6	32 + half stairs top-down	3.2	2.1	2.7
7	32 + half stairs top middle	2.9	2.1	2.6
8	32 + half stairs, 1 x Sky Lobby	0.0	0.1	0.0
9	32 + 4 Shuttle Zones	3.2	2.0	2.7
10	32 + 4 Shuttle Zones + 10 Stairs	3.2	1.8	2.6
11	32 + 4 x Sky Lobbies	0.5	1.3	0.5

In Scenario 6 all agents initially located in the lower half of the building used the stairs to evacuate (50% of the population) and agents initially located in the upper half of the building had the option to use either a lift or stair to travel to the ground floor. Due to all agents in the lower half of the building using the stairs an increased proportion of stair users (63.6%) were recorded compared to Scenario 5 (see Figure 1). The TET for this scenario was comparable to the 32 lift scenario (Scenario 5) at 29.4 min. It can be seen in Figure 2 that very few agents in the lower half of the building used a lift in Scenario 5. As such forcing those agents to use the stairs in Scenario 6 had little impact on the TET. The time to clear the upper half of the building took 2 min longer in Scenario 6 than in Scenario 5. This reflects the increased crowding on the stairs in the lower half of the building in Scenario 6. This increased crowding was caused by agents all directly going to the stairs in the lower half of the building (in Scenario 6). Whereas in Scenario 5, almost a third of agents (28.8%) in the lower half of the building initially went to use a lift before redirecting to the stairs. This staggered their arrival time to the stairs. A comparable average LWT for lift users was recorded in Scenario 6 (3.2 min) compared to Scenario 5 (3.8 min) (see Table 3).

Similar to Scenario 6, in Scenario 7 agents in the lower half of the building used the stairs to evacuate with agents in the upper half of the building having the option to use a lift to take them to the central floor before using the stairs to evacuate. The TET for this scenario was comparable to the stair only scenario as all agents were required to use the stairs to traverse the lower half of the building. As in Scenario 6, the impact of restricting lift usage to agents in the top half of the building had little effect on the proportion of agents that used a lift (see Figure 2). The increased number of agents entering the stairs on the central floor (from using a lift) restricted the flow of agents on the stairs coming from the upper floors. This resulted in the time to clear the upper part of the building taking marginally longer (1.7 min (8.4%)) than the stair only scenario.

The single sky lobby scenario (Scenario 8) where agents in the top half of the building had the option to use a lift on the central floor, produced the second shortest evacuation with a decrease in TET of 30.6% (11 min) compared to the stair only scenario. Despite this, the time to clear the upper half of the building was only marginally less (2.9min (14.3%)) than the stair only scenario at 17.4 min. The majority of agents (36.8%) that considered using a lift to evacuate did so with a small proportion redirecting to the stairs due to congestion (0.1%) or lift wait time expiration (0.1%) (see Figure 1 and Figure 2). This was caused by the staggered arrival of agents into the sky lobby as they were required to initially traverse the stairs. This meant that very few agents experienced high levels of congestion in the lift waiting area. This was further contributed to by there being four lift banks available on the sky lobby floor. In addition, due to the lifts only servicing two floors (sky lobby floor and the ground floor), agents did not have to wait a long time for the lifts (see Table 3). As such this scenario produced one the shortest average LWTs (0.0s).

In Scenario 9, four shuttle zones were employed and each agent had the option to use a lift on their current floor. The TET for this scenario reduced to 26.6 min, some 25.9% faster than the stair only scenario. It took a similar period of time (13.3 min) to evacuate the top half of the building compared to the 24 and 16 lift scenarios. However, this strategy was the third quickest scenario to evacuate 50% of agents before decreasing to the fourth quickest scenario overall (see Table 2). This signifies that the initial evacuation efficiency using this strategy is reasonable but becomes increasingly inefficient towards the end of the evacuation with the last stair user evacuating some 15.8 min (59.4% longer) than the last lift user. This highlights that the lifts were under-utilised towards the end of the evacuation with just over a quarter (27.7%) of agents using a lift to evacuate with 23.9% redirecting to the stairs (see Figure 1). From Figure 2 it can be seen that more agents initially located on higher floors within a shuttle zone used lifts. This was because agents initially located on lower floors within each shuttle zone had to wait longer for a lift to service their floor and so were more likely to redirect to the stairs due to wait time expiration. The overall proportion of agents that redirected due to congestion whilst not being very high (7.5%) was the highest recorded for all scenarios. This was contributed by the fact that there was only a single lift bank available on each floor which caused the increased levels of congestion in each lift waiting area. Comparable LWTs with Scenario 6 for both the lift users and non-lift users were also recorded.

Scenario 10 extended the concept employed in Scenario 9 by requiring agents on the bottom 10 floors to use the stairs with the remaining floors being partitioned into four shuttle zones. Very few agents elected to use a lift to evacuate on the bottom 10 floors in Scenario 9 (see Figure 2). As such forcing them to use the stairs in Scenario 10 was of little consequence to those agents. However, this did mean that the remaining shuttle zones had fewer floors; only having 10 instead of 12 floors. Despite this, only a marginal decrease in TET by 3.3% (0.9 min) (see Table 2) was observed compared to Scenario 9.

The four sky lobby scenario (Scenario 11) produced the shortest TET (24.0 min) of all scenarios, representing a 33.1% decrease compared to the stair only scenario (see Table 2). Almost all agents who considered using a lift did so (see Figure 1). The time to evacuate the top half of the building was only 18.7% (3.8 min) shorter than the stair only case. The overall evacuation efficiency had more agents evacuated at any point than in any other scenario (see Table 2). However, the efficiency decreased considerably towards the end of the evacuation. This was contributed to by agents being evacuated faster on the lower sky lobbies due to the decreased lift travel distance. As such those lifts were unused towards the end of the evacuation. In addition, contraflow occurred on the sky lobby floors around the stair entrances. In these locations one flow of agents were attempting to enter the sky lobby (intending to board a lift) whilst others were redirecting to the stairs from the lift waiting areas. Both of these factors caused a decrease in evacuation efficiency.

In all scenarios, agents using the stairs were the last to evacuate with differences between the last lift user and stair user evacuation time ranging between 0.1 min (Scenario 7) to 20.5 min (Scenario 6). This suggests that the lifts were under-utilised. It is also noted that the two scenarios that had the greatest lift usage i.e. 48.1% in Scenario 11 (four sky lobbies) and 36.8% in Scenario 8 (one sky lobby), produced the shortest overall evacuation time (24.0 min and 24.9 min respectively). Clearly utilisation of lifts is critical in determining evacuation efficiency.

Identical evacuation scenarios using the original simplified agent-lift model have been previously reported[5]. The earlier simulations considered the simplified case in which the agents were considered compliant. In these simulations, every agent that was assigned a lift used a lift and each agent that was assigned a stair used the stair. Thus, agents did not decide to use a lift based on floor number or redirect due to congestion in the lift waiting area or lift wait time. In these simulations the scenario which produced the shortest TET was Scenario 11, with a reduction in TET of 49% compared to the stair only case. In addition, the scenarios which produced the shortest time to empty the upper 50% of the building were Scenarios 6 and 7 which were both 39% faster than the stair only case. Using the enhanced agent-lift model, which includes more realistic agent behaviour, Scenario 11 also produced the shortest TET. However, the TET only reduced by 33% compared to the stair only case. In addition, a different scenario produced the shortest time to empty the upper half of the building, Scenario 5; this was 46% faster than the stair only case. Thus including more realistic agent behaviour may have a complex non-intuitive impact on the model predictions.

The four sky lobby scenario (Scenario 11) produced the greatest reduction in TET for both models. However, using the original agent-lift model with simplified agent behaviour, the overall TET was half that of the stair only case, while the enhanced agent-lift model with more realistic agent behaviour produced a smaller reduction in TET - two thirds that of the stair only case. Using the original agent-lift model with simplified agent behaviour, the scenario that produced the shortest time to empty the upper half of the building was Scenario 7, the scenario where all the lifts only serviced the upper half of the building. However, using the enhanced agent-lift model with more realistic agent behaviour, the scenario that cleared the upper half of the building in the shortest time was one where the lifts serviced all the floors from the top down (Scenario 5). In addition, the original agent-lift model produced the smaller reduction in time to clear the upper half of the building, being only 39% faster than the stair only case, while the enhanced agent-lift model achieved a 46% improvement. The better performance of the enhanced agent-lift model is due to both stairs and lifts being utilised to empty the upper half of the building.

Thus to determine the most appropriate lift dispatch strategy to achieve the best evacuation outcome and the level of efficiency likely to be achieved, it is essential that realistic human behaviour is included in the lift evacuation model. Assuming compliant agent behaviour may produce over optimistic results in some cases and pessimistic results in other cases and may lead to different and potentially inappropriate lift dispatch strategies being selected. The human behaviour employed in the enhanced agent-lift model was derived from a large international survey[18]. As such the data is subject to the uncertainties associated with surveys. While this data is useful in determining likely human behaviour in actual evacuation situations, it is essential that more reliable data on human-lift interaction in evacuation situations is generated through full-scale experimentation.

CONCLUSION

This paper has presented a brief description of the enhanced agent-lift interaction model developed within buildingEXODUS. The human behaviour model is based on data collected through an online international survey. The model represents the likelihood people will use a lift for evacuation taking into consideration the initial floor that the person is located on, the congestion in the lift waiting area and the time a person is prepared to wait for the lift. The model was demonstrated using a series of 11 evacuation scenarios involving a hypothetical 50 floor building consisting of four staircases and up to four lift banks, each with eight lifts and a building population of 7,840 agents. Findings from the investigation include:

- In all scenarios examined the lifts were under-utilised with most agents electing to use the stairs. This reflects peoples' reservations about using a lift, waiting in large crowds or waiting for a given period of time for a lift during an evacuation.
- The shortest overall evacuation times were recorded in scenarios which achieved the greatest proportion of people using lifts.
- The most efficient strategy to evacuate the entire building involved multiple sky lobbies were agents travelled down the stairs to their nearest sky lobby and then used lifts from the sky lobby to the ground (Scenario 11). This strategy staggered the arrival of agents to the lift waiting areas which subsequently decreased the levels of congestion in the lift waiting areas and decreased the average time waiting for a lift. However, the impact of contraflow of occupants redirecting to/from sky lobbies when utilising such a strategy requires further investigation as this has the potential to decrease the effectiveness of such a strategy.
- The most efficient strategy to empty the upper half of the building in the minimum time involved all lifts being used to service all floors from the top down (Scenario 5). Thus different lift strategies may be required to achieve different evacuation goals. This strategy was the most efficient as it enabled agents to utilise both stairs and lifts to evacuate. Thus, selecting the correct lift evacuation strategy to employ in a particular building is dependent not only on the number and capabilities of the available lifts, but also on the nature of the particular emergency scenario being addressed and the life safety priorities associated with the scenario.
- In addition to the number and capabilities of lifts, human factors can considerably decrease the efficiency of a lift evacuation and alter underlying evacuation dynamics. The extent of this influence is dependent on the lift strategy employed. The results suggests that if more occupants would consider waiting in crowds for longer in the lift waiting area, the efficiency of the evacuation could be improved with more agents using the lifts.
- Some lift evacuation strategies may be less susceptible to decreases in efficiency due to human factors. These include lift evacuation strategies where sky lobbies and shuttle zones are employed that either disperse the arrival time of agents to the lift waiting areas and/or decrease the levels of congestion in the lift waiting areas.

It has been demonstrated that representing human behaviour associated with human-lift interaction can have a significant impact on the dynamics associated with high-rise building evacuation involving both stairs and lifts. While an attempt has been made to better understand human behaviour associated with the use of lifts during evacuation through survey based studies, it is essential that more reliable data on human-lift interaction in evacuation situations is generated through full-scale experimentation.

REFERENCES

1 Averill, J., Mileti, D., Peacock, R., Kuligowski, E., Groner, N., Proulx, G., Reneke, P., Nelson, H., 'Federal Building and Fire Safety Investigation of the World Trade Center Disaster – Occupant Behavior, Egress and Emergency Communications', NIST NCSTAR 1-7. US Government Printing Office, Washington, 2005.
2 Brannigan, V. and Miller-Hooks, E., 'Phased Evacuation in High-rise Buildings: Technical and Regulatory Issues' 11th International Conference Baurecht and Brandshutz (Building Law and Fire Safety), 2007.
3 Galea, E.R, Sharp, G., Lawrence, P.J., Holden, R., 'Approximating the Evacuation of the World Trade Center North Tower using Computer Simulation', Journal of Fire Protection Engineering, Vol 18 (2), 85-115, 2008. DOI:http://dx.doi.org/10.1177/1042391507079343
4 British Standards Institute, 'BS 9999: Code of practice for fire safety in the design, management and use of buildings', 2008.
5 Kinsey, M.J, Galea, E.R, Lawrence, P.J, 'Investigating Evacuation Lift Dispatch Strategies using Computer Modelling', Fire and Materials, DOI: 10.1002/fam.1086, 2011.
6 ICC - International Code Council, '2009 International Building Code', 2009.
7 National Fire Protection Association - NFPA 101, Life Safety Code, Quincy, MA, USA, 2009.
8 National Fire Protection Association - NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, Quincy, MA, USA, 2010.
9 Klote, J.H., Alvord, D.M., Levin, B.M. and Groner, N.E., 'Feasibility and Design Considerations of Emergency Evacuation by Elevators', NISTIR 4870, National Institute of Standards and Technology (NIST), Gaithersburg, 1992.
10 Kinsey, M.J, Galea, E.R, Lawrence, P.J, 'Investigating the Use of Elevators for Highrise Building Evacuation through Computer Simulation', Proceedings of the Human Behaviour in Fire Conference, pp85-96, 2009.

11 Pauls, J., 'Management and movement of building occupants in emergencies' Proceedings of Second Conference on Designing to Survive Severe Hazards', pp103-130, 1977.

12 Galioto,C. , Heller, J., Fletcher, M.S., Spiewak, B., Meyers, R., Barlund, K., Jong, J.D., Edgett, S., Kinnaman, S., Siikonen, M., Solomon, R., Harper, J., Adams, W., Freidenfelds, L., 'Emergency Evacuation Elevator Systems Guideline', Technical report, Council for Tall Buildings and Urban Habitat (CTBUH), 2004.

13 Wong, K., Hui, M., Guo, D. & Luo, M., 'A Refined Concept on Emergency Evacuation by Lifts', Fire Safety Science-Proceedings of the Eighth International Symposium', Proceedings of the Eighth International Symposium on Fire Safety Science (IAFSS)', pp599-610, 2005.

14 Kinsey, M.J, Galea, E.R, Lawrence, P.J, 'Stairs or Lifts? – A study of Human Factors associated with Lift/Elevator usage during Evacuations using an online Survey', Proceedings of the Pedestrians and Evacuation Dynamics Conference, National Institute of Standards & Technology (NIST), US, pp627-236, 2010.

15 Heyes, E. and Spearpoint, M., 'Lifts for evacuation – Human behaviour considerations', Proceedings of the Human Behaviour in Fire Conference, pp73-84, 2009.

16 Groner, N. and Levin, B., 'Human Factors Considerations in the Potential for Using Elevators in Building Emergency Evacuation Plans', NIST GCR 94-656, 1992.

17 Zmud, M., 'Public Perceptions of High Rise Building Safety and Emergency Evacuation Procedures Research Project', The Fire Protection Research Foundation, Massachusetts, USA, 2007.

18 Kinsey, M.J, Galea, E.R, Lawrence, P.J, "Human Factors Associated with the Selection of Lifts/Elevators or Stairs in Emergency and Normal Usage Conditions", Fire Technology, Vol 48 (1), pp3-26, DOI: 10.1007/s10694-010-0176-7, 2010.

19 Galea, E.R., Lawrence, P.J., Gwynne, S., Filippidis, L., Blackshields, D. and Cooney, D., 'BuildingEXODUS v 4.06 user guide and technical manual', Fire Safety Eng. Group, University of Greenwich, 2006.

20 Gwynne S., Galea E R., Lawrence P J. and Filippidis L., 'Modelling Occupant Interaction with Fire Conditions using the buildingEXODUS Evacuation Model', Fire Safety Journal, Vol 36, Issue 4, pp327–357, 2001.

21 Kinsey, M.J, 'Vertical Transport Evacuation Modelling', University of Greenwich, UK, PhD Thesis, 2011.

22 Chartered Institution for Building Service Engineers (CIBSE), 'Guide D: Transportation Systems in buildings', 2005.