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Finding the optimal positioning of exits to minimise egress time: A study case using a square room with one or two exits of equal size

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Abstract

In this paper, we use an egress computational simulation model to determine the optimal positioning of exits around the perimeter of a square room in order to minimise egress times. The solution is found through trial and error exploration of the possible significant exit locations. The egress simulations were conducted assuming idealised conditions of zero response times and population behaviour such that occupants elect to move towards their nearest exit. The analysis reveals that strategic positioning of even a single exit on the perimeter of the room can result in reduced egress times. Even greater advantage can be gained by the strategic positioning of two exits of equal size. It was also noted that the advantage offered by the identified optimal locations diminishes as the size of the exit increases while keeping the population serviced by the exits constant, or the size of the population serviced by the exit decreases while keeping the size of the exits constant.

Keywords
egress simulation,
egress time,
optimal positioning of exits

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1 Introduction

A common problem faced by fire safety engineers in evacuation analysis concerns the optimal positioning of exits within an arbitrarily complex structure in order to minimise evacuation times. To a certain extent, building codes provide guidelines for the positioning of exits; however, these constraints are more concerned with ensuring safety rather than minimising evacuation times. For an arbitrarily complex room, ignoring constraints imposed by regulations such as minimising travel distances and avoiding dead-end corridors, where should exits be placed in order to minimise evacuation times? Indeed, for an arbitrarily shaped room with a given number of exits, does the distribution of exits around the perimeter impact the egress time?

This problem becomes more difficult as the available options and hence complexity of the evacuation scenario increases. It can reasonably be expected that for a given population size, the solution of the problem will be dependent on the shape and size of the compartment, the number and relative size of the available exits. For a specified problem the engineer could examine several possible exit location options and select the configuration which produces the smallest evacuation time, but this would not necessarily produce the optimal configuration or the global minimum egress time. Using this approach the engineer would have to examine every significant combination of exit location to be sure that the global minimum had been found.

For an arbitrarily complex shaped room with a large number of exits of varying size the number of possible permutations of exit size and location would measure in the hundreds if not thousands. The simplest variation of this problem involves a square room with one or two exits of equal size. While the brute force trial and error method may be too daunting for the large arbitrarily complex problem, it is viable for the simpler, yet surprisingly unresolved problem. In this paper we attempt to determine the relative location of one and two exits of equal size in a square room which minimises the egress time for an arbitrary number of occupants. The solution is found through trial and error exploration of the possible significant exit locations. The egress times for each exit configuration are determined through evacuation simulation.

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2 Problem specification

The problem to be investigated can be stated very simply as follows, for a room of given size, containing an arbitrarily large population, is there an optimal location for the exit or exits that will minimise egress times?

For simplicity, our investigation is limited to square rooms containing one or two exits. In the two exit case, each exit has identical dimensions. The square room used in the analysis has an area of 100 m^2 and exits of width 1.0 m and 2.0 m are investigated. The population of the room consists of 200 people producing a population density of 2 people/m^2.

3 Solution methodology

The approach adopted involves the use of computer simulation software to simulate the egress for each relevant exit configuration.

3.1 Simulation software

To determine the egress times for the various configurations the STEPS evacuation/pedestrian software is used. The basis of the model has frequently been described in other publications (Wall and Waterson 2002; Waterson 2001; Rhodes and Hoffmann 1999, 2002; Hoffmann et al. 1998; Newman et al. 1998; Hoffmann and Henson 1997a, b; STEPS 2009) and so it will be briefly described here.

The STEPS (Simulation of Transient Evacuation and Pedestrian MovementS) evacuation software was developed by Mott MacDonald Group. The STEPS model is an agent-based model.

This model is used to represent occupants' movement under both normal and emergency situations. For this reason, STEPS is considered a "hybrid" model, since it can function as an evacuation model as well as a pedestrian model.

The STEPS model has been widely used for large-scale and complex scenarios, such as metro stations, airports, shopping malls. In fact, it has been applied for several applications: from transportation to crowd management. Amongst many reasons for that, the following ones can be mentioned:

- it is a hybrid model (i.e., it can work in evacuation mode as well pedestrian mode);
- it can model elevators, escalators, vehicles etc.;
- it is robust and well recognized.

This model uses coarse nodes to represent the space. Despite this, STEPS produces real-time 3D simulations which make it easy to interpret the results by both non-specialists and experts, see Fig. 1.

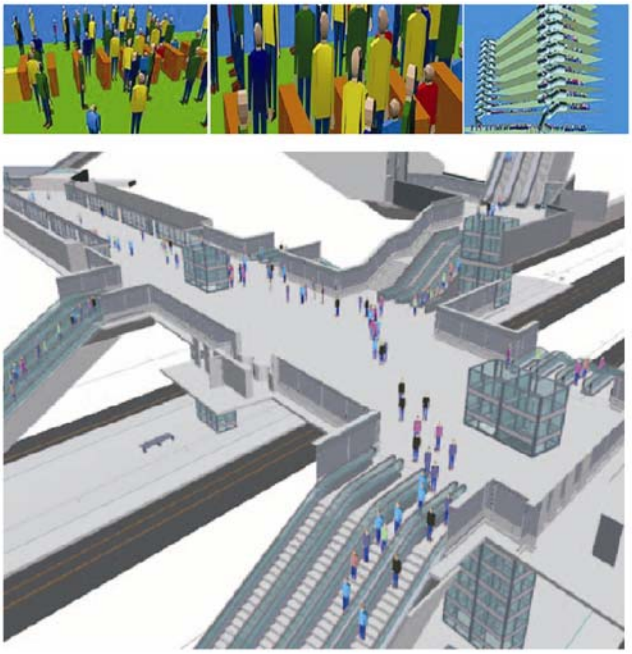


Fig. 1 3D representations using STEPS evacuation model

With this feature, important issues found during evacuation processes can be identified, such as: bottlenecks, congestions, preferred exits, queuing etc.

In STEPS, each occupant uses one cell at any given time and moves in the desired direction if the next cell is empty. Each occupant has its own characteristics, such as patience and familiarity behaviour factors.

According to Mott MacDonald Group, STEPS main capabilities can be summarized as follows:

- efficient handling of large and complex models;
- direct import of 2D and 3D CAD models;
- 3D interactive (virtual reality) graphical user interface.

Another useful feature of STEPS is that it can be used in conjunction, in real-time 3D simulation, with fire modelling outputs obtained from CFD (computational fluid dynamics) fire models. Besides that, a new version of STEPS will be released soon (by the end of 2009), in which a direct interaction with FDS (fire dynamics simulator) (NIST 2000) will be enabled. This will be extremely helpful, because FDS has been largely used by fire engineers, since its release.

Despite its application in practical and real situations, there are very few available publications about this model.

Table 1 presents a summary of the STEPS evacuation model.

3.2 Model parameters

Clearly, evacuation times will depend on the response time of the participants which typically take a log-normal

Table 1 STEPS evacuation model's summary

Features	STEPS
Modelling method	Microscopic (agent-based model)
Computer language	Unknown
Type of grid	Coarse
Use of CAD drawings	Yes
Inclusion of fire data	Yes
Human behaviour	Yes

distribution (Purser 1998). This means that some occupants may have quite long response times which could impact the overall evacuation times. In these cases, the overall evacuation time will be strongly influenced by the nature of the response time distribution rather than simply the exit location. In these simulations we remove the influence of response time by assuming that the entire population reacts instantly. This means that all the simulated occupants react immediately at the start of the simulation. The population was randomly generated. The combination of instant response times, travel speeds and relatively short travel distances combine to produce large areas of congestion around the exits almost immediately.

Behaviour exhibited by people during egress and evacuation situations can be quite complex (Gwynne et al. 1999; Tavares et al. 2006), even in relatively simple situations involving a square room. For example, room occupants may: move in groups and at the speed of the slowest member of the group, attempt to re-unite separated groups prior to egress, select an exit for which they are most familiar, follow the movement of other unrelated room occupants, recommit to different exits during the egress and so on. In order to simplify the analysis and isolate issues associated with room configuration and exit location these complex behaviours are greatly simplified. The behavioural response imposed on the population is such that occupants will elect to move towards their nearest exit and furthermore, that the occupants know the location of their nearest exit. While this behaviour may be considered simple it is nevertheless reasonable for our purpose. Indeed, this type of assumption is not very dissimilar to the type of assumptions implicit in most building regulations and used in many performance-based evacuation analyses.

Regarding the grid size, the STEPS model divides surfaces on which the occupants are able to walk into smaller entities called cells. Each cell is 0.5 m × 0.5 m in size and they are connected together to form a grid. Therefore, each plane defined within the model has a corresponding grid that is calculated when the plane is created or recalculated when one of its parameters is changed. In terms of representing the occupants' movement, one person always occupies one grid cell only and one cell can only accommodate one person. The effect of this is that the fundamental law of physics ("*two bodies cannot occupy the same space at the same time*") is realistically represented.

It is relevant to mention that the potential flow rate at the door was 1.31 occ/(m·s); and that the simulations were not extended outside of the room. In other words, once the occupants reached the exit(s), it was assumed that they were within the place of safety.

The simulations were repeated a total of 50 times for each scenario. Thus all the results presented in this paper represent an average over 50 simulations. At the start of each simulation, the starting location of the population was also randomised. This ensured that the population was distributed throughout the confines of the geometry with little bias resulting from population starting position contributing significantly to the overall results.

3.3 Scenarios investigated

Two types of scenario are investigated: one involves a square room with a single exit while the other type involves the same compartment with two exits. Each scenario is further sub-divided into four cases involving different exit widths namely, (a) 1.0 m, (b) 1.5 m, and (c) 2.0 m. Finally, each case is sub-divided into a number of sub-cases representing exit location. The walls of the compartment are numbered Wall 1, Wall 2, Wall 3, and Wall 4, progressing in a counter clockwise direction with the south wall labelled as Wall 1. It is also important to observe that these geometrical assumptions fit in with the grid size defined by the STEPS model as discussed previously.

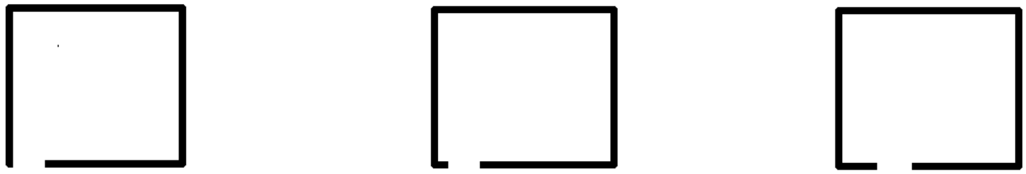
For the single exit scenario, it is possible to identify at most six unique exit locations representing the nearest corner of the door being located (i) 0 m, (ii) 1.0 m, (iii) 2.0 m, (iv) 3.0 m, (v) 4.0 m from the front left room corner and (vi) centrally located (see Fig. 2). Note that not these entire exit locations will produce unique sub-cases for all the exit widths, for example, for the 2.0 m case, sub-cases (iv) and (vi) are identical. Any other exit location is considered a non-significant variation of these six cases. For the two exit scenario, it is possible to identify some 13 unique exit locations (see Fig. 3).

4 Results and discussion

In total, 300 cases were run for Scenario 1 and 650 cases were run for Scenario 2. The detailed results for these scenarios are presented and discussed in this section.

4.1 Single exit scenarios

Detailed results for the 1.0 m and 2.0 m wide exits are presented here. We note that with a 1.0 m exit compartment



(i) Position 1: exit located in the corner of the south wall

(ii) Position 2: exit edge located 1.0 m from the corner

(iii) Position 3: exit edge located 2.0 m from the corner

(iv) Position 4: exit edge located 3.0 m from the corner

(v) Position 5: exit edge located 4.0 m from the corner

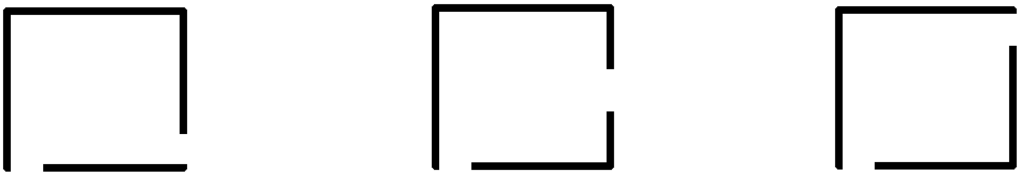
(vi) Position 6: exit located in the middle of the south wall

Fig. 2 Exit locations for single exit cases with 1.0 m wide door

(i) Position 1: two exits side by side in the corner of Wall 1

(ii) Position 2: one exit located in the corner of Wall 1 and one located in the middle of Wall 1

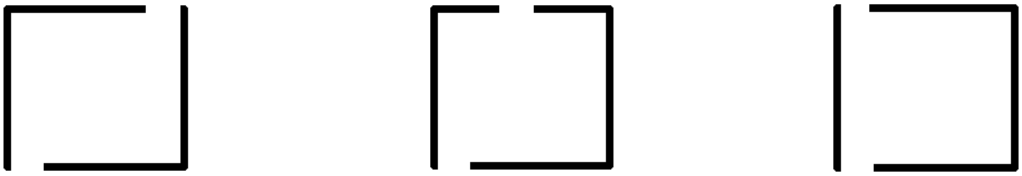
(iii) Position 3: each exit located in each corner of Wall 1



(iv) Position 4: one exit located in the left corner of Wall 1 and the other exit located in the lower corner of Wall 2

(v) Position 5: one exit located in the left corner of Wall 1 and the other exit located in the middle of Wall 2

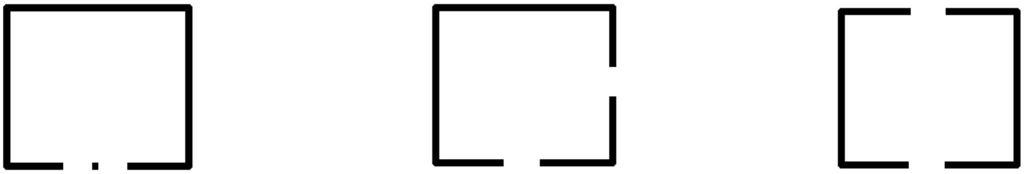
(vi) Position 6: one exit located in the left corner of Wall 1 and the other exit located in the upper corner of Wall 2



(vii) Position 7: one exit located in the left corner of Wall 1 and the other exit located in the right corner of Wall 3

(viii) Position 8: one exit located in the left corner of Wall 1 and the other exit located in the middle of Wall 3

(ix) Position 9: one exit located in the left corner of Wall 1 and the other exit located in the left corner of Wall 3



(x) Position 10: two exits placed side by side located in the middle of Wall 1

(xi) Position 11: one exit located in the middle of Wall 1 and the other one exit located in the middle of Wall 2

(xii) Position 12: one exit located in the middle of Wall 1 and the other exit located in the middle of Wall 3

(xiii) Position 13: the two exits placed side by side located between the corner and middle of Wall 1

Fig. 3 Exit locations for two exit cases empties in approximately 166 seconds while with a 2.0 m exit the compartment empties in 84 seconds, approximately half the time of the narrower exit. Also as expected, for the cases with the 1.0 m exit, the occupants experienced considerably more congestion than those for the 2.0 m exit case.

If we now consider the egress times for the different cases in Scenario 1 with the single 1.0 m exit, we note that with the exception of Position 1, all the cases produce virtually identical egress statistics and that Position 1 produces slightly shorter egress times (Table 2).

The average evacuation time for the exit located in Position 1 is some 1.1% smaller than the average evacuation time for the other exit locations. This is clearly shown in Fig. 4. The shorter evacuation times are produced despite the fact that on average occupants travelled further in the Position 1 scenario than in the other cases.

These results suggest there is a slight advantage in placing the exit in the corner of the room. Placing the exit in any other location will produce longer egress times and furthermore, outside the corner region, the egress time is not strongly dependent on exit location.

An explanation of these results can be found in the nature of the flow dynamics around the exit. As an instant response time distribution is used in these simulations, a large crowd develops around the exit almost immediately creating a large characteristic arch (see Fig. 5). Occupant movement within the arch is chaotic with people interacting with all of their neighbours creating many conflicts for space.

Table 2 Egress data for room with 200 occupants and a single 1.0 m exit

Exit positions	Average evacuation times (s)
Position 1 (corner of wall)	162.5
Position 2	166.2
Position 3	166.1
Position 4	166.5
Position 5	166.3
Position 6 (middle of wall)	166.4

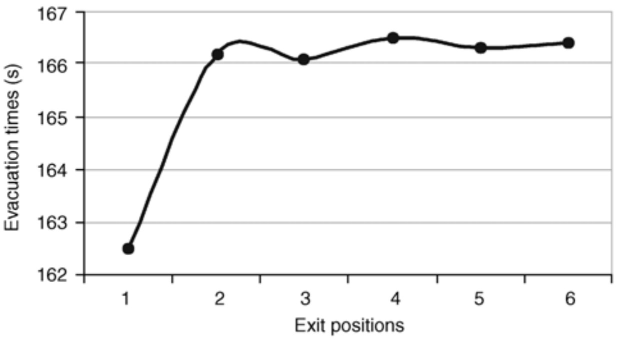


Fig. 4 Average evacuation time for the 1.0 m exit cases

This produces large amounts of time spent in congestion. However, when the exit is located hard up against the corner of the room, the compartments confining wall (Wall 4) allows occupants pressed up against the wall (and those immediately near the wall) to take a more direct path to the exit, reducing the opportunity for conflicts from the "wall side" (see Fig. 6) while travelling to the exit. The wall effectively provides the occupants with a barrier protecting them from time wasting conflict interactions from one side.

Therefore, this can be summarized as follows: the bigger is the arch (*AA*) formation, bigger the congestion (*C*) becomes, and consequently the flow rate (*FR*) becomes lower. As consequence of that, the evacuation time (*ET*) becomes slower:

$$AA \uparrow C \uparrow FR \downarrow ET \uparrow$$

The greater the physical extent and duration that the occupant arch is in contact with the confining walls, the greater the advantage provided by the wall. When the exit is located in the corner, more of the arch comes into contact with the confining walls then if the exit was located away from the corner. Furthermore, occupants immediately surrounding an exit and located at the wall normal to the exit, will experience fewer conflicts or challenges to pass through the exit then occupants immediately surrounding an exit which is located away from the corner. This is not unlike the well known phenomena observed at sports grounds when large crowds attempt to exit through a gate (Helbing et al. 2000). In such situations exits with a barrier positioned perpendicular to the centre of the exit produce higher throughput than exits without the perpendicular barrier.

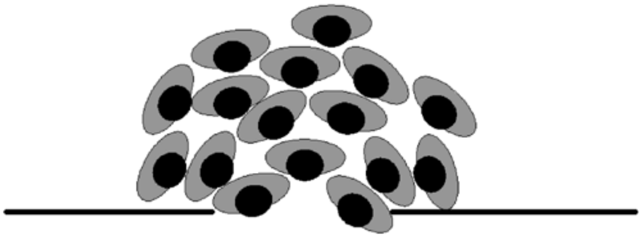


Fig. 5 Typical occupant arch formed around a congested exit located away from a room corner

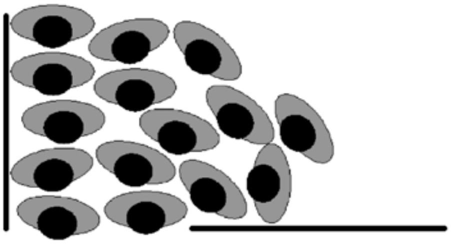


Fig. 6 Typical arch formation around congested exit located in a room corner

If the above explanation is correct, we would expect to find that as the exit width is increased while keeping the population size fixed, the advantage offered by the corner location should diminish. This is because the wider exit provides greater exit capacity resulting in more rapid egress. With a more rapid egress the extent and duration of arch contact with the confining walls will diminish. Furthermore, if the population size was decreased while keeping the exit size fixed we would also expect to find the advantage offered by the corner exit to diminish.

When the exit width is increased to 2.0 m (see Table 3 and Fig. 7) we note that the corner exit still provides an advantage over the other exit locations, producing the minimum egress time. The average evacuation time for the exit located in Position 1 is some 0.6% smaller than the average evacuation time for the other exit locations. This is clearly shown in Fig. 7.

However, the advantage offered by the corner location is half that for the smaller 1.0 m exit. Furthermore, if the population of the room is decreased to 100 we find that the 1.0 m exit located in the corner provides only a 0.8% advantage over exits located away from the corner. Both these observations support the explanation suggested above.

The above analysis suggests that for a crowd of given size, an exit placed in the corner of a square room will produce slightly better egress efficiencies than the same sized exit placed away from the corner. In these examples a small compartment was used which effectively minimised the influence of travel distance on egress efficiency. The relatively small room implies relatively short travel distances and hence travel times and this combined with the instant response times generates large areas of congestion around the exits very early in the evacuation. In the case of the corner located exit, this maximises the influence of the corner wall on evacuation efficiency. Thus for small compartments, the time involved in travelling to the exit (or the exit queue) does not exert a significant influence on the overall egress times or egress efficiencies.

Table 3 Egress data for room with 200 occupants and a single 2.0 m exit

Exit positions	Average evacuation times (s)
Position 1 (corner of wall)	83.4
Position 2	84.1
Position 3	84.3
Position 4	84.3
Position 5	84.2
Position 6 (middle of wall)	84.2

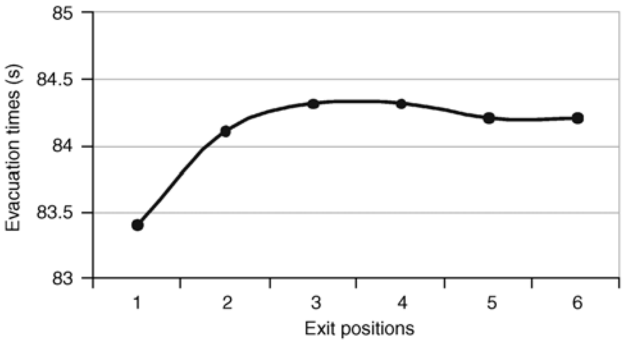


Fig. 7 Average evacuation time for the 2.0 m exit cases

As the size of the compartment increases, while the population size remains constant, the time required to reach the exit increases in significance while the advantage offered by the corner located exit decreases. This is due to the decrease in effective crowd size formed at the exit at any one time resulting from the greater staggered arrival times. As the compartment size continues to increase, eventually the staggered arrival times resulting from the increased travel time (i.e., distance) will dominant the evacuation process. While no attempt was made to determine the critical compartment size for a population of 200 people, a 30 m×30 m compartment was found to provide an advantage for the corner located exit while a 60 m×60 m compartment provided a slight advantage for the exit located in the centre of the wall.

4.2 Two exit scenarios

Detailed results for the cases with two 1.0 m and two 2.0 m wide exits are presented here. We note that with two 1.0 m exits the compartment empties in approximately 82 – 95 seconds, depending on exit locations while with two 2.0 m exits the compartment empties in approximately 43 – 46 seconds. As to be expected, we note that with two 2.0 m exits, the compartment empties in approximately half the time of the compartment with two 1.0 m exits. Also, on comparing these times with the equivalent times for the appropriate single exit cases of Scenario 1, we find that former are approximately twice as fast as the latter. Again as expected, for the cases with two 1.0 m exits the occupants experienced considerably more congestion than those for the two 2.0 m exit cases.

If we now consider the egress times for the different cases in Scenario 2 with two 1.0 m exits (Table 4), we note that there is a complex spread of average evacuation time ranging from 82.5 s for Position 1 to 95.4 s for Position 8. This difference is more significant than the difference found in the single exit cases and suggests that the relative positioning of two exits in a compartment can have a significant impact on expected egress times.

Table 4 Egress data for room with 200 occupants and two 1.0 m exits

Exit positions	Average evacuation times (s)
1	82.5
2	94.2
3	85.1
4	84.3
5	90.5
6	84.2
7	84.6
8	95.4
9	84.4
10	82.2
11	83.2
12	84.1
13	82.7

Examination of Fig. 8 suggests there is a pattern in the distribution of egress times, with exits located in Positions 1, 10 and 13 producing the shortest egress times (82.5 s, 82.2 s and 82.7 s, respectively), exits located in Positions 2, 5 and 8 producing the longest egress times (94.2 s, 90.5 s and 95.4 s, respectively) and all the other exit configurations producing similarly small egress times close to those of those of the shortest egress times.

On examining the exit locations associated with these clusters of exits (see Fig. 3) we note that the shortest egress times (Positions 1, 10 and 13) are produced by exits placed adjacent to each other, the longest egress times (Positions 2, 5 and 8) are produced by exits positioned asymmetrically around the compartment and the intermediate egress times (Positions 3, 4, 6, 7, 9, 11 and 12) are produced by exits positioned symmetrically or near symmetrically around the compartment. When the exits are presented graphically clustered into configuration groups the differences between the configuration groups becomes apparent (see Fig. 9).

To explain the difference in performance between the exit configuration groups it is necessary to consider the behaviour of the evacuating population. Recall that within the model, the occupants follow the idealised behaviour of moving towards their nearest exit. If the exits are symmetrically placed around the perimeter of the room, using a distance algorithm to allocate floor area to a particular exit, the room floor area will be divided equally between the two exits, 50% of the floor area being located closer to one exit than the other exit. As the behaviour imposed on the population is to utilise their nearest exit, if the population is randomly positioned within the room, it is reasonable to expect that 50% of the population will go to one exit and 50% will go to the other exit. If the exits are asymmetrically placed around the perimeter of the room, using the same distance algorithm, one exit will be allocated more than 50% of the floor area and will therefore attract more than 50% of the randomly placed population. Thus in the asymmetrical cases there will be an imbalance in the number of people using the exits, thereby prolonging the overall evacuation.

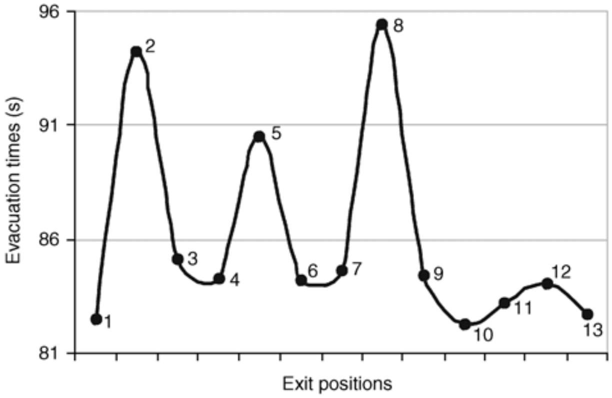


Fig. 8 Average evacuation time for the 13 cases with two 1.0 m exits

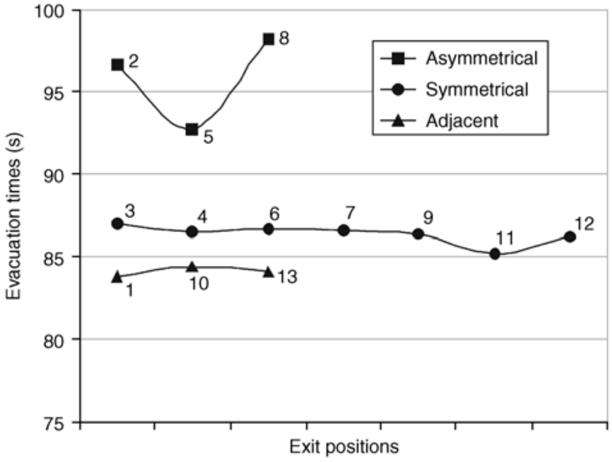


Fig. 9 Average evacuation time for the 13 cases with two 1.0 m exits clustered in groupings of exit configuration type

The results also suggest that two exits placed side by side produce better egress times than two exits distributed around the perimeter of the room. The adjacent exit positions (Positions 1, 10 and 13) produce an average egress time of 82.4 s while the symmetrically placed exits (Positions 3, 4, 6, 7, 9, 11 and 12) produce an average egress time of 84.3 s. Of the adjacent exit locations, the exit pair located in the corner (Position 1) produced the best time for the same reasons as highlighted for the single exit cases.

It is worth noting that in the adjacent exit cases, the two 1.0 m exits were placed side by side, not as a continuous opening of 2.0 m, but as two separate 1.0 m exits with a partition separating the exits. The partition between the exits act as a barrier preventing interaction and hence time wasting conflicts between occupants attempting to utilise the exits. Thus the egress time produced by these two adjacent exits is better than the egress time produced by a single exit of width equal to the sum of the two adjacent exits. This can be seen by comparing the results for the single 2.0 m exit located in Positions 1 (83.4 s) and 6 (84.2 s) see Table 3, with the equivalent cases using two adjacent 1.0 m exits, Position 1 (82.5 s) and Position 10 (82.2 s) respectively, see Table 4.

If we now consider the egress times for the different cases in Scenario 2 with two 2.0 m exits (see Table 5, Figs. 10 and 11), we note that spread in average evacuation time has decreased.

Thus the improved egress efficiency offered by strategically placed exits decreases as the size of the exits increases while keeping the population size fixed. This is particularly true for the difference between adjacent and symmetrically placed exits.

Table 5 Egress data for room with 200 occupants and two 2.0 m exits

Exit positions	Average evacuation times (s)
1	43.2
2	43.8
3	43.1
4	43.9
5	45.2
6	43.8
7	43.7
8	46.2
9	43.7
10	43.1
11	43.0
12	43.9

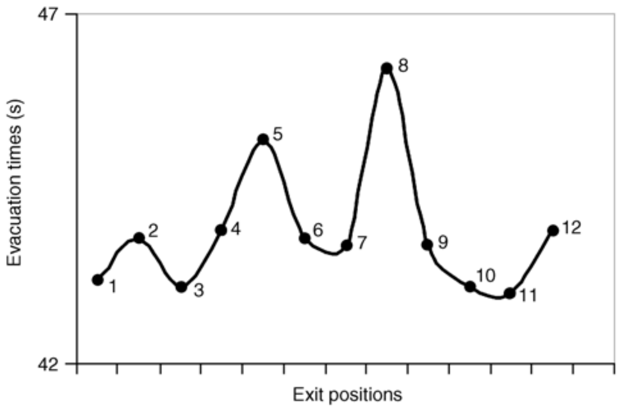


Fig. 10 Average evacuation time for the 12 cases with two 2.0 m exits

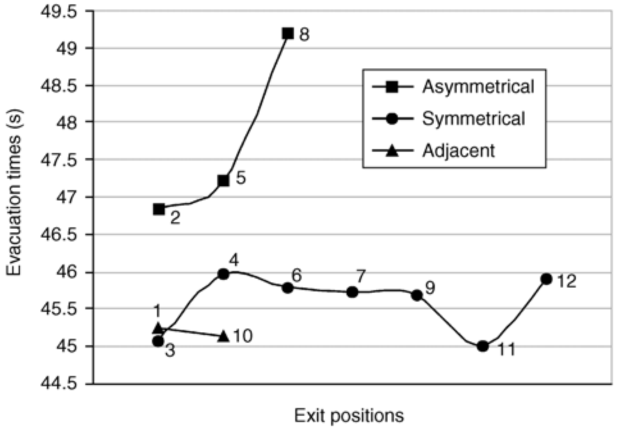


Fig. 11 Average evacuation time for the 12 cases with two 2.0 m exits clustered in groupings of exit configuration type

5 Concluding comments

In this paper, we have explored the optimal positioning of exits around the perimeter of a square room in order to minimise egress times. The egress simulations were conducted assuming ideal conditions of zero response times and population behaviour such that occupants would move to their nearest exits. Both assumptions are made to simplify the analysis and to isolate issues associated with exit location.

The analysis revealed that for square rooms with a single exit, there is a slight advantage in positioning the exit in the corner of the room. Placing the exit in any other location will produce longer egress times and furthermore, outside the corner region, the egress time will not be dependent on exit location. The advantage offered by placing the exit in a room corner diminishes as the size of the exit increases while keeping the population serviced by the exit constant or the size of the population serviced by the exit decreases while keeping the exit width constant.

With two exits a much larger range of exit positions are available for consideration. This investigation revealed that significant advantage can be derived from the strategic positioning of the exits. Analysis suggests that exits placed adjacent to each other produce the minimum egress times, exits positioned symmetrically around the perimeter of the room is next best while exits placed asymmetrically around the perimeter of the room produce the longest egress times. Furthermore, adjacent exits located in the corner of the room produce the best egress times and separate but adjacent exits produce better times than a single exit of width equal to the two adjacent exits. The difference between the best and worst configurations is more significant in the case with two exits than in the case with a single exit. The advantage offered by the adjacent exits decreases significantly as the exit size increases or the size of the population serviced by the exit decreases. To a lesser extent, the advantage offered by the symmetrically placed exits over the asymmetrically placed exits also decreases as the exit size increases or the size of the population serviced by the exit decreases.

It is important to note that the results presented here are based on simulation alone and have not been verified by full-scale experimentation. Furthermore, the simplifying assumptions have ignored factors arising from complex human behaviour and do not take into account constraints offered by building regulations. However, the author believe that the findings have relevance to practical fire engineering and may assist engineers to optimally position exits even within a constraining regulatory environment.

While the analysis presented in this paper may be viable to address the relatively simple problem of a square room with two exits of equal size, it clearly is impractical for assessing more complex situations involving many more exits, exits of varying size and complex shaped compartments. How would the engineer find a solution and how would the engineer know that an optimal or near optimal solution had been found? A possible solution to this problem may be found in numerical optimisation techniques. Numerical optimisation techniques have been applied in a range of different fields such as structural analysis and have been shown to be powerful tools for designers, saving time and reducing costs. The author have already explored the concept of combining Numerical Optimisation Techniques and associated concepts, like Design of Experiment techniques and Response Surface Modelling, with evacuation simulation in order to develop a systematic methodology to efficiently optimise evacuation safety aspects of structural designs (Tavares 2008; Tavares and Galea 2008, 2009). The approach appears to be able to identify reasonable solutions to these problems. Further testing of the method continues to determine its robustness.

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