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Innovative Applications of O.R.

Effect of exit placement on evacuation plans

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ABSTRACT

Human behaviour while trying to escape a room via its main means of egress is an important issue in social science, complex systems research, and architectural planning. Disasters resulting from human crowding have increased in recent years. In such cases, it is important to consider several factors, including the smooth flow of pedestrians and the positions of obstacles and exits. This paper describes the effects of exit placement in environments congested with pedestrians. An evacuation system was designed and implemented with multiple exits in four different arrangements. The system utilised two artificial intelligence (AI) techniques—simulated annealing (SA) and depth-first search (DFS)—to examine the optimal balance between the placements of the various exits. Simulation and experimental results demonstrated that adjacently placed exits resulted in increased crowding at some exits over others when a nearest-exit path technique (DFS) was adopted as the evacuation strategy, resulting in longer evacuation times. Of the two examined evacuation techniques, SA proved superior, as it optimally balanced the pedestrian distribution over all available exits in all scenarios. In addition, the optimal-path technique (SA) did not suffer the ill-effects of adjacent exit placement. The simulation results confirm the importance of developing optimal evacuation plans, which could significantly outperform commonly employed nearest-exit evacuation strategies.

1. Introduction

Research interest in the evacuation performance in crowded pedestrian areas, such as airport terminals, has increased in recent years, as a direct result of an increase in disasters resulting from human crowding. An abundance of early literature in this field highlights the main issue of emergency evacuation: the insufficiency of outbound capacities in evacuation networks. The inadequacy of outbound paths, considering the number and capacity of exits required to evacuate a vast number of people, is best alleviated by exploiting existing infrastructures (Afandizadeh, Jahangiri, & Kalantari, 2009; Taromi & Afandizadeh, 2003). In addition, during architectural planning, it is of vital importance to consider the positions of obstacles in the designs, as well as the locations of exits.

Evacuation time is also a feature to be considered during architectural planning. This refers to the time required for pedestrians to move from the danger area to a safe area once a danger is recognised and the evacuation begins (Ng & Chow, 2006). In a room with multiple exits, pedestrians are faced with the decision of which exit to use, which is influenced by several factors. For instance, a general observation in evacuation situations is that people prefer familiar exit routes and tend to follow other pedestrians. Invariably, one of the main factors that pedestrians consider for their selection of an exit is the time required for egress (Heliövaara, Kuusinen, Rinne, Korhonen, & Ehtamo, 2012; Yue, Zhang, Shao, & Xing, 2014).

An effective evacuation plan is tailored to and suitably distributed among the pedestrians in a facility. This being the case, the plan should successfully lead each pedestrian to safety to achieve an optimal evacuation performance (Abdelghany, Abdelghany, Mahmassani, Al-Ahmadi, & Alhalabi, 2010; Abdelghany, Abdelghany, Mahmassani, & Al-Zahrani, 2012; Abdelghany, Abdelghany, Mahmassani, & Alhalabi, 2014). Nevertheless, evacuation plan research often revolves around pedestrian behaviour, as it should, but fails to address the interaction with obstacles within a facility's layout (Kneidl, Borrmann, & Hartmann, 2012). This in turn leads to an imbalanced distribution of exit positions, which

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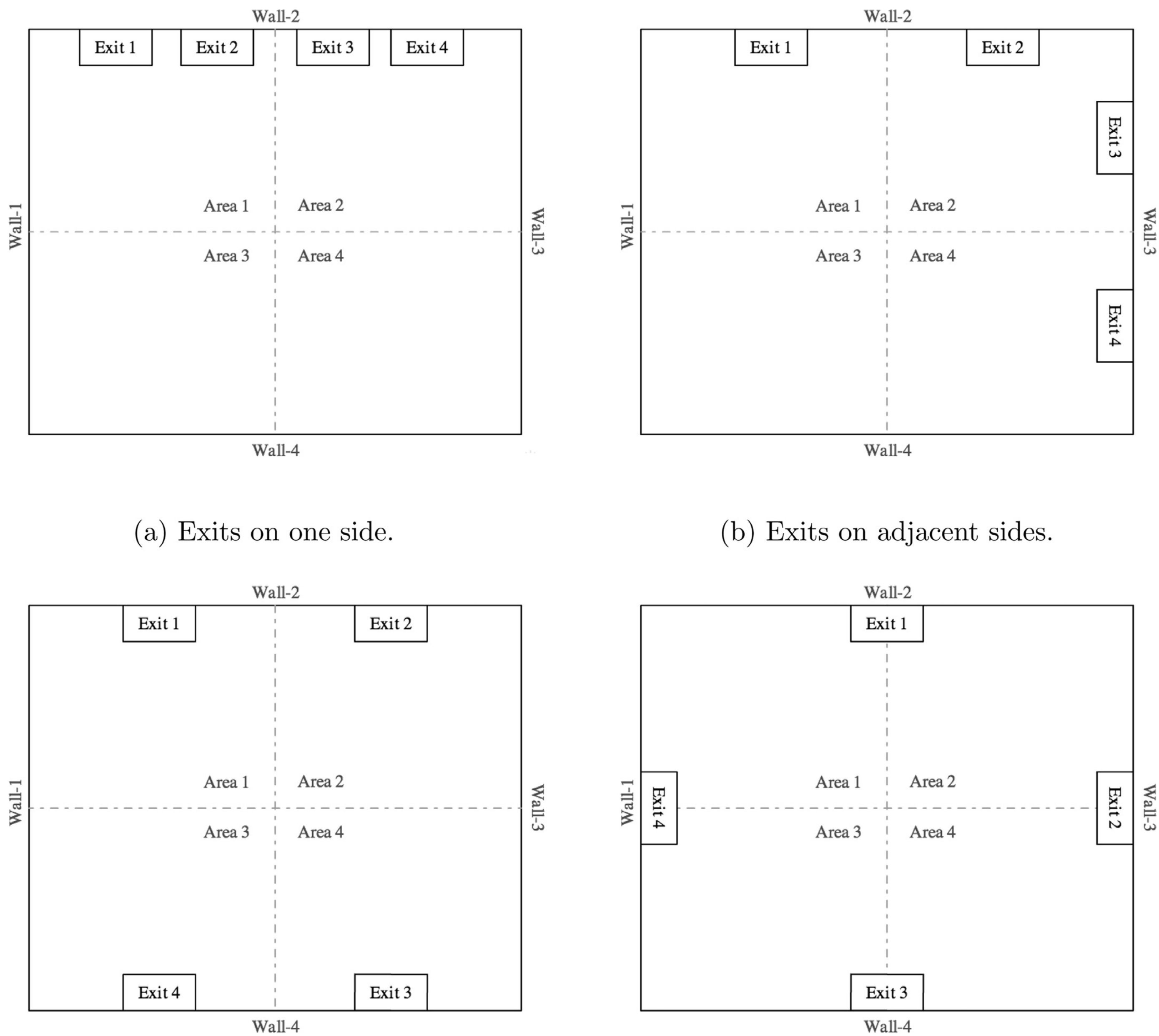


(a) Exits on one side.

(b) Exits on adjacent sides.

(c) Exits on opposite sides.

(d) Exits on all sides.

Fig. 1. Four different arrangements for the placement of four exits.

lends itself to clogging and overcrowding. This problem is studied in this paper by comparing four exit placements (see Fig. 1):

- All exits are on one side.
- Exits are on adjacent sides.
- Exits are on opposite sides.
- Each exit is on a different side.

A purpose-built simulator was developed to compare the spatial placement of exits using a traditional nearest-exit evacuation strategy and an optimal evacuation strategy, by measuring the rate of crowding and the evacuation time at each exit. The simulation utilised two artificial intelligence (AI) techniques—simulated annealing (SA) and depth-first search (DFS)—to determine an optimal solution that balances the effectiveness of the four exit placements. The results of this simulation can be used during the design of pedestrian evacuation strategies in architectural planning.

The research presented in this paper contributes to the existing literature in several aspects. As described in the following section, there has been limited research on the placement of exits during evacuation. The developed simulation and results close this gap by evaluating exit placement and its impact on evacuation plans. Our research also presents a comparison of the effects of exit placement on traditional nearest-exit evacuation strategies and optimal evacuation strategies. The results obtained emphasise the importance of the spatial placement of exits, as this could significantly impact evacuation times at each exit and the rate of crowding.

The remainder of this paper is organised as follows. First, the related work section reviews existing work regarding evacuation simulations and models. Second, the development of a simulator is

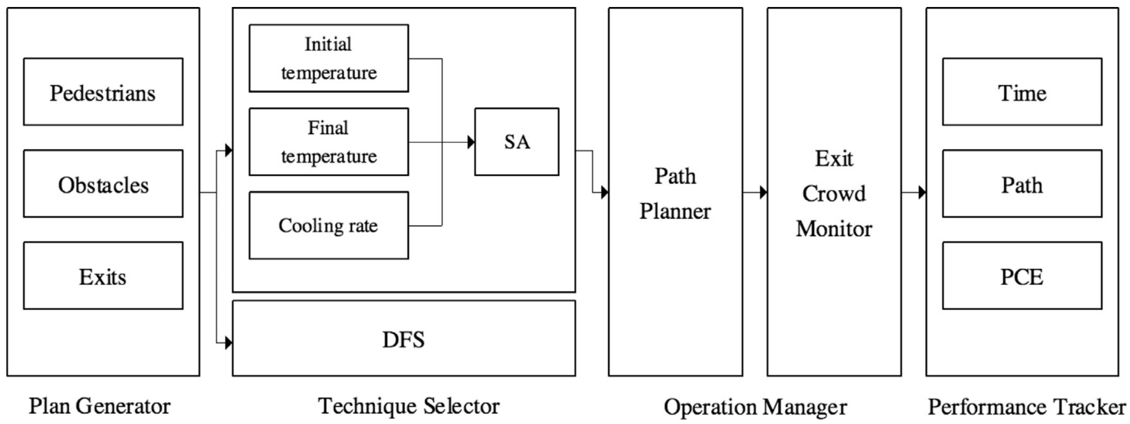


Fig. 2. The architectural design of the proposed model.

Table 1
Summary of feature-based models for evacuation simulation.

Study	Technique	Performance measure
Kisko et al. (1998)	Network (nodes and arcs)	Evacuation time
Pu and Zlatanova (2005)	3D graphs	Number of survivors
Christakos (2006)	WSN graph	Sensor feedback
Daoliang et al. (2006)	2D cellular automata model	Exit width and door separation
Khair Alla Alidmat et al. (2016)	2D cellular automaton model	Evacuation time and nearest exit
Chen and Feng (2009)	Fast flow control	Evacuation time and number of evacuees for each path
Zhang et al. (2012)	Hierarchical route	Evacuation time
Kinateder et al. (2014)	VR and SI	Destination choice, pre-movement, and evacuation time

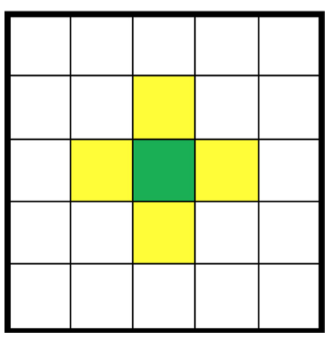


Fig. 3. The four possible action directions of agents (i.e., pedestrians).

described to compare the effects of the placement of exits when we use the nearest-exit (DFS) and optimal (SA) evacuation path strategies. Third, the experimental set-up and procedure for conducting simulations is described. Fourth, experimental results are presented and discussed. The final section then summarises and concludes the paper, and briefly discusses future work.

2. Related work

A review of evacuation simulations and models, as well as their impact on human behaviour in the evacuation process, was conducted. These models can generally be classified into two categories: feature-based and optimisation-based. Feature-based models develop an evacuation plan that determines optimal paths based on several factors taken into account during an evacuation (see Table 1). Such factors include the shortest path and the minimum time for different crowd management schemes. Optimisation-based models determine the optimal evacuation plan for a facility using an optimisation-based methodology (see Table 2).

2.1. Feature-based models

EVACNET4 is an interactive software that models building evacuations and produces optimal evacuation paths (Kisko, Francis, & Nobel, 1998). The modelling tool represents buildings and rooms as nodes in a network, in which arcs illustrate corridors and paths. Capacities can be assigned to nodes and arcs, as can the travel time to each of these components. A linear programming approach is employed by the model to determine the shortest path for evacuation. The software has been revised and modified in several studies, one of which applied the tool to the evacuation of high-rise buildings (Batty, Desyllas, & Duxbury, 2003). In Pu and Zlatanova (2005), it was shown that evacuation routes can also be generated by applying shortest path solutions to 3D graphs representing building layouts. In that work, different AI solutions were analysed, such as breadth-first searches, DFS, and Dijkstra's algorithm.

An evacuation model was developed for a wireless sensor network (WSN) topology graph based on the shortest path feature in Christakos (2006). The model computes the shortest path by acquiring data from all the sensors within the WSN. This local exchange of data results in performances that are similar to those produced by pedestrians who are globally informed of the risk situation. Another feature-based model focused on evacuation from a large room with one or two doors, using a two-dimensional cellular automata scheme (Daoliang, Lizhong, & Jian, 2006). This model simulated the exit dynamics of pedestrian evacuation to provide feedback on exit width and door separation. Similarly, a cellular automaton model simulated pedestrian evacuation under fire-spreading conditions (Khair Alla Alidmat, Tajudin Khader, & Hafinaz Hassan, 2016). In this approach, discrepancies between reality and the simulation were limited by introducing non-static fire-spreading behaviour.

A fast flow control algorithm was proposed to evacuate people from a danger zone through exits within the shortest possible time in Chen and Feng (2009). The proposed model calculated evacuation paths according to a floor plan and the total number

Table 2
Summary of optimisation-based models for evacuation simulation.

Study	Technique	Performance measure
Dijkstra and Timmermans (2002)	2D cellular automata model	Behaviour and decision-making process
Zhao and Gao (2010)	2D cellular automata model	Evacuation time
Cepolina (2005)	Network (nodes and links)	Last evacuee's movement time
Deng et al. (2008)	Relaxation and queuing theory	Evacuation time
Davidich and Köster (2012)	Genetic algorithm	Density and flow
Hassan and Tucker (2010)	Heuristic search	Efficiency and safety
Cristiani and Peri (2016)	Particle swarm optimisation	Evacuation time

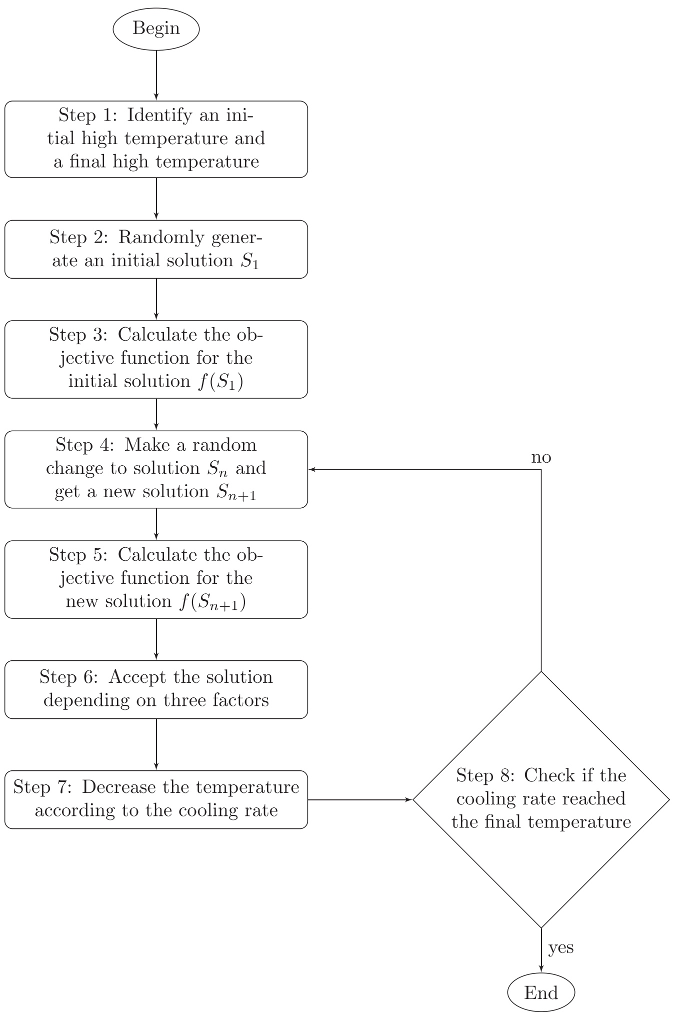


Fig. 4. Simulated annealing (SA) algorithm.

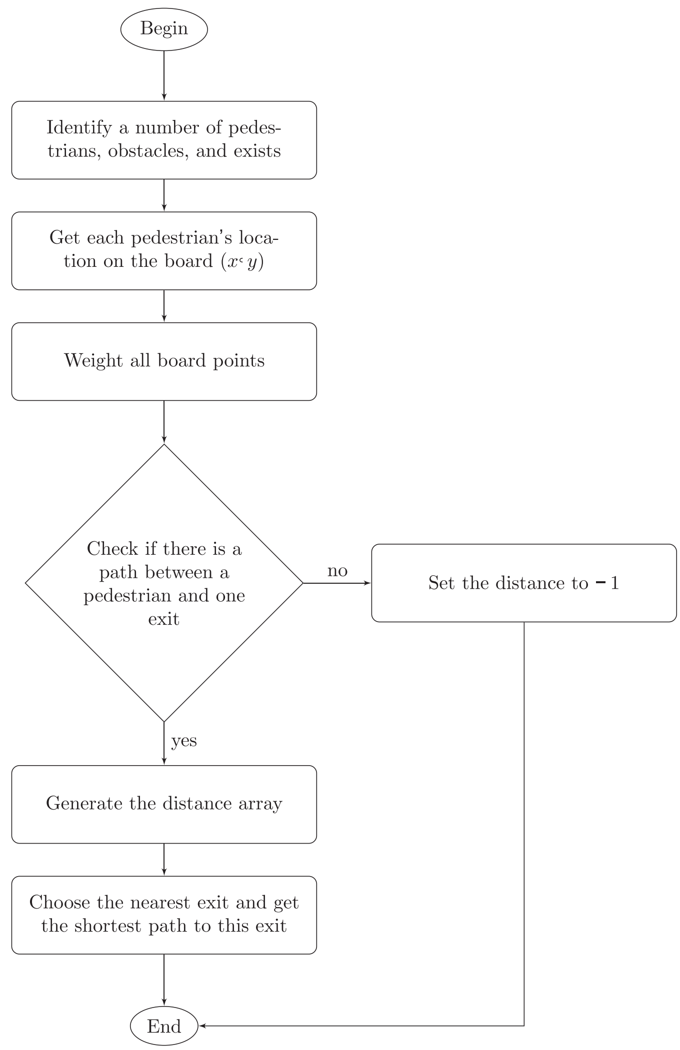
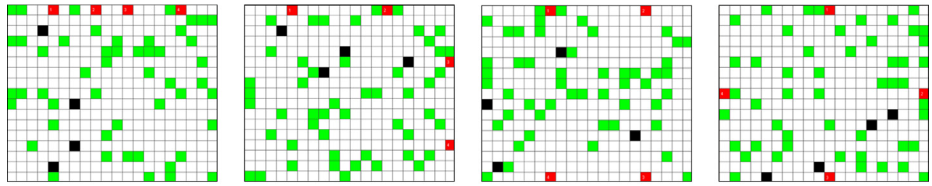


Fig. 5. Depth-first search (DFS) algorithm.

of evacuees. This calculation was based on the minimum overall evacuation time and an optimal number of evacuees for each evacuation path. A multi-node hierarchical data model was presented to express the inner structures of buildings (Zhang, Wang, Shi, & Zhang, 2012). This data model utilised a hierarchical route algorithm to determine the most favourable evacuation path for guiding evacuees to exits. A hybrid model was also developed to simulate crowd and pedestrian movement in an evacuation scheme in Xiong, Tang, and Zhao (2013). This model integrated macroscopic and microscopic models to simulate crowd evacuation, and it takes crowd movement tendencies and individual diversity into account. The effect of social influence (SI) as a factor on route and destination choices during evacuation was examined for fire emergencies in tunnels in Kinateder et al. (2014). This experiment evaluated the performance of an SI agent group and another group without an SI agent. While there were no differences observed between the groups regarding the destination choice, the latter group was more likely to choose a longer route.

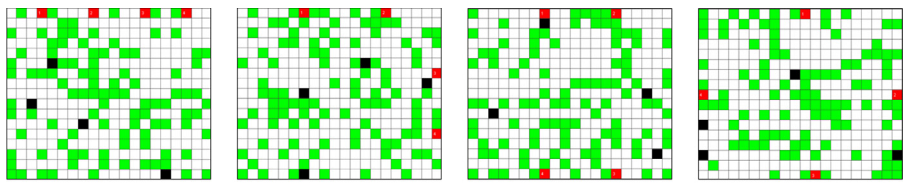
2.2. Optimisation-based models

Several researchers have focused their efforts on developing simulation platforms to test the effectiveness of evacuation schemes, while less work has been devoted to adopting optimisation-based approaches that improve evacuation schemes. A new system based on cellular automata and multi-agent simulation technology was introduced to visualise simulated user behaviour in Dijkstra and Timmermans (2002). These visualisations were used to support the assessment of evacuation plan designs. A modified cellular automata model that simulated pedestrian evacuation behaviour out of a multi-exit room from the perspective of



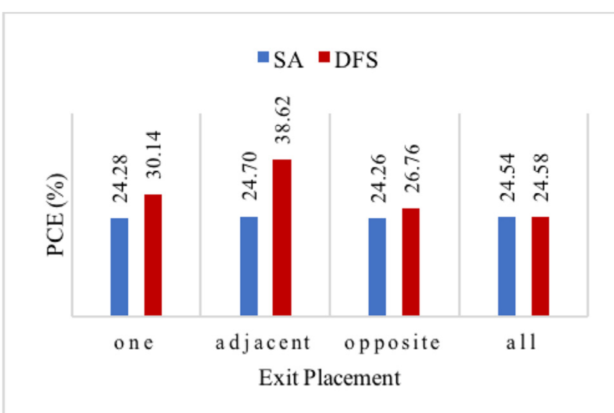
(a) Exits on one side. (b) Exits on adjacent sides. (c) Exits on opposite sides. (d) Exits on all sides.

Fig. 6. Distribution of exits (red cells), pedestrians (green cells), and obstacles (black cells) in the simulations with $N = 50$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

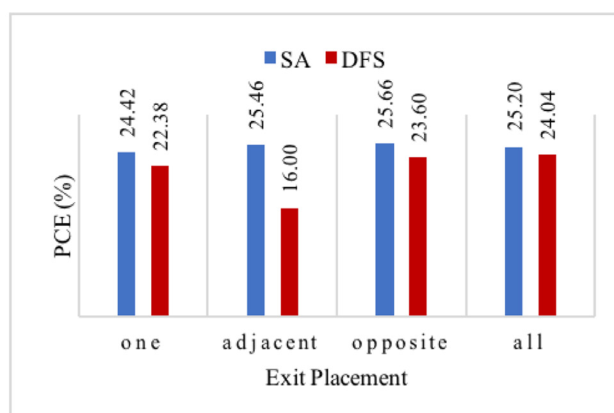


(a) Exits on one side. (b) Exits on adjacent sides. (c) Exits on opposite sides. (d) Exits on all sides.

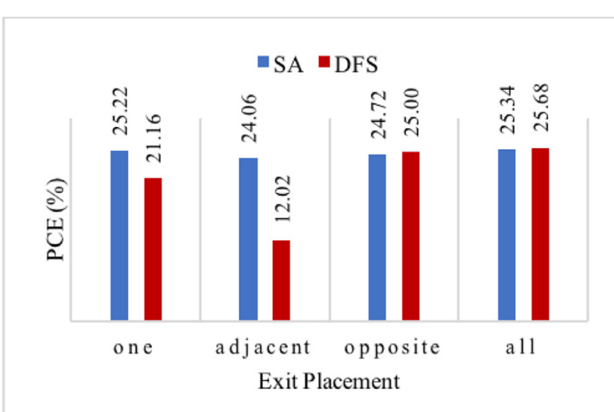
Fig. 7. Distribution of exits (red cells), pedestrians (green cells), and obstacles (black cells) in the simulations with $N = 100$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



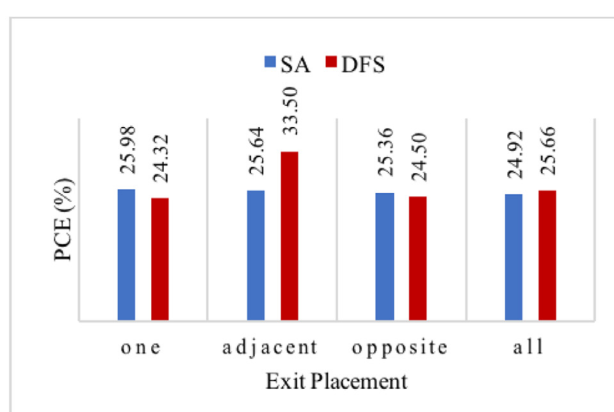
(a) Exit 1



(b) Exit 2

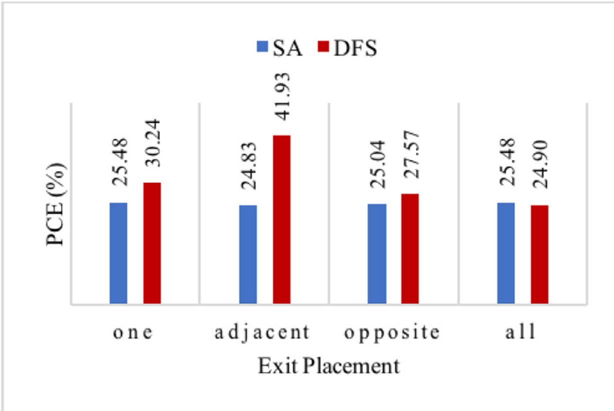


(c) Exit 3

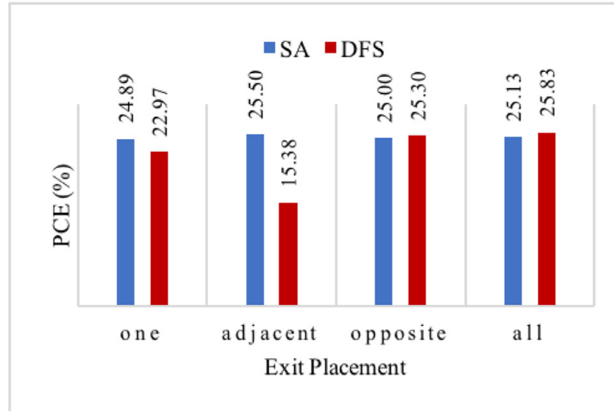


(d) Exit 4

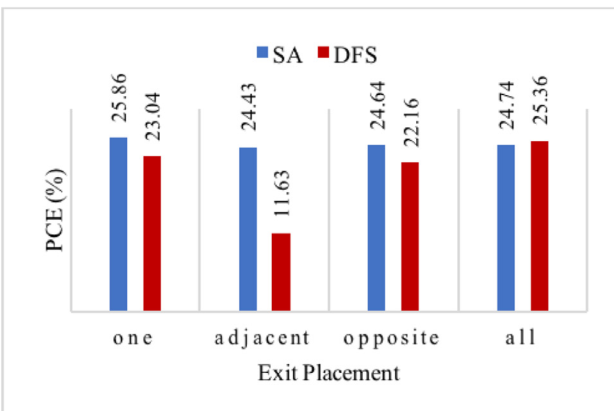
Fig. 8. Crowd percentage at each exit in the simulation with $N = 50$ pedestrians.



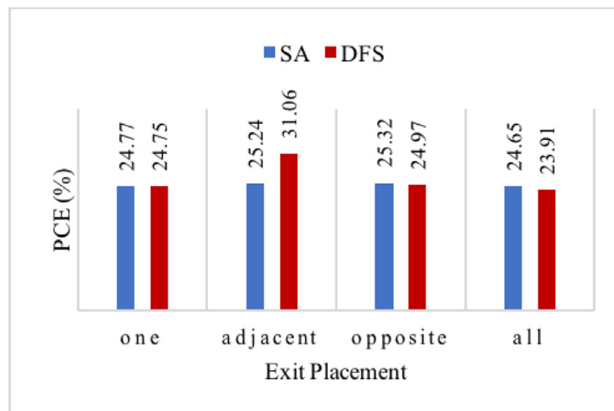
(a) Exit 1



(b) Exit 2



(c) Exit 3



(d) Exit 4

Fig. 9. Crowd percentage at each exit in the simulation with $N = 100$ pedestrians.

the reserve capacity of the exit was discussed in Zhao and Gao (2010). The simulation results showed decreased evacuation times.

Another study devised a methodology that aimed to specify the best set of evacuation routes (Cepolina, 2005). This study solved the optimisation problem in which the objective function minimised the last evacuee's movement time and state space. The scheme used direct evacuation, which assumed no fire exits were present. Based on this assumption, the best set of evacuation routes was chosen off-line. A model was developed based on the analysis and optimisation of occupancy evolution in a large building in Deng, Chen, Mehta, and Meyn (2008). This model focused on the efficient evacuation of a building in the event of an emergency by utilising the queuing theory to extract relaxation techniques. A different model was later proposed that utilised two fast automatic calibration methods to calibrate pedestrian stream simulations based on fundamental diagrams, density-flow relationships, and robust parameter sets in Davidich and Köster (2012). This model's methods relied on genetic and threshold accepting algorithms to determine the optimal evacuation path.

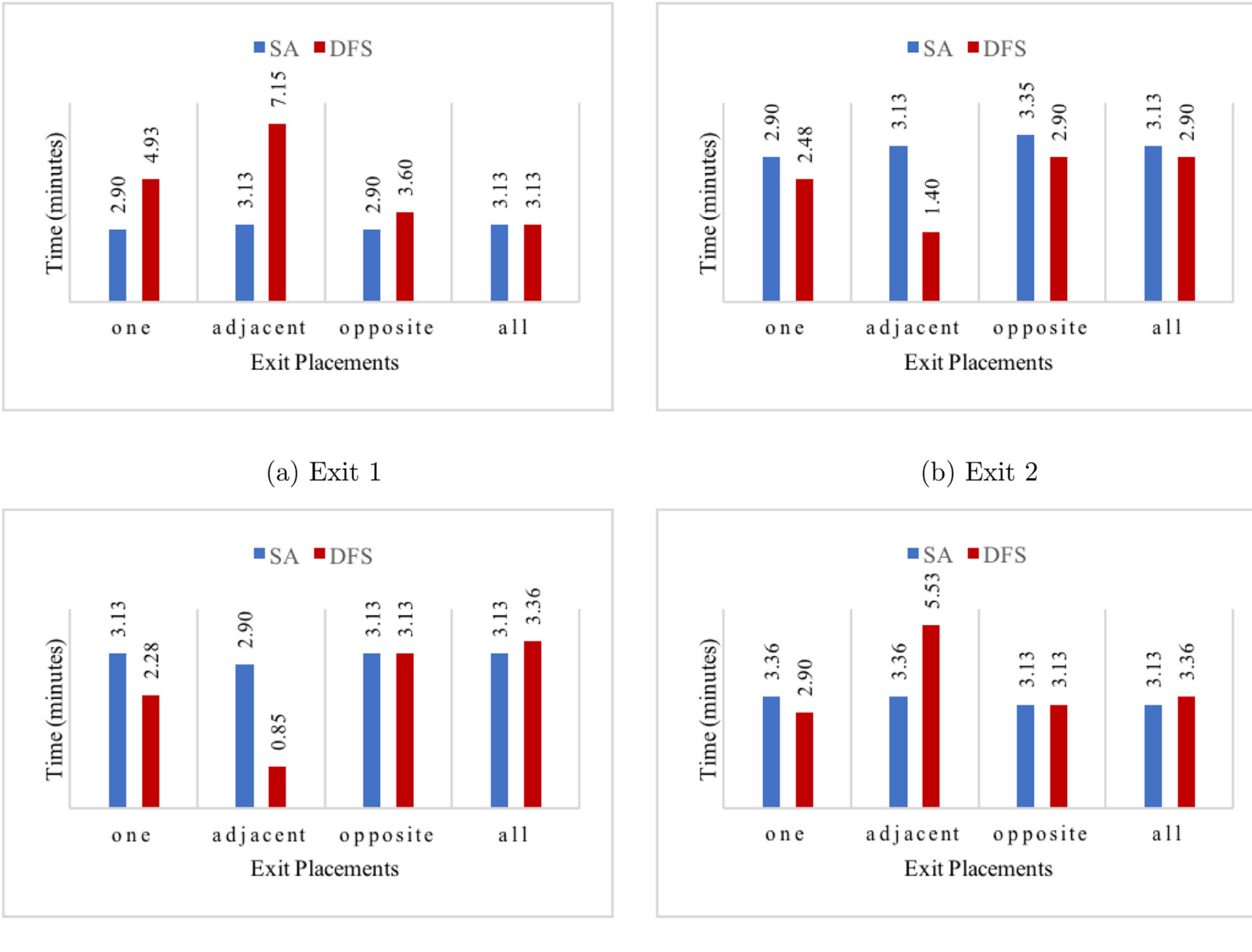
To explore pedestrian flow at a microscopic level, a cellular automata model was developed to simulate pedestrians in Hassan and Tucker (2010). Pedestrian flow statistics were generated from feasible seating layout solutions, using heuristic search techniques such as hill climbing, SA, and genetic algorithm style operators. A new technique was proposed to guarantee both the permeability and opacity of obstacles in an evacuation scenario in Cristiani and Peri (2016). Using the particle swarm optimisation (PSO) method, the outflow of pedestrians was improved. The PSO method has been suggested to yield better results than genetic algorithms (e.g., Davidich & Köster, 2012; Johansson & Helbing, 2007; Shukla, 2009).

2.3. Summary

Several studies have presented simulation models for evacuation, and the effects of human behaviour on this process (see Tables 1 and 2). Some of these have noted the effect of exit placement as an influencing factor that affects crowd behaviour (e.g., Albi, Bongini, Cristiani, & Kalise, 2015; Davidich & Köster, 2012; Johansson & Helbing, 2007; Shukla, 2009). However, there has been little or no research examining this influence and its impact on the evacuation process. To optimally balance the distribution of exits and evacuees in an evacuation system, a number of factors need to be considered. These include average evacuation times for pedestrians, cumulative exit throughput during a given period, and exit placement. This paper focuses on the placement of exits, in order to show how an evacuation plan considering an optimal exit could significantly outperform nearest-exit evacuation strategies.

3. Methodology

A Java-based evacuation system was developed to examine the effect of exit placement on the efficiency of evacuation plans. The system simulates a facility of size m-by-n, congested with pedestrians. The facility has four exits, which are placed in four different



(d) Exit 4

Fig. 10. Evacuation time at each exit in the simulation with $N = 50$ pedestrians.

arrangements (see Fig. 1). In addition, multiple obstacles are randomly placed around the facility. The remainder of this section describes the system model, problem formulation, AI techniques for evacuation, and procedure.

3.1. Proposed system model

The architectural design of the proposed model is shown in Fig. 2. The system is divided into the following four components:

Plan generator: The system generates three elements within a facility, i.e., pedestrians, obstacles, and exits, to model a real environment. It also generates the parameters required for the SA algorithm: initial temperature, final temperature, and cooling rate.

Technique selector: This component is used to select one of the two evacuation path techniques, i.e., SA and DFS. These two techniques differ in their performance, as the former considers an optimal path and the latter a nearest-exit path.

Operations monitor: The first operation carried out by the proposed system involves finding the evacuation path for each pedestrian. The second involves monitoring congestion at exits to balance the distribution of pedestrians.

Performance tracker: This component tracks and registers the output generated by the system. This includes:

- Path: The path followed by each pedestrian to the exit.
- Evacuation time: The duration from the time the first pedestrian passes through to the time the last pedestrian passes through at each of the exits (Fry & Binner, 2016). This value is calculated based on Eq. (1):

$$n_i/K_i + J_i, \tag{1}$$

where n_i is the number of pedestrians allocated to exit i, K_i is the width of exit i, and J_i is the pedestrians' speed.

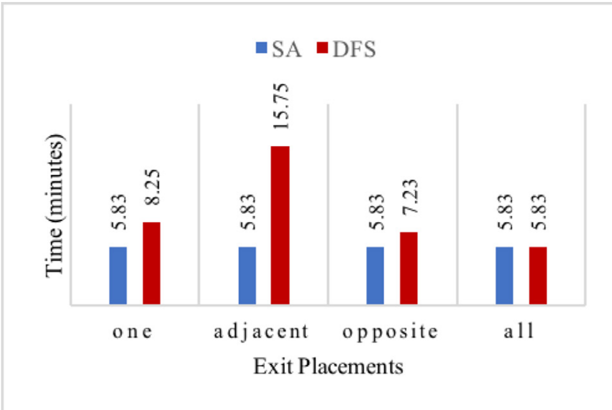
- Percentage of crowds at exits (PCE): This value is calculated based on Eq. (2):

$$n_i \times 100/N, \tag{2}$$

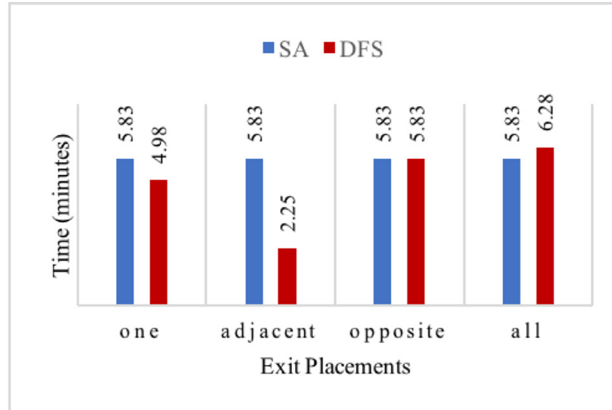
where n_i is the number of pedestrians that exited from exit i, and N is the number of pedestrians.

3.2. Problem formulation

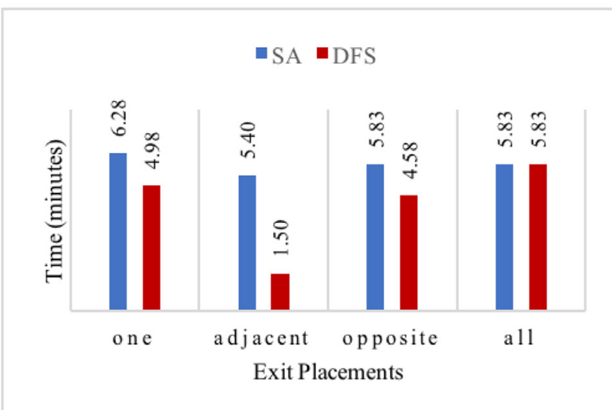
In this work, we consider the pedestrian evacuation problem in a room with certain specifications. The facility is of size m-by-n, with multiple exits and obstacles. It is presented as a two-dimensional grid, in which each cell can be empty, occupied by a pedestrian, or occupied by an obstacle (e.g., a chair). A pedestrian can only occupy a single cell. At each cell, the pedestrian has four possible action directions (see Fig. 3): forwards, backwards, left, and right. The model assumes that all pedestrians have access to exit information, i.e., pedestrians are aware of the placement of



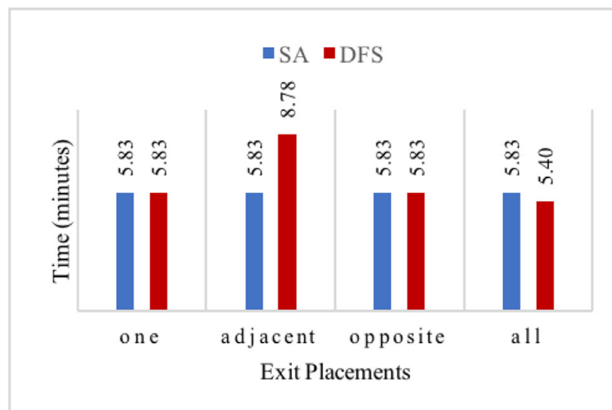
(a) Exit 1



(b) Exit 2

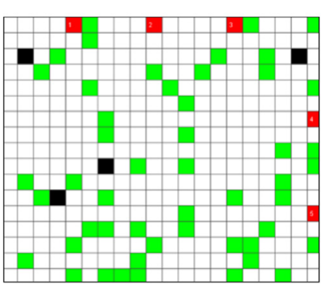


(c) Exit 3

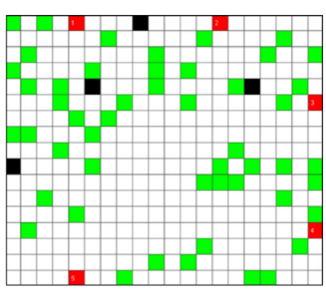


(d) Exit 4

Fig. 11. Evacuation time at each exit in the simulation with $N = 100$ pedestrians.



(a) New exit adjacent to Exit 1.



(b) New exit opposite Exit 1.

Fig. 12. Distribution of exits (red cells), pedestrians (green cells), and obstacles (black cells) in the simulation when a new exit is introduced with $N = 50$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

exits. This is a feasible assumption, as pedestrians know the entrance location once they enter a room. Pedestrians may change their path to reach an exit because of obstacles and other pedestrians blocking traffic.

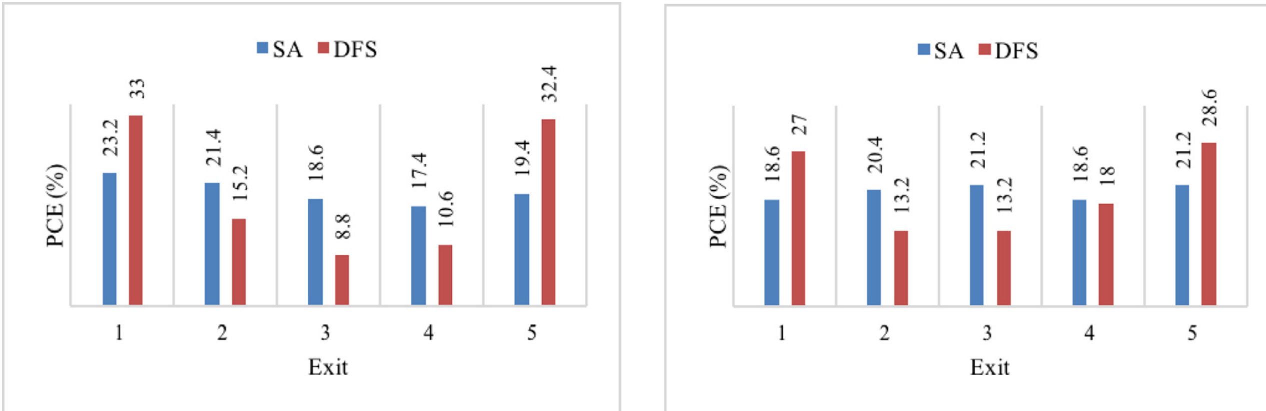
3.3. Modelling framework

Artificial intelligence techniques were utilised to solve the main problem addressed in this paper, i.e., human crowding around exits. The two AI techniques used differ in terms of their objective function: SA finds an optimal evacuation strategy, and DFS attempts to find the nearest-exit strategy.

3.3.1. Simulated annealing

Simulated annealing is a probabilistic search heuristic technique, which mathematically mirrors the cooling of a set of atoms to a state of minimum energy (Kirkpatrick, Gelatt, & Vecchi, 1983). This technique draws an analogy between the cooling of a material (i.e., searching for the minimum energy state) and the solving of an optimisation problem. Unlike traditional optimisation techniques (e.g., hill climbing), this approach cannot become stuck in a local optimum. Fig. 4 illustrates the framework of a crowded pedestrian evacuation plan using SA. The detailed steps of the algorithm are as follows:

Step 1: Identify an initial high temperature and final high temperature.
Step 2: Randomly generate an initial solution S_1.
Step 3: Calculate the objective function for the initial solution $f(S_1)$.
Step 4: Apply a random change to the solution S_n and obtain a new solution S_{n+1}.
Step 5: Calculate the objective function for the new solution $f(S_{n+1})$.
Step 6: If $f(S_{n+1}) < f(S_1)$ then the probability of accepting this solution is computed based on three factors: crowd density,



(a) New exit adjacent to Exit 1.

(b) New exit opposite Exit 1.

Fig. 13. Crowd percentage at each exit in the simulation when a new exit is introduced with $N = 50$ pedestrians.

initial and final temperatures, and the distance between the pedestrian and exit.

Step 7: Decrease temperature according to the cooling rate.

Step 8: Check if the cooling rate reaches the final temperature. If yes, return the solution S_{n+1}. Otherwise, let $n = n + 1$ and return to step 4.

After an initial high temperature is provided, the temperature is slowly lowered through successive iterations. The process should be sufficiently slow to allow enough time for the state to reach a balance at each temperature.

3.3.2. Depth-first search

The DFS algorithm is a technique used for the traversal of a network to find the shortest path. For finding the nearest exit, DFS requires the positions of all pedestrians on a board, identified with (x, y). It then weights all board points by checking every point on the board against its neighbours (forward, backward, left, and right) until a destination or obstacle is reached. After generating the distances and storing them in an array, the distances between pedestrians and the various exits are calculated as the number of steps required to reach the exit. The resulting distances are sorted, the nearest exit is identified, and the shortest path to this exit is acknowledged. The steps of the DFS algorithm are illustrated in Fig. 5.

4. Procedure

The simulations were conducted in a room of size 17×20 square metres, with four exits and four obstacles. The positions of pedestrians and obstacles were randomised, but identical for each test case. The width of exits was found to impact evacuation time (Xiong et al., 2013), and thus it was set at 1 m, as it is in real-life situations. This width has also been adopted in several other studies (e.g., Cristiani & Peri, 2016; Heliövaara et al., 2012; Shukla, 2009; Xiong et al., 2013). The pedestrian speed is set at a value of 1 metre per second (Fry & Binner, 2016). The number of pedestrians (N) was varied between 50 and 100. The two cases are illustrated in Figs. 6 and 7, respectively. Table 3 shows the parameters used in the simulation, and their assigned values.

A hundred test cases were carried out. The PCE and evacuation time were calculated from Eqs. (2) and (1), respectively. The average PCE and evacuation times over the test cases were later computed.

Table 3
Simulation parameters and assigned values.

Parameter	Assigned value
Room size	17×20 square metres
Number of exits	4
Number of obstacles	4
Number of pedestrians	50, 100
Exit width	1 metre
Pedestrian speed	1 metre per second

5. Results

This section analyses the effect of exit placement on evacuation plans using two AI techniques: determining the optimal exit using SA and the nearest-exit using DFS. In the following sections, we will examine the effect of exit placement on an evacuation plan. The analysis is carried out separately for two different metrics: PCE and evacuation time.

5.1. Crowd Percentages at Exits

The PCE was categorised as low, medium, or high, where a low percentage ranges from 0% to 33%, a medium percentage ranges from 34% to 66%, and a high percentage ranges from 67% to 100%.

Fig. 8 illustrates the PCE at each of the four exits for an evacuation scenario with 50 pedestrians and randomly placed obstacles. Fig. 8(a) shows the effect of exit placements on the PCE at Exit 1 when the exits are placed either on one side, on adjacent sides, on opposite sides, or on all sides. When the doors were placed on adjacent sides, The PCE at Exit 1 was 38.62% (i.e., medium crowd percentage) using the DFS path technique. This was expected, as all pedestrians in Areas 1 and 3 of the room will egress from Exit 1 using the DFS technique (see Fig. 1). For the three other exit placements the PCE was lower, at values ranging from 24.26% to 30.14% using either the DFS or SA techniques. For Exit 4, the PCE when the doors were placed on adjacent sides was on the borderline between the low and medium categories at 33.50%. This indicates that some of the pedestrians from Area 3 will also egress from Exit 4 using the DFS technique (see Fig. 8(d)). Exits 2 and 3 (see Fig. 8(b) and (c)) exhibited low PCE scores for the various exit placements and techniques. In general, there were slight variations between the DFS and SA techniques, although these variations were insignificant. Nevertheless, SA tends to distribute pedestrians across exits more evenly than DFS.

The effects of exit placement are further demonstrated in Fig. 9 for when the number of pedestrians was doubled to 100. Similarly to what was observed in Fig. 8, the PCE at Exit 1 was categorised as medium when the exits were placed on adjacent walls using the DFS technique. The same arguments given previously apply here, where pedestrians in Areas 1 and 3 of the room will egress from Exit 1 using the DFS evacuation path strategy. The low PCEs at Exit 1 ranged from 24.90% to 30.24% using the DFS technique, and from 24.83% to 25.48% using SA. Fig. 9(b), (c) and (d) illustrate the resulting PCEs for Exits 2, 3, and 4, respectively, all of which were at the low end.

5.2. Evacuation times at exits

The effects of varying the exit placement and evacuation path techniques on the evacuation time when 50 pedestrians are in the facility are illustrated in Fig. 10. Fig. 10(a) illustrates the time required for pedestrians to evacuate through Exit 1. The evacuation times when the SA technique was used ranged from 2.90 to 3.13 minutes, whereas for the DFS technique the times ranged from 3.13 to 7.15 minutes. While the majority of evacuation times at Exit 1 were under 5 minutes, they increased slightly for paths planned using DFS, when exits were placed on adjacent walls. This could be explained by the higher PCE resulting from the increased traffic from Areas 1 and 3. The results from Exits 2, 3, and 4 (see Fig. 10(b), (c), and (d), respectively) exhibit evacuation times of less than or equal to 5.5 minutes with various exit placements and evacuation path techniques.

The effect of exit placement was also considered with 100 pedestrians in the facility (see Fig. 11). As expected, the evacuation times increased across the various placements and techniques. At Exit 1, evacuation times were under 8.5 minutes excluding one case (15.75 minutes). In this case, the exits were placed on adjacent sides of the room, and the evacuation path was devised using the DFS approach. The evacuation times at Exits 2, 3, and 4 (see Fig. 11(b), (c), and (d), respectively) were under 9 minutes for all exit placements and evacuation paths. For Exit 2, the values ranged from 2.25 minutes to 6.28 minutes using the DFS technique, and for the SA technique the value was 5.83 minutes. The DFS technique reduced the evacuation times from Exit 3 when the exits were adjacent, on account of the increased crowding at Exit 1. Exit 4 evacuation times ranged from under 6 minutes to a little under 9 minutes for both techniques. The difference in the ranges between SA and DFS clearly shows that SA allocates pedestrians to exits more evenly than DFS.

6. Discussion

The results returned the least desirable PCE and evacuation time values when exits were placed on adjacent sides of the facility, and DFS was used to plan an evacuation path. Figs. 8 and 9 show that while the PCE was medium at Exit 1, it was much lower at Exits 2 and 3. As illustrated in Fig. 1, with exits on adjacent sides (i.e., Exit 1 on the left side of the room), pedestrians in Areas 1 and 3 will egress from this exit when applying the DFS technique and some from Area 3 will also egress from Exit 4. For Exits 2 and 3, the number of pedestrians near the exits was comparatively low in Area 2. Therefore, to balance the pedestrian distribution around exits in this room, there should be one exit per 100 square metres. This should fairly balance the evacuation exits, with a ratio of 1:30 (pedestrians to metres). As the ratio of pedestrians to metres increases, the number of exits should also be gradually increased in each area.

To elaborate further, when exits are placed on one side of the facility, each exit will typically cater to certain areas (see Fig. 1). For this type of placement, the following phenomena occur using the DFS algorithm:

- Exit 1, will egress some pedestrians from Areas 1 and 3, approximately 100 square metres.
- Exit 2, will egress some pedestrians from Areas 1 and 3, approximately 100 square metres.
- Exit 3, will egress pedestrians from Areas 2 and 4, approximately 100 square metres.
- Exit 4 will egress pedestrians from Areas 2 and 4, approximately 100 square metres.

In the case of exits placed on adjacent sides (see Fig. 1) the following occurs using DFS:

- Exit 1 will egress pedestrians from Areas 1 and 3, approximately 200 square metres.
- Exit 2 will egress some pedestrians from Area 2, approximately 50 square metres.
- Exit 3 will egress some pedestrians from Area 2, approximately 50 square metres.
- Exit 4 will egress pedestrians from Area 4, approximately 100 square metres.

Thus, pedestrian evacuation is not balanced across the main means of egress, which results in clogging at the exits. When the exits are positioned on opposite sides or on all sides, there is a better balance between the various areas and their nearest exits. This problem was not encountered with the SA technique, as it balanced pedestrians almost equally across the various exit placements. The remainder of this section proposes a solution to overcome the ill-effects of uneven exit placements using the SA and DFS techniques.

6.1. Proposed solution

To overcome the ill-effects of placing exits on adjacent sides of a facility (see Figs. 8–11), an exit can be introduced in Wall 2 or Wall 4: the walls adjacent to or on the opposite side of Exit 1, respectively (see Fig. 12). The proposed solution was examined, and the results are illustrated in Fig. 13. Placing an exit adjacent to or opposite Exit 1 resulted in a better performance and lower PCE. An exit opposite Exit 1 fared better, achieving the lowest PCE of 27%, compared to 33% when locating the new exit adjacently.

Based on these results, we recommend adding an exit to the opposite side of Exit 1, if possible, as this decreases the PCE to under 30%, thus balancing pedestrian egress across all exits. In comparison, the SA algorithm balanced the distribution of pedestrians more evenly than the DFS approach (see Figs. 8–11). In all cases, the PCE for the SA algorithm did not exceed 30%, and in fact it decreased to under 25% when a fifth exit was introduced to the facility.

7. Conclusion and future work

A clear gap in the literature has been identified, as existing research falls short of addressing the effect of exit placement on evacuation strategies. In this paper, this effect was examined when four exits are placed in a number of arrangements: all exits on one side of the room, exits on adjacent sides, exits on opposite sides, and exits on all sides. A simulation model was developed to study the effect of this factor. Evacuation plans were generated using two AI algorithms: SA and DFS. The PCE and mean evacuation times at each exit were computed for each algorithm to identify the ideal exit placements. This information can be used to prevent clogging and overcrowding around exits.

The results of the simulations demonstrated that placing exits on adjacent sides led to increased PCE and evacuation times using the DFS technique. It was also found that compared to DFS, the SA algorithm achieved a better balance in the distribution of pedestrians across exits. Nevertheless, pedestrians tend to adopt a DFS approach when evacuating during dangerous situations.

The main contributions of this paper can be summarised as follows:

- The development of a system model to examine the effect of varying exit placements using generated evacuation plans, one of which considers the nearest exit and the other the optimal exit.
- The evaluation of the impact of exit placement, obstacle placement, and pedestrians using the developed simulation model.
- The facilitation of evacuation with a proposed solution to overcome the ill-effects of exits placed adjacently using the nearest-exit algorithm (DFS).

In future work, we intend to improve and extend the simulation, and examine various factors, in the following ways:

- Enhancing the system by varying the size and shape of the examined facility, as well as varying the number of obstacles.
- Exploring the symmetry of door placement when exits are located adjacently (see Fig. 1(b)). This approach was previously examined with two exits on one side of a room, where an even symmetry proved more efficient than an asymmetric distribution of exits (Daoliang et al., 2006).
- Generating evacuation plans using other algorithms.
- Improving the inclusivity of the system by considering individualistic characteristics of pedestrians, e.g., individuals with impaired mobility.

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