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TABLE OF CONTENTS

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INVESTIGATING THE USE OF ELEVATORS FOR HIGH-RISE BUILDING EVACUATION THROUGH COMPUTER SIMULATION

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ABSTRACT

This paper presents a description of a new agent based elevator sub-model developed as part of the buildingEXODUS software intended for both evacuation and circulation applications. A description of each component of the newly developed model is presented, including the elevator kinematics and associated pedestrian behaviour. The elevator model is then used to investigate a series of full building evacuation scenarios based on a hypothetical 50 floor building with four staircases and a population of 7,840 agents. The analysis explores the relative merits of using up to 32 elevators (arranged in four banks) and various egress strategies to evacuate the entire building population. Findings from the investigation suggest that the most efficient evacuation strategy utilises a combination of elevators and stairs to empty the building and clear the upper half of the building in minimum time. Combined stair elevator evacuation times have been shown to be as much as 50% faster than stair only evacuation times.

INTRODUCTION

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. As a result there has been little appetite to seriously explore the use of elevator systems for evacuation. However, since the September 11th World Trade Centre attack, there has been a renewed interest in the possible use of elevators for evacuation of high-rise buildings[1,2]. Such events have also highlighted the need for high-rise buildings to be able to accommodate full scale evacuations and not simply cater for a defend in place strategy whereby only select floors/areas are evacuated. Furthermore, recent computer simulations of high rise building evacuation suggest that there is a critical floor population density for a given staircase capacity which effectively limits the height of high rise buildings that can be practically evacuated by stairs alone[3]. As a result, it is necessary to explore alternate means of evacuation, such as the use of elevators for high towers catering for large building populations.

Whilst fire protected elevators are considered a viable means for fire fighting services to fight fire and also assist in the evacuation of disabled occupants, most standards have yet to accept fire protected elevators as a viable means for the general population to evacuate during a fire. An exception is the current NFPA 101 Life Safety Code 2009 which stipulates in Annex B that elevators that meet a prescribed level of fire safety can be used to evacuate occupants prior to emergency Phase 1 recall (i.e. before smoke is detected in an elevator lobby, elevator machine room or shaft)[4]. Considering the added egress capacity elevator banks could provide a building population during an evacuation compared to using only stairs it is somewhat surprising that elevators have been ignored for so long. However, the key factor with most building codes for not allowing the use of elevators during an evacuation is the potential lack of safety and reliability afforded by such devices during a fire. The NFPA 101 Code for Safety to Life from Fire in Buildings and Structures in 1976[5] identified a number of concerns such as, possible malfunction of elevators during a fire related evacuation, exposure of a waiting population to fire hazards and jamming of elevator doors due to the pressure of large waiting crowds. Further to this, a number of authors[6,7,8] have stated potential technical problems with regards to using elevators during an evacuation which include power failure, overheating/short-circuiting of electrical equipment with serious consequences such as entrapment, smoke inhalation, doors opening on fire floors etc.

Despite there being a number of incidents in the last 40 years in which people have either died[9,10] or were trapped [9,11] inside elevators during fire situations, a number of technological solutions to address these issues have been suggested thereby making elevator systems more resilient[10,12]. Indeed there have been incidents in the last 40 years in which elevators have successfully been used to evacuate large populations of people in high-rise buildings. Such incidents include the Joelma building fire in Brazil of 1974 where some 300 of the 422 survivors evacuated using elevators[10], the Hiroshima Motomachi fire in Japan of 1996 where in excess of 50% of the building occupants safely used elevators either in part or for the entire vertical evacuation[10,13], and the Forest Laneway Fire in Canada of 1995 where some 162 (74%) survivors surveyed used the elevator to evacuate[14]. In addition, there are a number of high-rise buildings throughout the world which currently allow elevators to be used during non-fire evacuations for the general population e.g. Petronas Towers (Malaysia), Tapei 101 (China), Stratosphere tower (US), Barclays tower (UK) etc. Further to this, elevators are the most common used form of ingress in most high-rise buildings and as such are far more familiar to building occupants than egress stairs which typically do not form part of normal circulation roots. Using familiar ingress roots during an evacuation has the potential to reduce confusion and is further supporting evidence to use elevators within high-rise evacuations[13].

The renewed interest in using elevators for building evacuation is now beginning to focus beyond the strictly mechanical aspects of elevator capabilities in emergency conditions to operational issues and human factors issues. The operational questions concern strategies to optimise full building evacuation. For example, should elevator usage be restricted to use by the disabled, if used by the full building population should normal downward peak dispatching algorithms be used or should some kind of shuttling procedure be developed? Should part of the building be expected to use stairs while other parts use elevators? The human factors issues concern how individuals/groups of people would behave on and around elevators during an evacuation. Would for example people be prepared to wait for elevators during a full building evacuation? How many people would consider taking the stairs, how does this depend on factors such as; crowd densities in the elevator waiting area, location of waiting floor, position relative to the incident, etc and how would this impact the building evacuation? The human factors issues can be explored through studying past incidents where elevators were used, e.g. the WTC, through experimentation (evacuation trials) and through survey/questionnaire techniques. The operational questions may be addressed using computer evacuation simulation. Clearly the two are linked as the human factors issues will influence the efficiency of operational strategies however, it is useful to understand the impact of proposed operational strategies in an environment where building occupants are expected to behave in an "ideal" way.

In this paper we present a detailed elevator model implemented within the buildingEXODUS evacuation software. The elevator model includes a detailed representation of elevator kinematics include the representation of jerk, acceleration, and maximum speed. In addition, the non-kinematic elevator parameters include door opening/closing times, motor delay and "typical" operational parameters.

ELEVATOR MODEL

The core software used in this work is the buildingEXODUS V4.06 evacuation model. The basis of the model has frequently been described in other publications[3,15,16] 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 newly developed elevator model is implemented within the buildingEXODUS software (see Figure 1). The key components of the elevator sub-model described here include:

- Agent behaviour
- Elevator Representation and Attributes
- Elevator Motion Control
- Elevator Kinematics

AGENT BEHAVIOUR

Within buildingEXODUS the concept of assignment and navigation to location targets for individual agents already exists. Agents can be assigned a target destination i.e. a place to travel to in the geometry, and be assigned a task to perform at the target destination e.g. wait etc. Using this existing capability, three aspects of the agent elevator selection process needed to be developed, namely: elevator bank selection, elevator lobby wait location selection, open elevator car selection (see Figure 1). Due to the lack of available data pertaining to how pedestrians actually perform such selection tasks, the current model is based on a number of simplifying assumptions. The model is sufficiently flexible to allow for future changes as and when data is available.

Elevator Bank Selection

Currently there are two possible approaches the agents can adopt in selecting which elevator bank they will adopt. These are:

- Closest serviced elevator bank assignment (agents select their closest elevator bank).
- Closest serviced elevator bank assignment with even elevator bank usage (agents select their closest elevator bank on a given floor which has not already been adopted by a number of other agents, so ensuring that each elevator bank on a given floor is adopted by approximately the same number of agents).

Once a simulation has started agents do not change their elevator bank selection or redirect to another elevator bank after the initial choice is made. Once the agent's response time has expired they move towards the chosen elevator bank.

Elevator Lobby Wait location Selection

When an agent enters an elevator bank waiting area, if the agent's target is the current elevator bank, they randomly select a location in the elevator bank waiting area to wait. The agent then moves to the chosen location where they will wait for an elevator to arrive.

Open Elevator Car Selection

When an elevator door opens in a given elevator bank, the nearest agents who are waiting in the elevator waiting area move to use the elevator. Only the number of agents which can fit inside the elevator (derived from the elevators maximum capacity and the proportion of this reached) attempt to board the elevator. As a result there is no competition for elevator boarding and the boarding process is orderly. If multiple elevator cars open their doors simultaneously at a given floor, the agents select the nearest un-oversubscribed opened elevator car. This ensures that the nearest agents to an opened elevator car will board the car. While this may appear to be an over optimistic representation of passenger boarding in emergency situations, until data is available describing these situations, these assumptions appear reasonable.

ELEVATOR REPRESENTATION AND ATTRIBUTES

Within buildingEXODUS an elevator shaft is defined as a series of transit nodes which span each of the floors within the geometry (see Figure 1). The dimensions of the shaft in addition to the size of the door on each respective floor can be defined within the model by altering the attributes of each transit node. Once the shaft is defined, then an elevator can be associated with the shaft. There are a number of attributes which are used to define an elevator within buildingEXODUS, these are listed in the table below:

Table 1: Defining Elevator attributes

Attribute	Description
Maximum Speed	Defines the maximum rated speed of the elevator car (m/s).
Acceleration	Defines the constant rate of acceleration of the elevator car (m/s^2).
Jerk	Defines the rate of change in acceleration before and after constantly accelerating/decelerating (m/s^3).
Start floor	Defines the floor the car will start at the beginning of a simulation.
Door opening time	Defines the time it takes an elevator door to open.
Door closing time	Defines the time it takes an elevator door to close.
Dwell time	Defines the duration the car doors will stay open after the car doors have fully opened to service a given floor (providing no one enters the elevator).
Sensor break adjusted dwell-delay	Defines the adjusted dwell time after the first occupant enters an elevator car.
Motor delay	Defines the time, after an elevator's doors have closed, before the car starts to move i.e. the time it takes the motor to start.
Capacity	Defines maximum physical number of agents that can enter a car.
Max capacity	Defines the percentage of the 'Capacity' which the car actually reaches.
Serve Floor Sequence	Defines a sequence of numbers which represent the series of floors the car will serve.
Shuttle Floor Sequence	Defines a sequence of paired numbers which represent a series of 'pick up' and 'drop off' floors the car will shuttle between.
Exit Floors	Defines a list of floor numbers which form the drop off floors for both Shuttle floor and Serve floor sequence. For both sequences, if an elevator arrives on an exit floor, everyone currently in the car will exit at the indicated floor.

ELEVATOR MOTION CONTROL

The current elevator model provides two methods for controlling elevators i.e. the floor selection. The first system, currently under development, allows users to provide a proprietary floor dispatching algorithm in a C++ library and connect via a standard interface. This allows users to test out different floor dispatching algorithms. This is particularly useful when the software is used to simulate normal circulatory flows within a building. As such the system can be reactive according to different landing requests in the simulation. The second system allows users to manually define the floors an elevator/group of elevators will service from within a script file. Unlike the first system, this does not allow the floor sequence to change or be reactive to different scenarios during the simulation.

This sequence can be defined in two different ways: floor-sequence or shuttle-floor-sequence, along with an exit floor list. Using a floor-sequence, a user specifies the sequence of floors an elevator will service during the simulation. The assigned elevator(s) will serve each of the floors specified in the sequence once. Using a shuttle-floor-sequence, a user specifies a paired-sequence of pick-up/drop-off floors where the elevator could pick people up from and shuttle them to. This shuttle process would repeat until their where no more people in the pick-up floor catchment area or floor (depending on the settings). The process is then repeated for the next pick-up/drop-off floor in the sequence. For both systems, the exit floor list defines which floor(s) the agents in the car will exit the elevator.

For the shuttle-floor sequence system, using a top-down strategy, if an elevator does not fill to it's maximum capacity at a pick-up floor, an optional feature is to then move the elevator to the next pick-up floor to fill up the remaining spaces in the elevator car. This reduces the amount of redundant shuttle trips an elevator makes when it is not full and so would increase the efficiency of the overall evacuation. This assumes that the number of passengers which enter each elevator is detected either via automated means e.g. weight sensors, or manually via an operator within the car.

ELEVATOR KINEMATICS

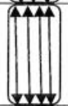
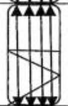
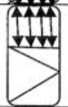
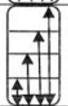
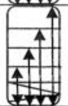
The kinematics or motion of an elevator car is defined by it's jerk, acceleration and maximum speed. There also are a number of other factors which influence an actual elevators journey such as friction, ware and tare of machine parts etc, however these are not considered within the current model. As such the kinematics of the elevator model should be considered "ideal". Specifying the cars jerk, acceleration and maximum speed is sufficient to determine the location of the car at any point in time. The time at which the elevator passes each respective floor between it's original location and it's destination is determined using a series of formula based on the work of Motz[17] and Peters[18].

SIMULATIONS

A series of 11 full building evacuation scenarios have been performed using the new elevator model using a hypothetical building (see Figure 1). The building consisted of 7,840 agents distributed over 50 floors with four stairwell cores and four elevator banks each containing eight elevators. In most of the scenarios all the elevators can service all floors. The purpose of allowing all elevators 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 elevator shafts. For each simulation, different combinations of elevators and stairs were used to evacuate the entire population. In each case, the priority of the elevators was to service the upper floors first, sequentially working down to the lower floors. Several scenarios examined the use of shuttle elevators and sky lobby arrangements. The full list of scenarios is summarised in Table 2.

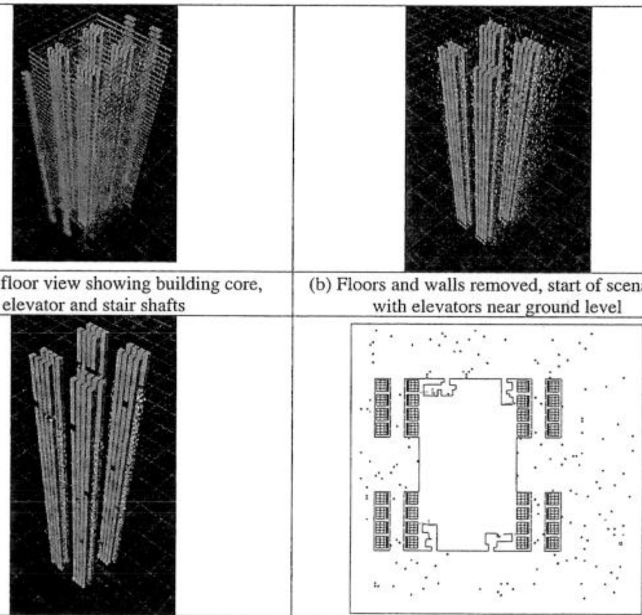
The different frequency of elevators used in certain scenario is intended to explore the impact of elevator number in evacuation efficiency and to explore the affects of elevator banks being rendered inoperable during an evacuation (e.g. due to fire, technical fault etc). For each scenario all elevators initially started on the ground floor. Due to the hypothetical nature of the building, aside from the external walls and the stair/elevator cores, no furniture or internal obstructions were represented within the simulation. With the exception of the ground floor, there were 160 agents located on each floor (7,840 occupants in total). Agents were modelled as non-connected individuals and were not constrained by groups. The population used the default population attributes within buildingEXODUS[15] 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.

Table 2: Overview of evacuation scenarios

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

During the elevator simulations, agents using the elevators were assigned to use their nearest lift bank which was not already over subscribed by agents i.e. an equal number of agents used each elevator bank on each floor. Likewise during simulations in which the stairs were used, an equal number of agents were assigned to use each stair on each floor. This concept of equal core load balancing was considered appropriate as unequal use of an elevator bank or stairwell has the potential to significantly increase total evacuation time and levels of congestion. While this may in fact occur in real situations, it was not considered appropriate to consider these issues in the current analysis as the primary concern here is to investigate optimal performance.

The defining attributes for the elevator kinematics and physical characteristics were based on the Chartered Institution for Building Service Engineers (CIBSE) Guide D: Transportation Systems in buildings[19]. Each elevator had a maximum capacity of 13 occupants, a maximum speed of 6 m/s, acceleration rate of $1.2 m/s^2$ and a jerk rate of $1.8 m/s^3$. In addition each elevator 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 28.4s 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 elevator started at the ground floor. For each elevator simulation not involving stairs, where elevators serviced multiple floors (i.e. non-sky lobby scenarios), a top-down-shuttle evacuation strategy was employed by each of the elevators whereby all the elevators evacuate the occupants on the top floor first and shuttle them to the ground floor. This process is repeated until all people evacuated that floor. The elevators then proceed to the floor below this and the process is repeated until all of the floors in the sequence have taken all occupants on those floors to the exit floor.



(a) Multi-floor view showing building core, elevator and stair shafts

(b) Floors and walls removed, start of scenario 5 with elevators near ground level

(c) Part way through scenario 5, with elevators at different levels, occupants gather in elevator lobbies.

(d) Two-dimensional view of a single floor, near start of scenario 5, showing distribution of agents around core, stairs and four elevator banks.

Figure 1: Sequence of views from buildingEXODUS of high-rise building elevator evacuation, (a), (b) and (c) depicting 3D virtual reality view and (c) depicting two dimensional view

RESULTS AND DISCUSSION

Still sequences from the simulation of scenario 5 are depicted in Figure 1. As part of the development of the elevator sub-model, a three-dimensional virtual reality visualisation capability has been developed which is integral to the buildingEXODUS user interface. The new interface is capable of displaying virtual reality three-dimensional graphics (see Figure 1a, b, c) as well as the usual two-dimensional visualisation (see Figure 1d). The three-dimensional representation shows the progress of the elevator cars during the simulation. The results for the various simulations are presented in Table 3 with the egress curves for the various scenarios presented in Figure 2.

Table 3: Summary of evacuation statistics for the various scenarios

Scenario	**Number of elevators**	**Total Evacuation Time (TET)**	**Time to clear upper half of building**	**Average PET**	**% Time saved (compared to stairs only)**	**Evacuation time of last stair user**	**Evacuation time of last elevator user**
1	0	36.1 min	20.9 min	17.6 min	-	36.1 min	-
2	8	81.0 min	48.1 min	46.1 min	-125%	-	81.0 min
3	16	43.1 min	24.8 min	24.4 min	-19.5%	-	43.1 min
4	24	34.2 min	19.5 min	19.2 min	5.1%	-	34.2 min
5	32	26.3 min	14.8 min	15.0 min	27.1%	-	26.3 min
6	**32 + half stairs top down**	18.1 min	14.9 min	9.1 min	49.9%	18.1 min	16.2 min
7	**32 + half stairs top middle**	35.2 min	12.2 min	17.6 min	0.32%	35.2 min	35.2 min
8	**32 + half stairs, 1 x Sky Lobby**	19.6 min	18.3 min	9.6 min	45.7%	18.7 min	19.6 min
9	**32 + 4 Shuttle Zones**	23.9 min	22.5 min	10.2 min	33.8%	-	23.9 min
10	**32 + 4 Shuttle Zones + 10 Stairs**	20.3 min	19.1 min	8.5 min	43.8%	13.0 min	20.3 min
11	**32 + 4 x Sky Lobbies**	18.2 min	17.0 min	7.4 min	49.6%	13.0 min	18.2 min

The base line comparison for all the cases is the stair only evacuation (scenario 1). This produced a Total Evacuation Time (TET) of 36.1 min with 20.9 min required to clear the top half of the building. The Average Personal Evacuation Time (PET) for the simulation was 17.6 min. This indicates that on average, a person required 17.6 min to exit the building. The TET for scenarios 2 (8 cars) and 3 (16 cars) are 48.1 min and 24.8 min respectively, both being considerably longer than the stair only case. From Figure 2 we also note that for these cases the evacuation rate increases towards the later stages of the evacuation unlike in the stair only case which tends to decrease towards the later stages of the evacuation. The increase in evacuation rate is due to the elevator cars having to travel a much shorter distance towards the end of the evacuation as the remaining agents are located on the lower floors. It is not until 24 cars are used in the evacuation (scenario 4) that the TET is marginally better than the

stair only case, being 34.2 min or 5.1% faster. However, even with 24 cars the average PET (19.2 min) is still greater than the stair only case. From Figure 2 we note that the stair only curve out performs the 24 car case right up to nearly the end of the evacuation (88.7% of the stair only case or 93.4% of the 24 car case). However, from Table 3 we note that the 24 car case (scenario 4) does clear the upper half of the building marginally faster than the stair only case (scenario 1), clearing the upper part of the building in 19.5 min compared to 20.9 min.

It is not until 32 cars are used (scenario 5) that we see a substantial improvement over the stair only performance. In this case the TET is 26.3 min, some 27.1% faster than the stair only case and the average PET is 15.0 min compared with 17.6 min for the stair only case. The upper half of the building is also cleared substantially faster than the stair only case, requiring only 14.8 min compared with 20.9 min. Comparing the 8 elevator scenario with the other elevator only scenarios, we can see there was a 2, 2.4 and 3 times speed-up in total evacuation time respectively for the 16, 24 and 32 elevator scenarios. This suggests that for a given population distribution and number of floors, the speed up in evacuation performance does not necessarily increase linearly with the number of cars used.

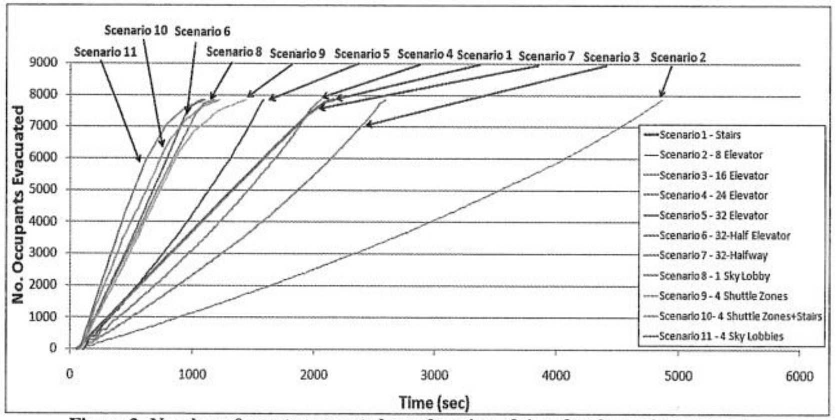


Figure 2: Number of agents evacuated as a function of time for the various scenarios

In scenario 6 we explore an evacuation strategy in which the bottom half of the building use the stairs to evacuate while the top half use 32 elevators to evacuate the occupants direct to the ground. This strategy produces the best overall evacuation time of 18.1 min; almost 50% faster than the stair only case. As is to be expected, the time to clear the top half of the building is similar to that of scenario 5 at 14.9 min but the average PET is greatly decreased to 9.1 min. In this scenario, the last agents out of the building are the stair users resulting in the decrease in the evacuation rate towards the very end of the evacuation as seen in Figure 2. Scenario 7 introduces a variation on scenario 6 in which the elevators take the upper occupants not to the ground but to the central floor. From here the occupants make their way down the stairs. We find that the TET for this scenario increases to 35.2 min, only marginally faster than the stair only case and the average PET, at 17.6 min is identical to that of the stair only case. However, we note that the time to clear the upper half of the building is the quickest of all the scenarios, requiring only 12.2 min. While the time to evacuate the entire building is equivalent to the stairs only case, using this strategy does provide the quickest way to clear the upper half of the building. For emergency situations where it is essential to evacuate the upper part of the building as quickly as possible this is clearly the best strategy. In scenario 8 we introduce a sky lobby.

Here the agents in the upper part of the building are required to descend to the central floor, by stairs, from where they can take an elevator to descend all the way to the ground. The agents below the central floor all must use the stairs to evacuate to the ground. In this case the TET is 19.6 min, some 46% faster than the stair only case. However, it requires some 18.3 min to clear the top half of the building. As a result, scenario 8 is not as efficient as scenario 6. Furthermore, it is noted that the last person to evacuate from the building made use of the elevators. Thus the elevator evacuation took longer than the stair evacuation. This is a result of the stairs providing a staggered arrival rate of agents to the elevators. As a result, on occasion, the elevator car is not filled to capacity or is forced to wait for agents. If local elevators could be used to shuttle agents to the sky lobby rather than requiring the agents to use the stairs, this may improve the performance of this scenario.

In scenario 9 four shuttle zones are introduced with each group of eight elevators servicing the 12 floors within their allocated zone (the bottom zone has 13 floors). In each zone the elevators service the floors from the top down. In this case the TET has increased to 23.9 min which is some 34% faster than the stair only case, but considerably slower than scenario 6. Using this approach also requires some 22.5 min to clear the upper half of the building, some 1.6 min slower than the stair only case. Clearly this is a very inefficient strategy for emptying the building and clearing the upper half of the building. In scenario 10 we extend this concept by making all the building occupants below the 10th floor use the stairs rather than the elevators. In this case we have four shuttle zones with each group of eight elevators servicing 10 floors. While this case represents an improvement over scenario 9, with a TET of 20.3 min which is 44% quicker than the stair only case, the time required to clear the upper half of the building is 19.1 min, only 1.8 min faster than the stair only case.

In scenario 11 we introduce four sky lobbies, one on every 10th floor with each sky lobby being serviced by eight elevators (a single elevator bank). Within each zone, agents must descend, using stairs, to the sky lobby where they can board an elevator which takes them directly to the ground. Below the 10th floor, all agents use the stairs to evacuate. This case produces a TET of 18.2 min which is some 50% faster than the stair only case and the upper half of the building is cleared in 17 min. This scenario produces comparable times to scenario 6 in terms of the overall evacuation time but a slightly longer time to clear the upper half of the building. However, we note that the average PET is only 7.4 min, considerably lower than any other scenario. Indeed, from Figure 2 we note that this scenario produces the best evacuation rate of all the scenarios for most of the evacuation duration. Over the first 17 min (93.3%) of scenario 11, more agents are evacuated using this strategy than in any other case. This means that the introduction of multiple sky lobbies makes it possible to evacuate a greater number of people in the same amount of time for the majority of the evacuation than in any other strategy examined. The performance of this scenario could potentially be further improved through the introduction of local elevator cars that ferry the occupants to the sky lobby rather than use the stairs. We further note from Figure 2 that scenarios involving zoning/multiple sky lobbies (scenarios 9,10,11) produce increasingly inefficient evacuation performance towards the end of the evacuation sequence. This is because the elevators servicing the zones/sky lobbies on the lower levels are left idle whilst the elevators servicing the upper levels are still in operation.

CONCLUSION

This paper has presented a description of the newly developed elevator sub-model within buildingEXODUS intended for both evacuation and circulation applications. A range of demonstration full building evacuation simulations were performed using the newly developed model exploring different evacuation strategies. The demonstrations apply to a hypothetical 50 floor building with four staircases and a population of 7,840 agents in which the agents behave in an "ideal" manner. The results suggest that for this type of building:

- For a given building population and number of floors, the speed up in evacuation performance achieved using an elevator only strategy - in which each elevator visits each floor – is sub linear with increasing number of elevator cars.
- Using an elevator only strategy in which each elevator visits each floor, the total evacuation time can be reduced by 27% and the time to clear the top half of the building reduced by 29% using 32 elevator cars compared to a stair only strategy.
- A more efficient evacuation strategy involves using elevators in conjunction with stairs. If 32 elevators are used to clear the top half of the building while the occupants in the lower half of the building utilise the stairs, the building can be emptied 50% faster compared with the stair only strategy. The time to empty the top half of the building is reduced by 29% compared to the stair only case.
- The most efficient overall strategy involved using 32 elevators arranged into four sky lobbies where the occupants on the first 10 floors used the stairs and within each sky lobby zone the occupants used the stairs to descend to the sky lobby. In this case the building could be evacuated 50% faster than the stair only case and the upper half of the building could be emptied 19% faster than the stair only case. While the upper half took 14% longer to empty than in the case where the elevators were used to evacuate only the top half of the building, this case produced the highest overall egress rate for more than 90% of required evacuation time.
- It is suggested that the performance of the sky lobby cases could be improved if local elevators were used to shuttle occupants from local floors to the sky lobbies.

The next phase in the development of the buildingEXODUS elevator modelling capability is to address some of the key human factors issues associated with occupant behaviour in selecting to use elevators or stairs. To date only a few studies have focused on these human factors issues. The EXODUS development team are attempting to address these issues through an international survey aimed at understanding and quantifying some of the factors associated with occupant device selection in both circulation and evacuation situations. The survey can be found on the FSEG web pages at: http://fseg.gre.ac.uk/elevator/. Thus far some 425 people from 23 countries have completed the survey. Interested readers are urged to complete the survey and to pass on the web address to as many people as possible, preferably from outside the fire engineering community.

With the increasing number of high-rise and super high-rise structures being planned and built around the world, the viability of using stairs only for full building evacuations is coming more and more into question. As a result, building engineers around the world are increasingly turning to elevators as a means to safely address full building evacuation scenarios. However, whilst there has been considerable progress in solving the mechanical issues associated with using elevators for evacuation, considerably more effort is required to fully address the operational and human factors issues associated with elevator usage in emergency situations.

REFERENCES

1 Bukowski, R.W, "Emergency Egress from Ultra Tall Buildings", Proceedings of CTBUH (Council on Tall Buildings and Urban Habitat), 2008

2 Koshak, J., "Elevator Evacuation in Emergency Situations", American Society of Mechanical Engineers (ASME) International, 2003

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 NFPA 101, Life Safety Code, 2009

[5] NFPA 101, Life Safety Code, 1976

[6] Klote, J.H, "Elevators as a Means Of Fire Escape", American Society of Heating Refrigerating and Air Conditioning Engineers Transactions, 1982

[7] Klote, J. H., Alvord, D. M., Levin, B. M. and Groner, N. E., "Feasibility and Design Considerations of Emergency Evacuation by Elevators", National Institute of standards, and Technology (NIST), Gaithersburg, MD NISTIR 4870, 1992

[8] Sumka, E., "Presently, Elevators are not safe in Fire Emergencies", Elevator World, 1988.

[9] Clark County Fire Department , "MGM Grand Las Vegas 11/21/1980 Fire Clark County F.D. Final Report", 1980

[10] Howkins, R.E., "In the Event of Fire - Use Elevators", Proceedings of ELEVCON, 2000

[11] Manning, W.A (Editor) et al, "The World Trade Center Bombing :Report and Analysis", Fire Engineering, 1998

[12] Bukowski, R.W., "Protected Elevators For Egress And Access During Fires In Tall Buildings", Workshop on Building Occupant Movement During Fire Emergencies, pp14-21, 2005

[13] Sekizawa, A., Ebihara, M., Notake, H., Kubota, K., Nakano, M., Ohmiya, Y. and Kaneko, H., "Occupants' Behaviour in Response to the High-rise apartments Fire in Hiroshima City", Proceedings of Human Behaviour in Fire Conference, 1999

[14] Proulx, G., Pineau, J., Latour, J.C, Stewart, L. ,"Study of the Occupants' Behaviour During the 2 Forest Laneway Fire in North York, Ontario, January 6, I995", Internal Report:IRC-IR-705, 1995

[15] 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

[16] 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, 327–357, 2001

[17] Motz, H.D, "On the Kinematics of the ideal motion of lifts" (republished in English), (First published in 'Foedern und Heben' Vol 26 (1976), No. 1 in German), Elevatori1, 1991.

[18] Peters, R.,"Ideal Lift Kinematics: derivation of Formulae for the equations of Motion of a Lift", International Journal of Elevator Engineering, Volume 1, 1996

[19] Chartered Institution for Building Service Engineers, "Guide D: Transportation Systems in buildings", 2005