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THE EFFECT OF PRE-EVACUATION DISTRIBUTIONS ON EVACUATION TIMES IN THE SIMULEX MODEL

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ABSTRACT: The evacuation time of a building in an emergency can be broken down into a number of constituent times including the pre-evacuation time and the travel time. This paper examines how distributions of pre-evacuation times affect the occupant travel time and hence their effect on the evacuation time in the Simulex model. A simple scenario is assessed mathematically and compared with the results from Simulex with further simulations carried out on a somewhat more complex scenario. Where we expect the pre-evacuation time to be characterised by a distribution of values simply adding the maximum pre-evacuation time and the movement time over-estimates the evacuation time. Furthermore, when the pre-evacuation distribution is small the travelling and queuing effects dominate the simulated evacuation time. When the pre-evacuation distribution is large then travel and queuing effects are not so important and it is the pre-evacuation time that dominates. Finally the paper examines some aspects of the Simulex model in situations where there is a high occupant density in a space.

KEY WORDS: evacuation, simulation, pre-evacuation, distributions, Simulex, queues.

NOMENCLATURE

D_o	Occupant density, [ppl/m^2]
N	Total number of occupants under consideration, [ppl]
n	Number of people, [ppl]
$\dot{n}$	Flow of people, [ppl/s]
t	Time, [s]
$\overline{t_p}$	Mean pre-evacuation time, [s]
$t_{max:ev}$	Maximum potential evacuation time, Equation (8), [s]
$t_{ev,p}$	Evacuation time for a given mean pre-evacuation time $\overline{t_p}$, [s]
$t_{ev,0}$	Base evacuation time, i.e. the evacuation time with no pre-evacuation time, [s]

Subscripts

a	Alarm activation
d	Detection
i	Investigation
t	Travel
m	Movement
q	Queue
p	Pre-evacuation
o	Decision
ev	Evacuation
min	Minimum
max	Maximum
most	Most likely

INTRODUCTION

Background

In many fire safety designs it is appropriate to assess the likely evacuation time of occupants and compare that evacuation time with the onset of any potential hazards. The determination of the evacuation time can be carried out using hand calculations or computer simulation models.

Hand calculations can be used to provide an initial assessment of the expected evacuation time but are really only suitable for simple scenarios. The Fire Engineering Design Guide [1] suggests that the evacuation time is a function of a number of constituent times such that

$$t_{ev} = t_d + t_a + t_o + t_i + t_t + t_q \,. \tag{1}$$

The fact that the evacuation can be determined by the sum of the constituent times implies that each constituent is independent of one another. We can group t_o and t_i into a component which represents the pre-evacuation time such that

$$t_p = t_o + t_i \tag{2}$$

and components t_t and t_q into an overall movement time such that

$$t_m = t_t + t_q \,. \tag{3}$$

So the evacuation time can be expressed as

$$t_{ev} = t_d + t_a + t_p + t_m \,. \tag{4}$$

Typically we might determine the occupant load and where in the building we expect these people to be prior to evacuation. We might then establish the pre-evacuation time, for example using the method proposed by Sime [2], and then obtain the movement time using equations such as those presented by Nelson & MacLennan [3]. The total evacuation time is then taken to be the sum of those two components plus the detection and activation times. However, calculating the movement times for topologically complex buildings with diverse populations soon becomes impractical using a hand calculation approach.

Furthermore, in a real evacuation we might expect the pre-evacuation time for the building occupants to be characterised by a distribution of values. This distribution of pre-evacuation times will affect the flow of people through the building since, for example, the rate of people entering door queues will be different where all of the people move together compared with situations in which the people begin moving at different times. In other words, the constituent times given in Equation (1) are not truly independent of each other. To assess this interaction between a distribution of pre-evacuation times and its effect on the movement time is likely to be almost impossible using hand calculations, particularly in a complex building and would instead require the use of a computer simulation model.

The objective of this paper is to investigate the effect on the evacuation time when the pre-evacuation time is characterized by a distribution of values. In particular the paper examines this effect within the Simulex [4] evacuation model.

Simulex

The Simulex evacuation model is often used to obtain evacuation times for buildings and other related structures. The model is a PC-based computer program capable of simulating the evacuation of large numbers of people through geometrically complex buildings. Building plans are imported from CAD tools and occupants are placed graphically on the floor plans. The user specifies exits from the building and stairs are used to connect different floor levels.

Simulex represents the physical presence of each person by using three overlapping circles. The dimensions of the circles are used to account for the size differences between men, women and children. The program includes several typical building occupant groups by varying the ratios of men, women and children within that group. The program models different types of movement such as normal unimpeded walking speed, reduction of walking speed due to the proximity of other occupants, overtaking, sidestepping and body twisting. Occupants assess their evacuation routes using distance maps that are generated from the floor plans.

The model also allows for a distribution of pre-evacuation times (termed response time in Simulex) to be applied to the occupants. The user can select one of three distributions; random, normal and triangular and supplies the mean and deviation of the distribution. This ability to incorporate pre-evacuation time distributions allows an investigation of the effect of such distributions on the movement of the people and thus examine the implications for the overall evacuation time.

ANALYSIS

The analysis presented in this paper is used to investigate how the congestion that might occur at a constriction affects the evacuation time when all of the occupants begin to move simultaneously compared with when the pre-evacuation time is characterized by a distribution. The calculated evacuation times are also compared with the maximum evacuation time that we might potentially expect for a particular scenario so that we can examine how the calculated evacuation times differ from where independently assessed pre-evacuation and movement times are summed. In order to investigate the effect on the evacuation time by varying the pre-evacuation distribution, a simple scenario is initially examined. A room with a square plan area, a single door midway along one of the walls and populated with *N* people is considered.

Although MacLennan *et al.* [5] suggest that a Weibull distribution is the most suitable way in which to describe the probability distribution of pre-evacuation times they also note that other distributions may be equally appropriate. In this paper the triangular distribution for the pre-evacuation times is principally used to analyze the single room scenario using the mathematical approach. The triangular distribution is selected so as to provide an insight into the effects of pre-evacuation on an evacuation without the mathematical investigation becoming too involved. A triangular distribution is also one of the three distribution types available in Simulex and could be used to reasonably approximate to distributions such as normal, Weibull, log-normal and others.

Maximum potential evacuation time

The maximum potential evacuation time $t_{max:ev}$ is defined here as the maximum pre-evacuation time plus the movement time. For a triangular distribution of pre-evacuation times this maximum potential evacuation time is shown in Figure 1 where $f(t)$ is the probability density function for a triangular distribution.

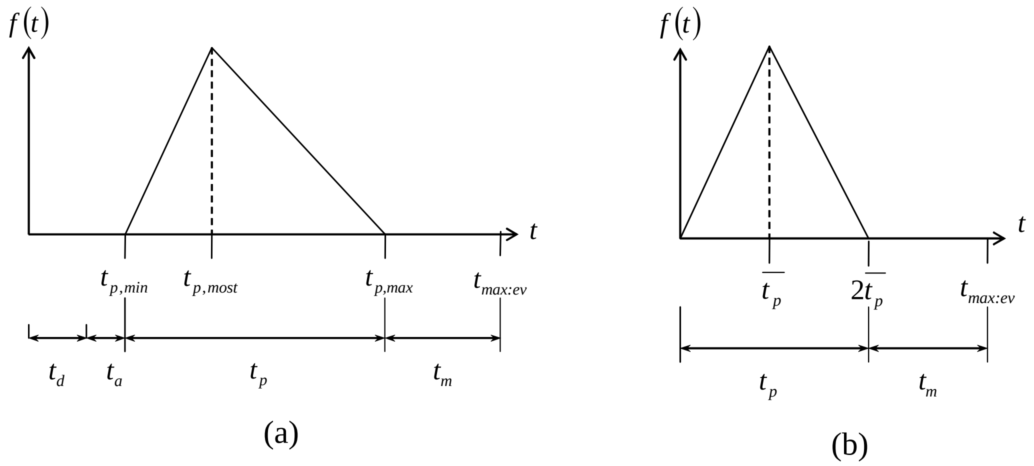


Figure 1. The maximum potential evacuation time $t_{max:ev}$ for a triangular distribution; (a) general form, (b) Simulex representation without t_d and t_a considered.

General evacuation movement in a building does not occur until the fire and/or smoke has been detected and an alarm raised. Thus, in terms of the overall evacuation, these times t_d and t_a in Equation (4) are fixed for a given scenario and we do not need to consider them in any further detail here. Hence we can simply write

$$t_{ev} = t_p + t_m \qquad (5)$$

The mean for the triangular distribution is given by

$$\overline{t_p} = \frac{t_{p,min} + t_{p,most} + t_{p,max}}{3} \qquad (6)$$

If we disregard t_d and t_a as discussed above so that effectively $t_{p,\min} = 0$, and since Simulex requires that the minimum and maximum deviation from the mean of the triangular pre-evacuation distribution be the same, it follows that $t_p = t_{p,max} = 2t_{p,most}$ thus $\overline{t_p} = t_{p,most}$. Therefore, as shown in Figure 1(b), from Equation (5) we obtain

$$t_{max:ev} = 2\overline{t_p} + t_m \qquad (7)$$

Clearly, as $\overline{t_p}$ varies, then $t_{max:ev}$ also varies and when $\overline{t_p} = 0$ then $t_{max:ev} = t_m$. For the Simulex simulations, the movement time can be obtained with no pre-evacuation time such that $t_m = t_{ev,0}$ so that Equation (7) becomes

$$t_{max:ev} = 2\overline{t_p} + t_{ev,0} \tag{8}$$

where we define $t_{ev,0}$ as the “base evacuation time”.

Door queue flow

During an evacuation congestion is more likely to occur at constrictions such as doors and narrow corridors. Where there are large numbers of people these constrictions slow their movement and can lead to the formation of queues in which the people wait to pass through the constriction. It is therefore important to consider door queue flows and their subsequent effect on the evacuation.

From Haimes [6], the probability density function for a triangular distribution has the general form

$$\begin{aligned} f(t) &= \frac{2(t-a)}{(b-a)(c-a)} && \text{if } a \le t \le b \\ f(t) &= \frac{2(c-t)}{(c-a)(c-b)} && \text{if } b \le t \le c \end{aligned} \tag{9}$$

where a = minimum; b = most likely; c = maximum. From our previous analysis we have found that a = 0; $b = \overline{t_p}$ and $c = 2\overline{t_p}$ so that the probability density function reduces to

$$\begin{aligned} f(t) &= \frac{t}{\overline{t_p}^2} && \text{if } 0 \le t \le \overline{t_p} \\ f(t) &= \frac{2\overline{t_p} - t}{\overline{t_p}^2} && \text{if } \overline{t_p} \le t \le 2\overline{t_p} \end{aligned} \tag{10}$$

The number of people in transition from pre-evacuation to movement at any given time is given by $N \cdot f(t)$. The rate of change of people entering the queue at the door of our simple room scenario is given by $\frac{dn_q}{dt} = \dot{n}_{in} - \dot{n}_{out}$. If we consider when $t \le \overline{t_p}$ then from Equation (10)

$$\frac{dn_q}{dt} = N\frac{t}{\overline{t_p}^2} - \dot{n}_{out} \tag{11}$$

Therefore, by integration, the number of people in the queue at time *t* is

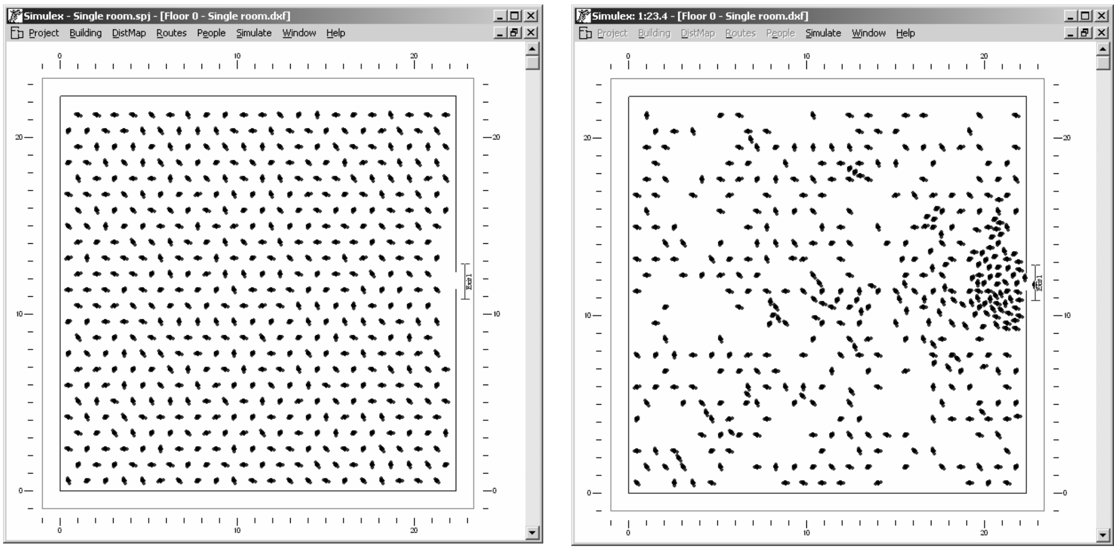
$$n_q = \frac{t}{2}\cdot\left[N\frac{t}{\overline{t_p}^2} - 2\dot{n}_{out}\right] \tag{12}$$

Equation (12) tells us that when $\overline{t_p} \to 0$ then $\frac{N\cdot t}{\overline{t_p}^2} \to \infty$ so that the number of people in the queue is predominately due to the total number of people in the space which directly relates to the occupant density. This is compared to when $\overline{t_p} \to \infty$ then $\frac{N\cdot t}{\overline{t_p}^2} \to 0$ and so n_q is small or possibly negative. This can be interpreted to mean that no significant queue forms, instead the evacuation is controlled by the pre-evacuation time related by $\overline{t_p}$. Similar results are obtained if we consider $t \geq \overline{t_p}$. This mathematical analysis suggests that when the mean pre-evacuation time is short the travelling and queuing effects dominate the evacuation time. When the mean pre-evacuation time is large then travel and queuing effects are not so important and it is the pre-evacuation time that dominates. When mean pre-evacuation times lie somewhere between these two extremes then the evacuation time is influenced by both the occupant density and the distribution of pre-evacuation times.

SIMULATIONS

Simple room

To examine whether the previous findings suggested by the mathematical analysis would also occur in Simulex, a single room scenario was created that consisted of a single room, 22 m square with a single door opening, 1 m wide, along the centre of one wall. The room was populated with a range of occupant densities in which individuals were uniformly spread throughout the room (Figure 2). The room size was arbitrarily selected so as to balance between a sufficiently populated room for the range of occupant densities and the computation time necessary to complete each simulation. A larger room would have required longer computation times at the high occupant densities and a smaller room would have been populated with too few people at the low occupant densities. The population type for the space was taken to be the "office" type characteristics as defined by Simulex. This population characteristic consisted of 40% males, 30% females and 30% average body types. Simulex selects a random unimpeded walking velocity for each person between 0.8 - 1.7 m/s.



(a) (b)

Figure 2. The single room scenario in Simulex; (a) initial setup, (b) during execution.

Simulations were conducted with the occupants having triangular or normal pre-evacuation distributions. The pre-evacuation distributions had $\overline{t_p}$ values between 1 and 1200 s (20 minutes) and the deviation for a given $\overline{t_p}$ was $\pm\overline{t_p}$ as indicated in Figure 1. Although there is not necessarily any upper limit on the pre-evacuation time, a $\overline{t_p}$ of 1200 s gave maximum pre-evacuation time of 2400 s (40 minutes) which compares with the maximum of 45 minutes that might be obtained using Sime [2]. It was also found that longer pre-evacuation times would not yield any additional insights for the simple room scenario. A $\overline{t_p}$ of zero was also used to obtain the base evacuation time, $t_{ev,0}$ for each scenario. The occupant densities were chosen so as to match typical occupant densities as specified in the New Zealand Approved Document [7] as shown in Table 1.

Occupant density, D_o [ppl/m^2]	Typical occupancy
0.02	Storage, garages
0.10	Offices and staffrooms, shops for furniture
0.20	Showrooms, teaching laboratories
0.50	Reading or writing rooms
1.00	Bar sitting areas, areas without seating or aisles
1.30	Space with loose seating
1.80	Stadia and grandstands
2.60	Standing space

Table 1. Occupant densities suggested by the New Zealand Approved Document.

Table 2 summarizes the single room Simulex runs conducted for each occupant density. The simulations conducted for each occupant density covered the range of mean pre-evacuation times, typically 0, 1, 30, 60, 120, 240, 480, 600, 900 and 1200s, with additional simulations carried out to obtain multiple results for selected mean pre-evacuation times and to fill in suitable intervening times where useful for the analysis.

Occupant density	Number of people	Distribution type	Base evacuation time, $t_{ev,0}$	Number of simulations
[ppl/m^2]	[-]		[s]	[-]
0.02	10	Triangular	16	17
0.10	50	Triangular	35	35
0.20	100	Triangular	66	21
0.50	250	Triangular	157	21
1.00	500	Normal	317	12
		Triangular	309	32
1.30	650	Triangular	417	27
1.88	940	Triangular	589	24
2.60	1300	Normal	822	13
		Triangular	822	21
3.00	1500	Triangular	945	29
Total				252

Table 2. Summary of single room Simulex simulation runs.

Earlier it was identified that the distribution of values for the pre-evacuation time might be characterized by a range of different functions of which Simulex can implement the triangular and normal distribution functions. In order to determine whether the selection of either of these distribution functions might be critical to the analysis, the results from two occupant densities were compared. Figure 3 shows the evacuation times calculated by Simulex using normal and triangular pre-evacuation distributions for 1.00 ppl/m^2 and 2.60 ppl/m^2. It can be seen that the results for the two distributions do not vary considerably for any given mean pre-evacuation time. Therefore, in terms of Simulex results, it is assumed the findings discussed for a triangular pre-evacuation distribution can also be generally applied to a normal pre-evacuation distribution.

Furthermore, Figure 3 shows the dependence between the total evacuation time and a distribution of pre-evacuation values. Except in the case of $\overline{t_p} = 0$, where a distribution of pre-evacuation times is used to obtain the evacuation time, the resultant evacuation time $t_{ev,p}$ is less than the maximum potential evacuation time, $t_{max:ev}$ and is a function of the mean of the distribution and the initial occupant density in the space. This reduction comes as no surprise since $t_{max:ev}$ is obtained from the movement time where the maximum congestion occurs summed with the longest pre-evacuation time that exists for a given distribution. When the occupant density is higher, the level of congestion is greater and consequently the reduction in the evacuation time is more significant once a distribution of pre-evacuation times is used. This can be seen when the results for 1.00 ppl/m^2 and 2.60 ppl/m^2 are compared in Figure 3.

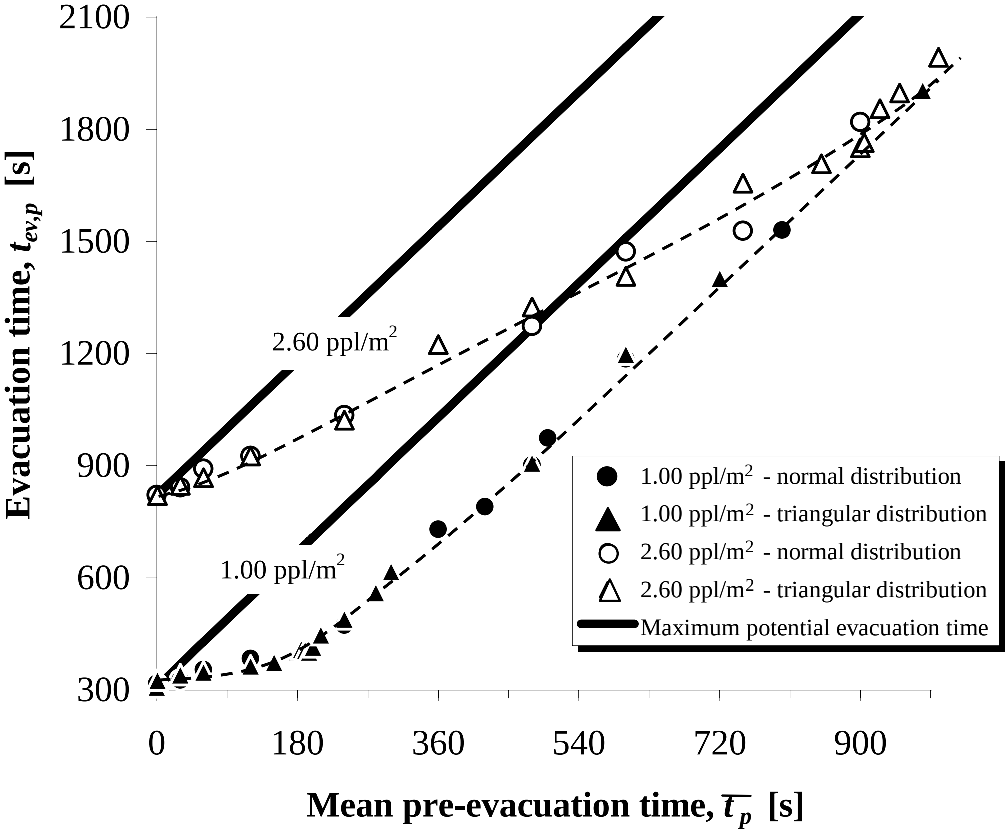


Figure 3. Comparison of evacuation times calculated by Simulex using normal and triangular pre-evacuation distributions with the maximum potential evacuation times for 1.00 ppl/m^2 and 2.60 ppl/m^2 in the square room scenario.

A more comprehensive analysis of the simple room scenario using the triangular pre-evacuation distribution is shown in Figure 4 where the simulated evacuation times are plotted as a function of the mean pre-evacuation time and occupant density. As suggested by Equation (12), Figure 4 shows that when the mean pre-evacuation time is small the evacuation time is a function of the occupant density. As $\overline{t_p}$ increases, the evacuation time becomes dominated by the pre-evacuation time and becomes independent of the occupant density. In this case, once $\overline{t_p} \geq 300\,\text{s}$ then the evacuation time from the room is effectively independent of the occupant density.

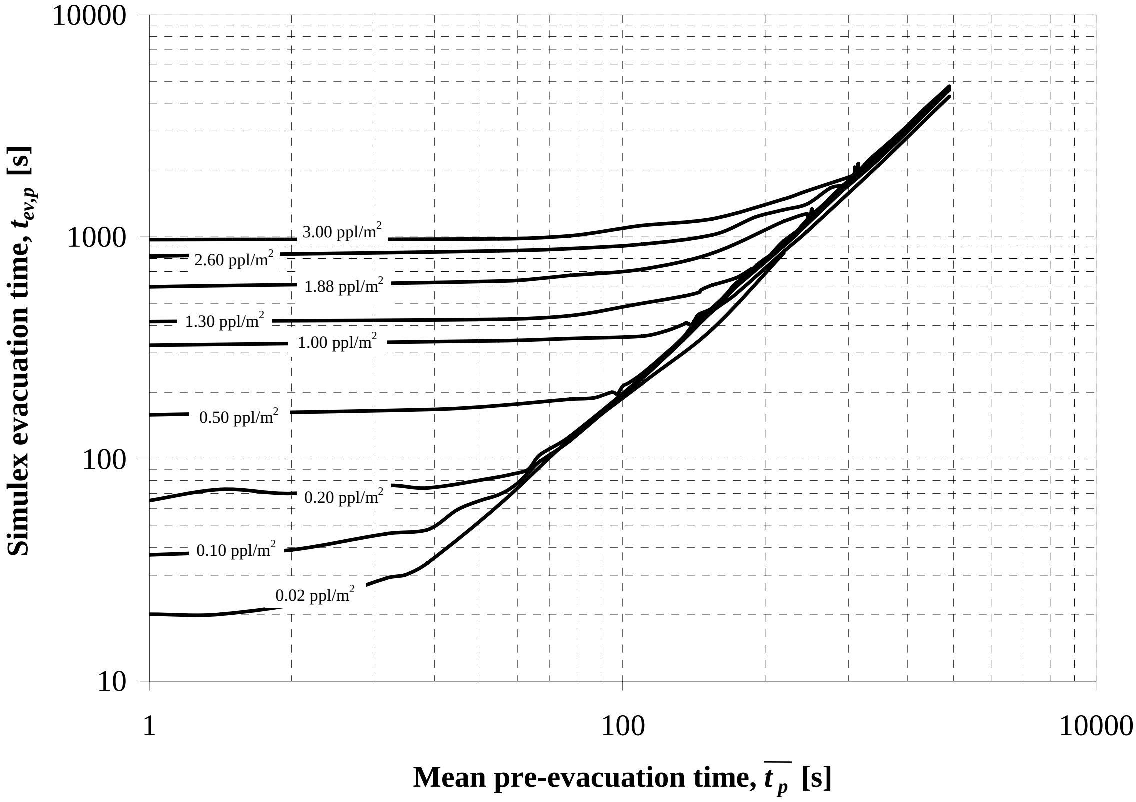


Figure 4. Simulex evacuation times for ranges of occupant densities and mean pre-evacuation times.

Hypothetical building

A hypothetical 3-storey office building was created as shown in Figure 5 in order to examine whether the findings for the simple square room are likely to occur in other situations. The building included a range of typical room occupancies such as a conference room, computer facility etc. The building was populated according the occupant densities suggested by the New Zealand Approved Document [7] as shown in Table 1.

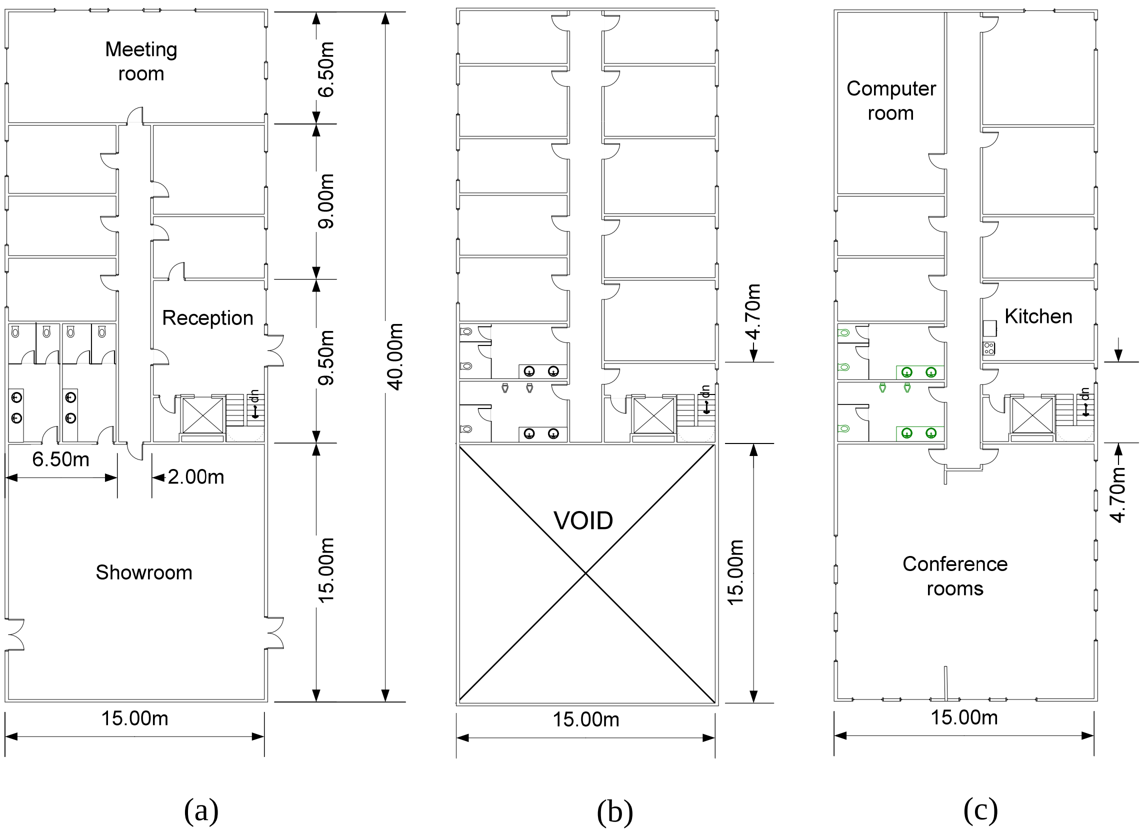


Figure 5. Hypothetical 3-storey office building (a) Ground floor (b) First floor (c) Top floor. Unlabelled rooms are offices or toilets.

Two scenarios were investigated in which the population in the top floor adjoining conference rooms was varied. In the first scenario it was assumed that the conference rooms were fully utilised such that the occupant density was 1.30 pp/m^2 which is equivalent to that specified by New Zealand Approved Document for space with loose seating. For the second scenario it was assumed that the conference rooms were only being used by the number of occupants equivalent to the office occupant density of 0.10 ppl/m^2 suggested by New Zealand Approved Document. Table 3 shows the number of people specified in the different types of rooms on each floor of the building for the two scenarios.

Floor	Room	Area	Scenario 1 - High load		Scenario 2 - Low load	
			Occupant density, D_0	Occupants	Occupant density, D_0	Occupants
		[m^2]	[ppl/m^2]	[ppl]	[ppl/m^2]	[ppl]
1	Showroom	225	0.20	45	0.20	45
	Reception	62	0.10	7	0.10	7
	Meeting room	99	0.20	20	0.20	20
	Offices	133	0.10	14	0.10	14
2	Offices	251	0.10	26	0.10	26
3	Computer room	70	0.04	3	0.04	3
	Conference room	225	1.30	293	0.10	23
	Offices	148	0.10	15	0.10	15
Total, N [ppl]				423		153

Table 3. Occupant loads for the two office building scenarios.

For each scenario, Simulex was used to obtain the base evacuation time and the evacuation times for a range of mean pre-evacuation times with triangular distributions. The maximum potential evacuation times, according to Equation (8), were also evaluated. In each case the Simulex "office" type population was specified for all occupants. Although the building layout is not highly complex it was impractical to compute the evacuation times with different pre-evacuation distributions using hand calculations.

Figure 6 shows the comparison between the simulated evacuation time using the range of mean pre-evacuation times and the potential maximum evacuation times. For any given mean pre-evacuation time, the calculated evacuation time showed approximately a 1% variation between simulations.

The results again show that the evacuation time is a function of the mean pre-evacuation time but is effectively independent of occupant load when the mean pre-evacuation time is large. Also, as with the square room, the potential maximum evacuation time, with the exception of when $\overline{t_p} = 0$, is always longer than the Simulex results.

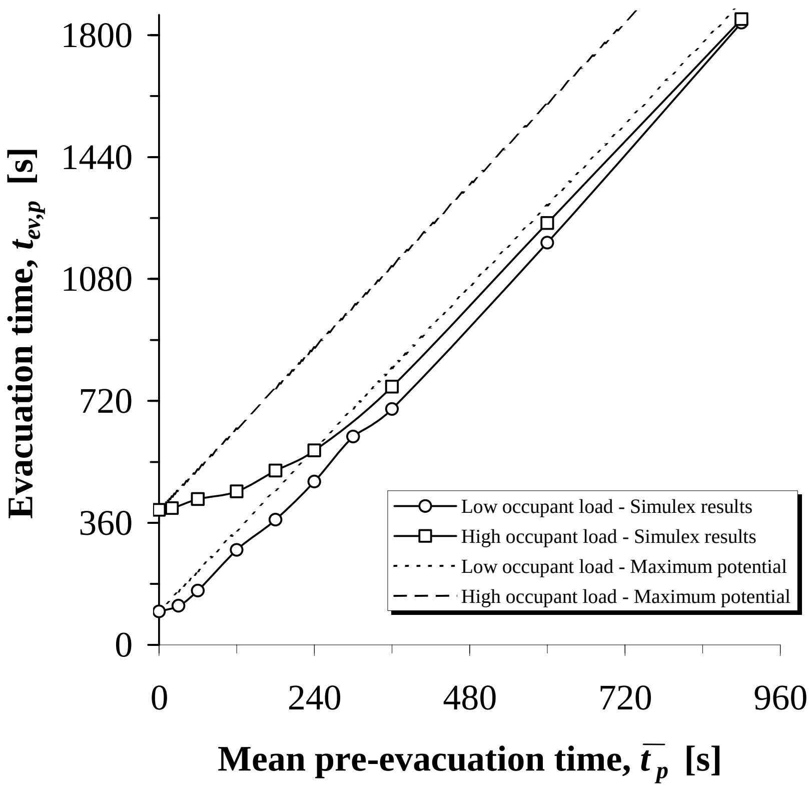


Figure 6. Comparison of Simulex evacuation times for the high and low occupant load scenarios as a function of the mean pre-evacuation time.

INTERMEDIATE QUEUES

During the Simulex simulations in both the simple room and the hypothetical building it was observed that at high occupant densities the simulations generated "intermediate queues" as those people who had yet to begin moving blocked people that had started to move. As these simulations continued, the blocking people began to start moving thus relieving the intermediate queues (Figure 7). In some cases this allowed groups of people to reach the exit and other cases it resulted in the amalgamation of intermediate queues.

For the single room scenario, instead of queuing occurring around the door, as was observed in the lower occupant density scenarios or where the pre-evacuation time was short, the queuing occurred in these intermediate queues. Eventually the intermediate queues broke down and the queuing predominantly occurred around the door. The development of the intermediate queues occurred when the occupant density was just above 1.00 ppl/m^2 but became significant once the occupant density went higher than 1.30 ppl/m^2.

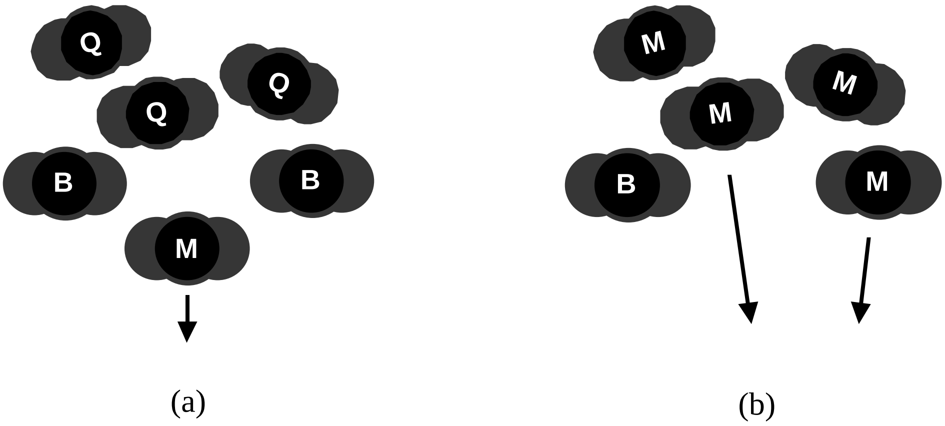


Figure 7. (a) Development of an intermediate queue in Simulex formed by blocking people [B], queuing people [Q] and moving people [M]; (b) intermediate queue breaks down once blocking people begin to move.

Undoubtedly this development of intermediate queues is an artefact of the Simulex model and the distribution of people in the space. In a real evacuation we would likely not get these intermediate queues but rather expect to see the people who are moving to negotiate past those who are standing still or possibly compel the static people to begin to move. It is therefore important to investigate how the formation of the intermediate queues impacts on the Simulex calculations.

In the single square room scenario we can assess the possible effect of the intermediate queues by examining the door queue. Where the door queue is continuously populated, it is flowing people at its maximum capacity. However, the continuous door queue may not exist for several reasons such as:

(i) At low occupant densities people reach the door infrequently and so no queue is able to form.

(ii) At high occupant densities and high mean pre-evacuation times it is possible that the intermediate queues prevent occupants forming the continuous queue at the door. The continuous queue will again not form because of the infrequent arrival of people but this could be simply as a result of the long time interval between people starting to move or due to moving people being blocked by those yet to begin moving.

The flow through the door $\dot{n}_{out}$ can be between 0 and the maximum flow capacity of the door. If the queue is fully populated then $\dot{n}_{out}$ remains at the maximum capacity. The average $\dot{n}_{out}$ for a given mean pre-evacuation time can be obtained from $\overline{\dot{n}_{out,p}} = \frac{N}{t_{ev,p}}$ and by plotting these for each occupant density (Figure 8) we find that for the simple square room scenario the maximum flow capacity of the door is just below 1.60 ppl/s shown when $\overline{t_p} \rightarrow 0$ and the occupant density $D_0 \geq \sim 0.50\,\text{ppl/m}^2$.

Figure 8 confirms that when the occupant density is low, people reach the door infrequently and so no queue is able to form such that the door flows at maximum capacity. Furthermore, Figure 8 shows that at high occupant densities and long pre-evacuation times the flow through the door is also not at its maximum capacity but it is not possible to determine if this is as a result of the slow breakdown of intermediate queues or simply due to the longer pre-movement times. Instead we need to examine the cumulative number of people that have exited through the door as a function of the evacuation time.

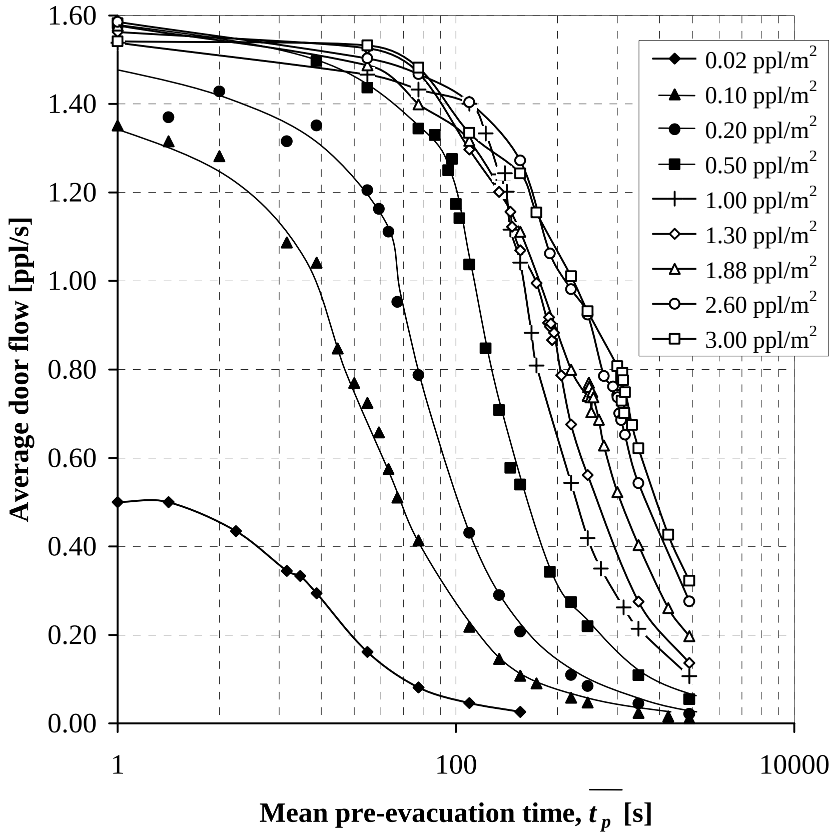
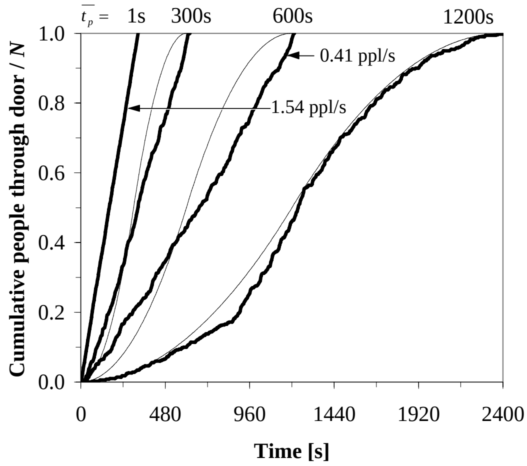
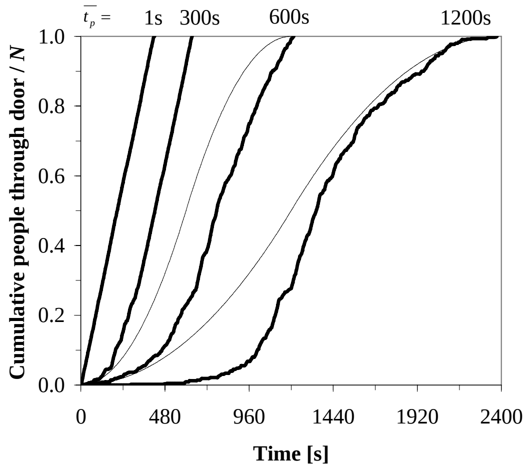


Figure 8. The mean door flow as a function of the mean pre-evacuation time for the simple square room scenario.

Figure 9 plots the ratio of the cumulative number of people exiting through the door with the total number of occupants *N* against time for three specific occupant densities. Figure 9(a) shows that for lower occupant densities, where blocking does not occur, the flow of people through the door is continuous albeit not always at full capacity as indicated by the gradient of the lines at longer mean pre-evacuation times. However as shown in Figure 9(c), at higher occupant densities the initiation of people flowing through the door is significantly delayed and thereafter the door is utilised at an almost constant capacity irrespective of the pre-evacuation time. Figure 9(b) shows the transition between the two other cases. The plots shown in Figure 9 demonstrate a significant difference in the way in which the Simulex people exit through the door between the high and low occupant density scenarios that is not apparent from simply considering the final evacuation time.



(a)



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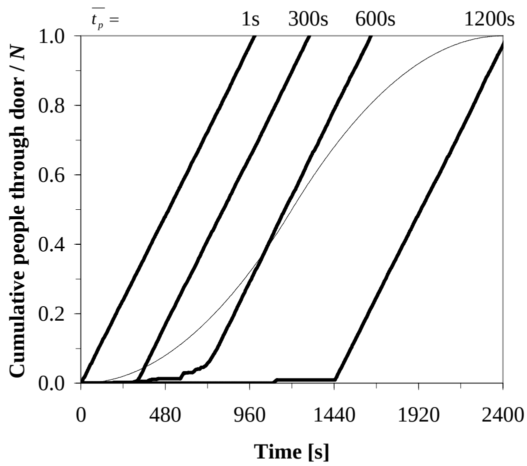

(c)

Figure 9. Normalised cumulative number of people exiting through the door against time for (a) 1.00 ppl/m^2; (b) 1.30 ppl/m^2; (c) 3.00 ppl/m^2 with mean pre-evacuation times of 1s, 300s, 600s and 1200s as indicated. Dark lines are Simulex results and light lines are from Equation (14).

It is important to note that the final evacuation time at these higher occupant densities is generally no different to what we might expect if blocking did not occur. We have already found that the evacuation time is dominated by the pre-evacuation time and independent of the occupant density when the mean pre-evacuation time is large. The probability distribution function is related to the integral of the probability density function such that for a triangular function

$$
\begin{aligned}
F(t) &= 0 && \text{if } t < a \\
F(t) &= \frac{(t-a)^2}{(b-a)(c-a)} && \text{if } a \le t \le b \\
F(t) &= 1 - \frac{(c-t)^2}{(c-a)(c-b)} && \text{if } b \le t \le c \\
F(t) &= 1 && \text{if } c < t\,.
\end{aligned}
\qquad (13)
$$

Thus for our Simulex case we obtain

$$
\begin{aligned}
F(t) &= 0 && \text{if } t < 0 \\
F(t) &= \frac{t^2}{2\overline{t_p}^2} && \text{if } 0 \le t \le \overline{t_p} \\
F(t) &= 1 - \frac{\left(2\overline{t_p} - t\right)^2}{2\overline{t_p}^2} && \text{if } \overline{t_p} \le t \le 2\overline{t_p} \\
F(t) &= 1 && \text{if } 2\overline{t_p} < t\,.
\end{aligned}
\qquad (14)
$$

Equation (14) can be used to determine what proportion of the occupants have begun to start moving and this will be approximately equivalent to the proportion that should have exited in the cases where the mean pre-evacuation time is large. Equation (14) is plotted in Figure 9 for selected simulations and it is clear that the termination points of the curves are comparable to the Simulex simulation results. Figure 9 also shows that Equation (14) is a reasonable approximation of the evacuation at the larger pre-evacuation times when the occupant density is lower. However comparing the form of the Simulex simulations and the expected results using Equation (14) there are significant differences in the high occupant density, large mean pre-evacuation time cases.

The results of this analysis show that if the intermediate queues break down sufficiently quickly then these intermediate queues do not affect the evacuation process. On the other hand, if they breakdown too slowly then the evacuation process will be affected. Clearly the formation and breakdown of the intermediate queues is a function of the mean pre-evacuation time. Where the mean pre-evacuation time is long we find that the breakdown of the intermediate queues is too slow, as those persons blocking the flow do not begin to move until after a considerable delay. When the mean pre-evacuation time is short, the formation of intermediate queues is short-lived since blocking people soon start to move thus quickly breaking down any intermediate queue.

The results also indicate that the final evacuation time is not significantly altered where we have intermediate queues that breakdown slowly. The worst-case scenario in which an intermediate queue could affect the evacuation time is where nearly all the people in a space have started to move but are blocked by the last two people to begin moving. In such a case there could then be a significant delay in the overall evacuation time as the people will then still have to flow through the remainder of the exit path. The probability of this happening is small since it only occurs approximately 1 in N^2 times and even then it is unlikely that the last two people to begin moving would be able to completely block everyone else in the space.

These findings have implications for using Simulex in high occupant density scenarios, in particular an important aspect to consider is if we had a case in which the single room fed into a larger building in which other people were involved in the evacuation. The significant delay caused by blocking means that the people in the room would not be interacting with other occupants and potentially affecting the downstream evacuation process. This could impact on the use of other escape paths and the overall evacuation time. An examination of the evacuation results for the hypothetical office building shows how such circumstances can occur. Firstly, a case in which the occupant density in the conference room was set to 0.90 ppl/m^2 and the mean pre-evacuation time was 180 s was considered. This occupant density was just below the 1.00 ppl/m^2 for intermediate queue development and it was noted that the people on the top floor not in the conference room intermingled with the people leaving the conference room throughout the simulation. When the conference room occupant density was increased to 1.30 ppl/m^2 it was found that the first person did not leave the conference room until 190 s had elapsed due to the blocking caused by other stationary occupants. By that time, 6 out of 19 people in the other rooms on the third floor had already left and their movement had not been modified by any people leaving the conference room as we might expect had blocking not occurred. Although in this case the overall effect on the evacuation was not critical there may be situations where the blocking in the conference room is important.

CONCLUSIONS

The effect of having a distribution of pre-evacuation values on the evacuation of spaces has been examined and a number of key findings have been identified.

Assuming the maximum pre-evacuation and movement times are independent such that they can be computed separately and then summed to obtain the evacuation time appears to conservatively over-estimate the result where we expect the pre-evacuation time to be a distribution of values. This paper demonstrates this over-estimate can be investigated with the use of a model such as Simulex in which a distribution of pre-evacuation times can be specified by the user.

The results from the simulations demonstrate that the pre-evacuation time can have a significant influence on the results generated by Simulex when a distribution of values is specified. Large pre-evacuation distributions result in evacuation times that are essentially independent of the occupant density whereas the occupant density is a major factor when the pre-evacuation distribution is small. Clearly the selection of a suitable range over which the pre-evacuation values can take must be made in order to obtain appropriate evacuation times. Similarly the occupant load for the building must be appropriately assessed. Where pre-evacuation distributions are expected to be large, we can see that obtaining an accurate occupant load is not as important as when pre-evacuation distributions are small.

As a result of the possibility of intermediate queues being formed in high occupant density scenarios, care must be exercised with the use of Simulex particularly where the space feeds into a larger building evacuation. Although the overall evacuation time may not be significantly affected, the utilization of exit routes during the evacuation may not be the same as would be expected if the intermediate queues were not present.

Although the general discussion provided in this paper is likely to be applicable to other evacuation models, the development of the intermediate queues is specific to Simulex due to the mechanisms it uses. It is also important to realize that the findings discussed this paper may not be appropriate for scenarios in which groups of people have different pre-evacuation distributions. For example, in a fire in which a proportion of the building's population can see fire or smoke whilst others rely on a warning from an automatic alarm system we might expect the pre-evacuation distribution for those in sight of the fire cues to be smaller than those remote from the fire cues and the pre-evacuation distribution for those remote from the cues may have a delayed offset compared to those in sight of the cues. This would lead to some occupants starting to move ahead of those with a delayed offset and the downstream interactions between occupants could be different from where all of the occupants have the same pre-evacuation characteristics.

The fact that similar results for both the square room and the somewhat more complex hypothetical building gave similar results regarding the dependence of occupant density and pre-evacuation distribution times lends itself to additional analysis which is the subject of further research.

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