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PUBLICATION

EFFICIENT EVACUATION METHODS IN TALL BUILDINGS

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ABSTRACT

The speed with which people can be rescued from a building can be crucial in saving lives in many emergency situations. In this article, evacuation studies have been made for an ideal situation where no smoke effects, or fire, and no damage to the building is considered. This is analogous to a situation where another site near the building is on fire, there is a bomb threat in the building, or a biological, chemical or nuclear threat in the surroundings. In cases such as these, the "safest" rescue method for the occupants is the fastest method. In this article, elevator simulations were carried out using KONE Building Traffic Simulator (BTS), and egress models were used to compute evacuation times by stairs. As a result, the most efficient methods of evacuating different types of buildings of various heights and sizes are suggested.

Keywords: Evacuation, high-rise buildings, elevators, stairs, simulation

1 INTRODUCTION

According to European evacuation plans, elevators are returned to the main entrance when a fire alarm is raised. Only stairs are used for evacuation during an emergency situation, which is not always the most efficient way. Furthermore, the regulations tend to forget the disabled and elderly people who may not be able to use the stairs at all.

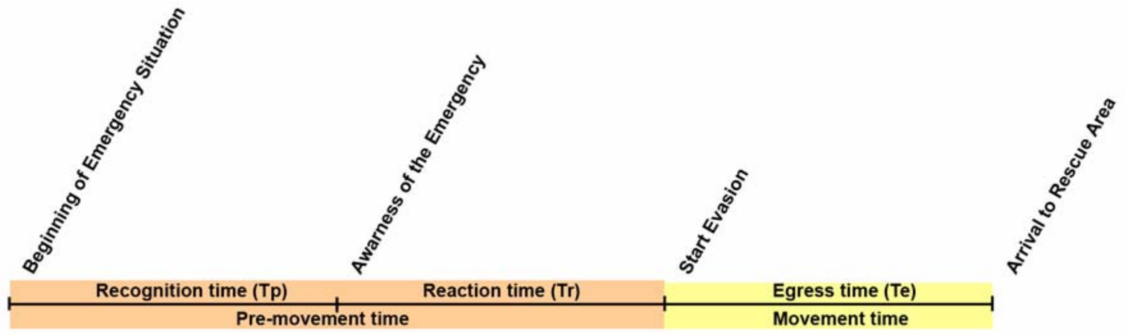

Figure 1. Time phases of total evacuation time in an emergency situation

The time from the beginning of an emergency until all people have reached an area of safety outside the building can be divided into three phases, i.e. recognition time, reaction time and egress time. Pre-movement time is the time before people start to egress the building. Its length is influenced by the signs of danger (e.g. people smell smoke), alarms, time of day and type of building. For example, one can expect that the pre-movement time is long in an apartment building at night. According to some studies, the pre-movement time is about three times longer than the actual movement time (Proulx 1995). Occupants become aware of the emergency after the recognition time. This is often the most critical part, when fire alarms have not yet been given. During the reaction time people try to get information about the situation, the source of the emergency, gather personal belongings, perhaps their children and so forth. Training for emergency situations also affects the reaction time. During the actual movement phase, people move out of the building until everyone has reached an area of safety. Evacuation studies often concentrate on finding out the egress time since it can be estimated theoretically.

Critical time ($Tcrit$) is defined as a time limit when the evacuation of people is safe and probably no injuries or deaths will occur.

$$Tp + Tr + Te \leq Tcrit \quad (1)$$

Critical time differs case by case. In the 1970s, a requirement of five minutes' exiting time down the stairs out of the building was given for tall buildings in the USA (Weckman et al. 1999). In most countries, the staircases and corridors are governed by the building codes. The number and width of stairs depend on the floor population and walking distances to the exits, but not on the number of floors and egress times out of the building. According to some country codes, to prevent congestion the minimum width of the staircases should be 1.050–1.28 meters (Lo et al. 2001). In most situations, two staircases are a minimum requirement for high-rise buildings.

Models and simulation programs for evacuation are developed for the use of stairs only (Schneider 2001; Weckman et al. 1999). In this article, methods to study an evacuation situation in high-rise buildings using the stairs, or elevator, or both, are presented. The pre-movement phase is omitted, and only the egress times are compared unless otherwise stated. KONE Building Traffic Simulator (BTS) software (Siikonen et al. 2001) is used for elevator traffic simulations.

2 EVACUATION BY ELEVATORS

2.1 Evacuation times vs. planning criteria

Elevators are usually planned for the up-peak situation since it is the most demanding situation for the elevator transportation capacity. In residential buildings, a typical handling capacity of 5 to 7.5 % of the population in five minutes is defined. This means that the whole population can be transported to the upper floors within 67-100 minutes. In office buildings, a typical range of up-peak handling capacity is from 13 to 18 % of the population in five minutes. This figure corresponds with building filling times of 29 to 40 minutes.

Down-peak or occupant evacuation is not normally considered at the planning stage of a building and in elevator arrangements. It has been stated that elevators should be capable of evacuating the population of a building within 15 – 30 minutes (Strakosch 1967), but this is not used as a criterion in elevator planning. Traffic with conventional control systems using up and down call buttons has been simulated by several authors. A rough conclusion from the simulations is that elevators can transport about 1.5 times more passengers in down-peak than in up-peak (Barney 1999). According to BTS simulations with modern control systems, down-peak handling capacity with modern control systems can even be 1.8 times greater than in up-peak. As an example, if elevators can transport 15 % of the population in up-peak, the same elevators can transport about 22.5 – 27 % of the population in down-peak. The reason is that the elevators have fewer car calls in down-peak and can reverse their direction more easily. This makes the elevator round-trip time shorter, which increases handling capacity in down-peak.

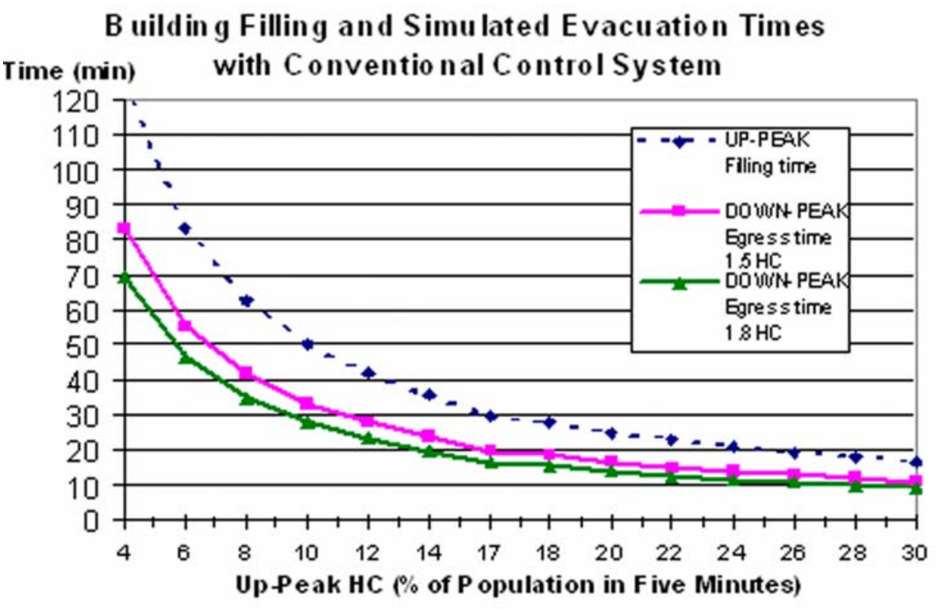

Figure 2. Building filling and passenger egress times with single-deck elevator

The building filling and evacuation times for different up-peak handling capacities are shown in Figure 2. Evacuation time in this context means only the egress time, and no recognition or reaction time of the emergency. From the figure it can be seen, for instance, that with 15 % up-peak handling capacity, the average egress time is 19–22 minutes. On the other hand, for an evacuation time of 15 minutes, the up-peak handling capacity is 19–22 % of the population in five minutes.

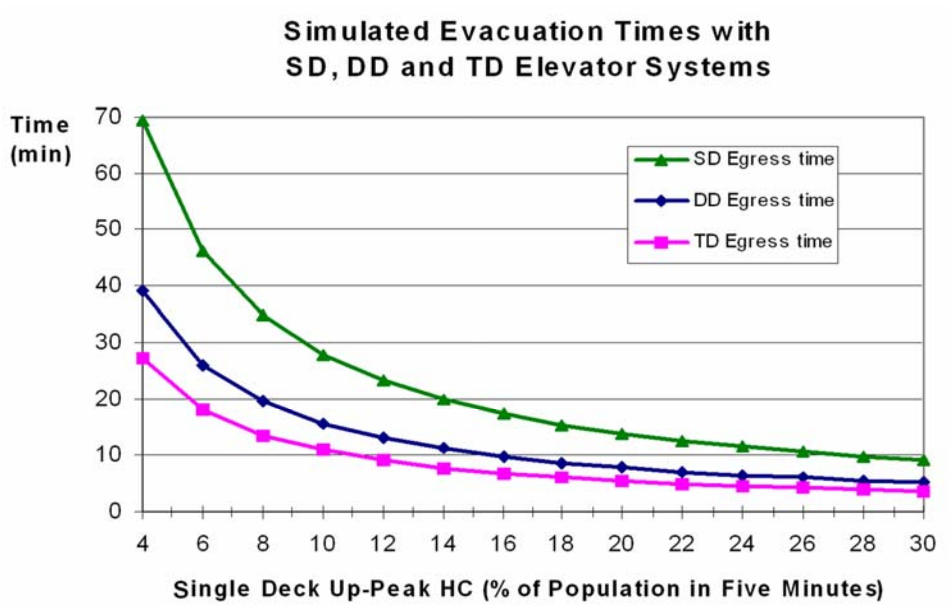

Figure 3. Simulated passenger egress times with single-deck, double-deck and triple-deck elevators requiring the same shaft space

Evacuation becomes faster if double-deck or triple-deck elevators are used to serve all floors of the building. Figure 3 shows egress times of double and triple deck elevators using the same shaft space as a single-deck elevator group. In the comparison, the number of double-deck and triple-deck elevators, their car sizes and speeds are the same as those of the single-deck elevators. According to Figure 3, the egress times with double-deck elevators are 50–60 % of the time with single-deck elevators. With triple-deck elevators, the decrease in egress time is relatively smaller than with double-deck elevators; about 40 % of the egress time of single-deck elevators. These results are based on simulations with BTS.

2.2 Zoning of elevator groups

The effect of zoning the served floors during down-peak was studied. Passenger traffic in a building is simulated so that passengers arrive at the elevators randomly with a given arrival rate. Passengers enter and exit elevators with a given transfer time, theoretically one second to enter and one second to exit an elevator. In a down-peak or evacuation situation, passengers arrive from upper floors and travel to the main entrance.

In the test simulations, all passengers arrive at the landing floors within 5, 7.5, 10, 12.5 and 15 minutes. This relates to different passenger pre-movement times. A 20-floor building with 60 persons per floor was used. Passenger traffic is served by an elevator group with six cars, a 17-person car size and a speed of 3.0 m/s. The handling capacity of this elevator group is about 14 % of the population, and the interval is 26 seconds. Three different cases were studied:

1) All floors are served by all cars
2) The served floors are divided into two zones that are each served by half of the elevators
3) Passengers gather at every third floor and elevators serve only those floors (an idea from 1970s)

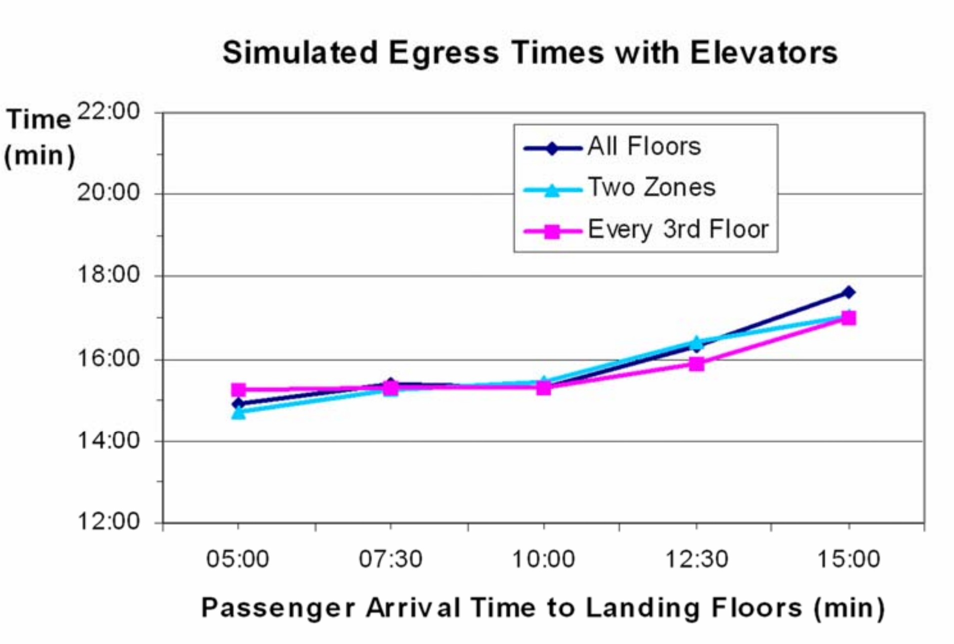

Figure 4. Passenger evacuation times with and without zoning as a function of how fast they have arrived at the landing floors

Figure 4 shows the egress times for passengers arriving within 5 to 15 minutes at the landing floors. According to the figure, the evacuation times increase if passengers arrive more slowly at the landing floors. The egress times of the three alternative cases are very similar, and zoning does not significantly decrease the evacuation time. Down-peak is the easiest situation for the group control since the car calls do not restrict elevator routes as much as in other traffic situations. Modern group control algorithms search for the best call allocations for each car so that elevators can reverse their direction at any upper floor. This decreases the elevator travel distance and the number of stops during a round trip, and brings the three alternatives close to each other.

2.3 Mega high-rise buildings

In a study of the behaviour people during an explosion below the World Trade Center plaza in New York City in 1993 (Fahy and Proulx 1998) the mean reaction time of occupants was 11.3 minutes in Tower 1, and 39.9 minutes in Tower 2. According to this study, the total evacuation time was from one to three hours. This time included the times passengers had spent waiting or resting in areas of refuge. Results of the same order were obtained from the terrorist attack on the WTC on 11th September 2001, where, for example, the window washer took 53 minutes to exit the building by the stairs from the 50th floor.

In the first incident in 1993, the occupants would probably have been able to use the elevators during the emergency. In buildings where sky lobby arrangements are used, the number of floors is at least 60 and the egress times by the stairs are very long. If elevators were used during the emergency, passengers above the sky lobby would have to use local and shuttle elevators during their way down to the main entrance. In mega high-rise buildings, shuttle elevators may become a bottle-neck during evacuation if they are planned with normal up-peak criteria. According to Figure 3, local elevator groups can empty all passengers from upper floors within 20 minutes, if the up-peak handling capacities of local groups are in the range of 14–17 % of population in five minutes.

Since the shuttle group has normally only two or three stops, the handling capacity is the same in both directions, up and down. As a result, the egress time is the same as building filling time in up-peak. For 15 % handling capacity, the filling and egress times for shuttle elevators are 33.3 minutes. In this case, during evacuation all passengers arriving from local groups to the sky lobby cannot be transported down by the shuttle elevators with the same rate as they arrive, and congestion will occur. In the previous example, passengers would be transported down within 20 minutes by the shuttle group, if its up-peak handling capacity was 25 % of the population in five minutes. In a shuttle elevator group with two stops only, double-deck or triple-deck elevators theoretically double or triple the handling capacity per shaft. The egress times are halved, or reduced to one third, respectively.

3 MOVEMENT TIME BY THE STAIRS

The movement of people in stairs can be modelled as unified crowd flows. The maximum flow per stair width unit has been measured for different types of staircases, riser heights and tread depths. The flow models give optimistic results, since they assume that stairs do not become overcrowded. In case there is heavy congestion, the walking speed and also the occupant flow drop significantly. If the occupant density is more than 3.8 persons per m2, the walking speed approaches zero (Pauls 1987).

Detailed simulations take account of movement speed at different densities and even factors like pressure, friction and some aspects of human behaviour (Schneider 2001; Lo et al. 2001). Simulations give more information about situations where the occupant density is very high and there is smoke and panic.

In the Melinek and Booth flow model (Melinek and Booth 1975), the evacuation situations can be roughly divided into two categories. In one case there is congestion on the stairs and the occupant flow is at maximum all the time. In the other case, occupants can walk freely. The egress time is the maximum of these two.

$$t_1 = \frac{nN}{F_s W} + t_s \qquad (2)$$

$$t_n = \frac{N}{F_s W} + nt_s \qquad (3)$$

where

t1	egress time (congestion)
tn	egress time (free walk)
n	number of floors
N	number of people per floor and exit
Fs	nominal occupant flow on stairs (persons/m/s)
W	width of the staircase
ts	walking time between adjacent floors (free walk)

The effective width should be used instead of the real width of the stairs to take into account the effect of walls and handrails. Typically, 150 mm is reduced from both sides of the staircase. As a result, the effective width of, for example, a 1.2 m wide staircase is 0.9 meters. A typical value for ts is 16 seconds, and Fs 1.1 persons per meter per second.

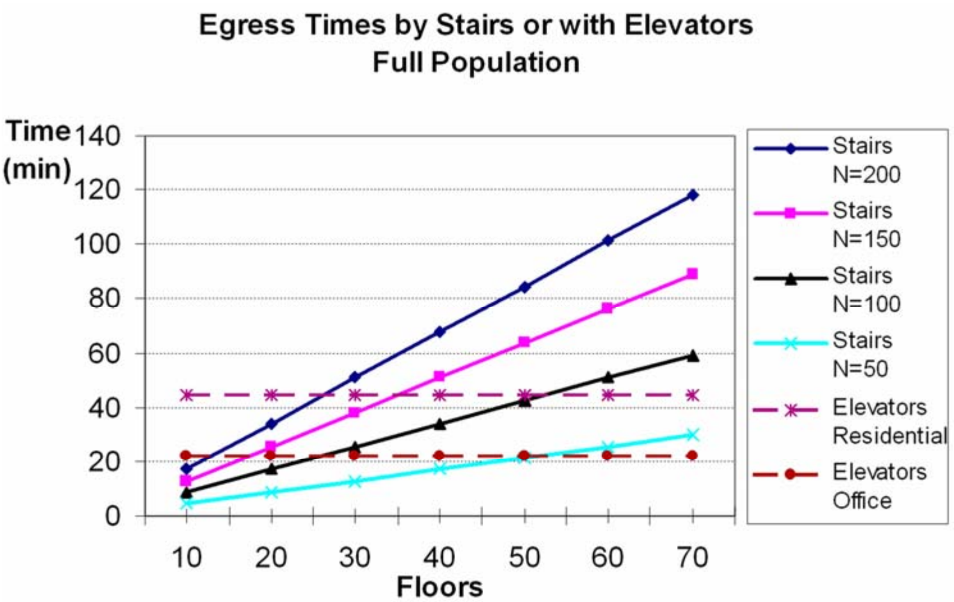

Figure 5. Egress times where N refers to the number of people per floor

Figure 5 shows the egress times for two 1.2 m wide staircases for buildings with different numbers of floors. The building heights vary from 10 floors up to 70 floors. Four different floor areas with 50, 100, 150 and 200 persons per floor are studied. In all the evacuation cases, congestion occurs on the stairs, and consequently the width is the limiting factor. Since the number and width of the staircases remains the same, the egress time increases linearly according to the number of floors and persons per floor.

In the figure, the egress times by elevators are shown for typical residential and office buildings. Egress times with conventional control systems are 44 and 22 minutes corresponding to up-peak handling capacities of 7.5 % and 15 % of the population in five minutes, respectively. If there are several elevator groups with about the same handling capacity in the building, and people use only one elevator when leaving the building, passenger egress times are about the same.

In a residential building, the egress times by elevators become more favourable for buildings with more than 100 persons per floor (50 persons per staircase) and with more than 50 floors, or for 200 persons per floor and with more than 25 floors. Typically, residential buildings are lower than 50 floors and the population per floor is less than 200 where the stairs are the fastest way for evacuation.

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 elevators is faster for 25 floors or more. For higher amounts of population per floor, elevators are faster for even 15–20 floor buildings.

4 EVACUATION BY ELEVATORS AND STAIRS

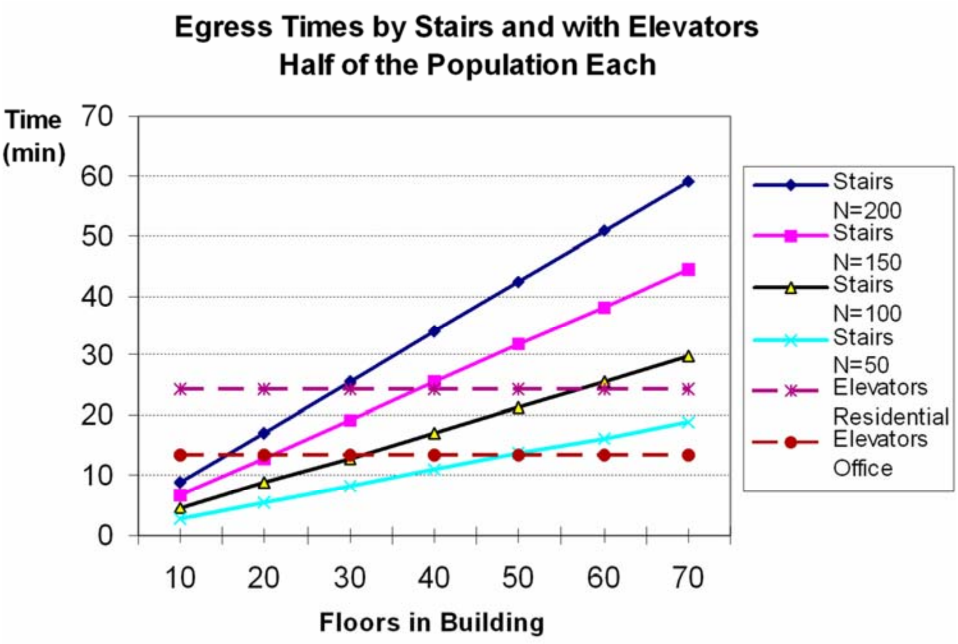

Figure 6. Egress times where N refers to the number of people per floor

If there are several ways to escape from the building, occupants try to use the quickest one. If the environment is not familiar, people may have difficulties in finding the emergency exits and they would rather use the same route by which they entered the building. Even if the environment is well known, it is difficult to choose the best route, since some of them become congested in an emergency situation. Therefore, at least one of the stairs should be placed in the proximity of the elevators so that those occupants can easily choose the best exit route.

An optimal situation for using the stairs and elevators would be that the last person from the stairs and the last person from the elevator exit the building simultaneously. Otherwise the longest egress time from either of the exit ways defines the total evacuation time. It is difficult to predict the proportion of people that would use elevators or stairs. A case where half of the population use elevators and half of them use stairs was studied for the same buildings as in the previous section. According to Figure 6, in an office building with 30 floors and with 100 persons per floor, the egress time by stairs and elevators drops to about 13 minutes. From Figure 5 it can be seen that by stairs it is 26 minutes, and by elevators 22 minutes. Using both exit ways considerably decreases the egress time up to about 50-floor buildings with about 100 persons per floor. For 200 persons per floor, using both stairs and elevators decreases the evacuation time for office buildings with 20 floors or lower.

Another example is that of a residential building with 10 floors. Evacuation of half of the population by elevators takes about 24 minutes, which defines the total evacuation time. If only the stairs are used, it is from 4 to 17 minutes, according to Figure 5. If less than 35 % of the occupants use the elevators during an emergency, the egress times decrease in typical residential buildings.

5 DISCUSSION

Building evacuation is usually considered in case of fire only, and not in other emergency situations. Some countries, such as Australia, have different stages of evacuation plans according to the type of the emergency situation. Evacuation plans should be made based on risk analysis, e.g. the effect of evacuation times on deaths and injuries in case of people using elevators, stairs, or both. In many emergency situations, elevators stay operative for the whole, or part of the emergency situation. After the evacuation plans have been decided, the occupants of the building should be regularly trained in different evacuation plans.

During an emergency situation, there can be a shorter or longer time period when fire, smoke and water do not reach the elevators. This time period could efficiently be used for evacuating the floors close to the emergency floor and above it (Howkins 2000). After no down calls from these floors occur, or all occupants from those floors are evacuated, the elevator system starts to serve passengers from floors below the emergency floor. This type of procedure could be adopted even with the current passenger elevators. On the other hand, the properties of fire elevators could be included in passenger elevators. It would naturally increase the cost of elevators, but also their durability during an emergency and reduce evacuation times dramatically.

Elevator arrangements in buildings are at the moment mostly planned according to up-peak criteria to define how fast buildings can be filled. In high-rise buildings where people have to use several elevator groups to get to their destination floors, evacuation studies should be included as a standard in the elevator planning phase to guarantee passenger safety. The requirement for evacuating high-rise buildings with elevators currently ranges from 5 to 30 minutes. A realistic range would be 15-25 minutes.

6 CONCLUSION

In this article, evacuation by elevators and stairs was studied. The BTS simulator was used for elevator traffic simulations, and egress times via stairs were obtained through crowd flow models. Elevator evacuation times were calculated from the up-peak handling capacity using a linear coefficient that depends on the capability of a group control system to handle down peak situation. According to the simulation results, arranging people on, for example, every third floor, or into zones during the evacuation does not decrease the evacuation time. Modern control systems can handle the down-peak situation effectively without zoning.

Evacuation times in buildings with different number of floors and with different proportions of population per floor were studied for stairs and elevators. In planning stairs in a building, only the floor population and walking times and distances to the nearest exits and stairways are considered. In tall buildings, current building codes do not take into account the number of floors and egress times by the stairs out from the building. In the comparison of this article, two staircases in each building were assumed. Elevator groups were selected with typical handling capacity and interval criteria for office and residential buildings. According to the results, if either stairs or elevators are used, evacuation times by elevators become shorter for office buildings with 15 floors or more depending on the number of people per floor. If both stairs and elevators are used equally, evacuation time usually decreases compared to using elevators or stairs only. In a typical residential building the stairs is the fastest way for evacuation since elevator handling capacity is usually small. If only a small percentage of occupants use the elevators, the egress time in residential buildings decreases compared to using only the stairs.

If elevators are used in mega high-rise buildings during an emergency situation, evacuation times can drop to 15-30 minutes instead of 2-3 hours. In these buildings, shuttle elevators may become a bottle-neck during the evacuation and down-peak. Handling Capacity of a shuttle elevator group with only two stops can be considerably increased with double-deck or triple-deck elevators.

REFERENCES

Barney, G.C. (1999). Up-peak, down-peak & interfloor performance. Elevator World, March, pp.100-103.

Fahy, R. F., and Proulx, G. (1998). Human beviour in the World Trade Center Evacuation. Fire Safety Science – Proceedings of the Fifth International Symposium, pp. 713-724.

Howkins, R.E. (2000). In the event of fire USE THE ELEVATORS. Elevator

World, December, pp. 140-142.

Lo, S. M., Fang, Z., and Chen D. (2001). Use of a modified network model for analyzing evacuation patterns in high-rise buildings. Journal of Architectural Engineering, June, pp. 21-29.

Melinek, S.J., and Booth, S. (1975), An Analysis of Evacuation Times and the Movement of Crowds in Buildings. Borehamwood, GB: Building Research Establishment, Fire Research Station. (BRE Current Paper CP 96/75 FRS)

Pauls, J. (1987). Calculating evacuation times for tall buildings, Fire Safety Journal, 12, pp. 237-245.

Proulx, G. (1995). Evacuation time and movement in apartment buildings, Fire Safety Journal, Vol. 24 (3), pp. 229-246.

Schneider, V. (2001). Application of the Individual-Based Evacuation Model ASERI in Designing Safety Concepts, International Symposium on Human Behaviour in Fire, Boston, 26/28 March, 17pp.

Siikonen, M-L., Susi, T. Hakonen, H. (2001). Passenger Traffic Flow Simulation in Tall Buildings, Elevator World, August, pp. 117-123.

Strakosch, G. R. Vertical transportation: elevators and escalators, John Wiley & Sons, Inc, 1967. 495pp.

Weckman, H., Lehtimäki, S., Männikkö, S. (1999). Evacuation of a theatre: Exercise vs. calculations. Fire and Materials, 23, pp. 357-361.

BIOGRAPHICAL DETAILS

Marja-Liisa Siikonen currently works as Traffic Planning Manager in the Major Projects Unit of the KONE Corporation. Formerly she worked in the research and development department of KONE Corporation. During that time she obtained the degree of Licentiate of Technology, and the degree of Doctor of Technology in applied mathematics from Helsinki University of Technology. Her current location is KONE Corporate Offices, Keilasatama, Espoo, Finland.

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