European Journal of Operational Research xxx (xxxx) xxx

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

A balanced evacuation algorithm for facilities with multiple exits

Heba Kurdi[a,b,*], Asma Almulifi[a,c], Shiroq Al-Megren[b,d,*], Kamal Youcef-Toumi[b]

[a] King Saud University, Computer Science Department, Riyadh 11451, Saudi Arabia
[b] Massachusetts Institute of Technology, Department of Mechanical Engineering, Cambridge, MA 02139, United States
[c] Majmaah University, Department of Computer Science, Majmaah 11952, Saudi Arabia
[d] King Saud University, Information Technology Department, Riyadh 11451, Saudi Arabia

A R T I C L E I N F O

Article history:
Received 20 April 2019
Accepted 4 July 2020

Keywords:
Simulation
Emergency evacuation
Multiple exits
Simulated annealing (SA)
Depth-first search (DFS),

A B S T R A C T

Over the last few years, there has been an increase in the number of disasters caused by human crowding due to evacuees attempting to exit during emergencies. This has led to a rise in optimization studies on emergency evacuation plans that mitigate the loss of life and injury. Although a substantial amount of this research focuses on guiding evacuees toward the nearest emergency exits, they do not always consider the problem of congestion. This paper will present an algorithm that will ensure that pedestrians safely evacuate facilities with multiple exits by introducing a balanced evacuation algorithm: BEME. This approach will help reduce overcrowding and congestion surrounding the exits by overcoming the limitations of traditional strategies such as approaching the nearest exit and ensuring optimal evacuation. BEME's performance was compared with two established artificial intelligence techniques: simulated annealing and depth-first search. The evacuation model evaluation considered a number of variations in the spatial placement of the exits, number of exits, and number of pedestrians. The results showed that the proposed algorithm could significantly reduce the number of pedestrians for every exit. BEME differs from the benchmarked techniques, as it is consistent regarding the various exit placements and hence supports the algorithm's use with existing infrastructures that utilize inefficiently placed exits. Moreover, this approach resolves the problem of overcrowding and congestion around exits using a balanced evacuation that helps maximize safety and avoid life-threatening hazards.

1. Introduction

There have been widespread and devastating examples of stampedes in congested pedestrian areas across the globe. One such incident occurred in Mina, Saudi Arabia in September 2015 as pilgrims performed Hajj (Chiu, Shiau, & Lai, 2018). Although it may not always be possible to avoid such calamities, implementing effective evacuation plans can help in drastically reducing the number of casualties in such incidents (Davidich & Köster, 2012; Patel, Min, & Lim, 2016). Because of the increasing number of such disasters caused by congesting during emergencies, several studies have begun focusing on how mass evacuation can be effectively performed in crowded pedestrian areas (Hu, You, Zhang, Wei, & Guo, 2018; Oh & Park, 2017; Poulos, de la Llera, & Mitrani-Reiser, 2017; Wu, Kang, & Wang, 2018). Most studies have emphasized evacuation networks' inadequate outbound paths as the major problem. Using existing infrastructure may be the best method for addressing this problem (Afandizadeh, Jahangiri, & Kalantari, 2009; Dhamala, 2015; Zhao, Ren, & Huang, 2016). Hence, it is important that architectural planning pay greater attention to the placement of obstacles and exit points to ensure safety of pedestrians and reduced economic impact (Assouline, Bastien, Brenot, Dumas, & Parmentier, 1987; Desai, Harris, & Gordon, 2019; Marzocchi, Garcia-Aristizabal, Gasparini, Mastellone, & Di Ruocco, 2012).

Pedestrian evacuation is the result of a decision-making process occurring when pedestrians are in a threatening situation and heading toward the exit to safety. Such evacuation decisions can be very complicated in real-world situations (Huang & Zheng, 2017). Moreover, there are several factors that impact this decision-making process such as architecture, psychology, social, and environmental factors as well as the individuals' characteristics, building geometry, number and position of exits, and obstacles (Bode, Miller, O'Gorman, & Codling, 2015; Lee, Nam, & Jun, 2017; Ren-Yong & Hai-Jun, 2010; Zhu, Jia, & Shao, 2012). All of these factors affect the evacuation time, which is the time required for pedestrians to identify danger and move to a safe area (Ng & Chow, 2006). This also impacts how many fatal as well

* Corresponding author at: Computer Science Department, King Saud University, P.O. Box 2454, Riyadh 11451, Saudi Arabia.
E-mail addresses: hkurdi@ksu.edu.sa (H. Kurdi), a.almulifi@mu.edu.sa (A. Almulifi), shiroq@mit.edu (S. Al-Megren), youcef@mit.edu (K. Youcef-Toumi).

https://doi.org/10.1016/j.ejor.2020.07.012
0377-2217/

as non-fatal casualties occur in an incident (Formolo & van der Wal, 2017). When there are numerous exits, pedestrians have to choose which exit can provide efficient evacuation for them. It has been noted that pedestrians prefer using familiar exits as well as following other pedestrians (Kurdi, Al-Megren, Althunyan, & Almulifi, 2018; Pan, Han, Dauber, & Law, 2006). Moreover, the time required to reach an exit and the exiting time are crucial factors that pedestrians tend to consider (Hao, Bin-Ya, Chun-Fu, & Yan, 2014; Heliövaara, Kuusinen, Rinne, Korhonen, & Ehtamo, 2012; Kurdi et al., 2018; Liao, Wagoum, & Bode, 2017). Hence, exit selection strategies can be classified into distance-based and time-based strategies (Hao et al., 2014).

The distance-based or nearest-exit strategy considers how far the pedestrian is from the exit, as it is also a major factor that impacts their exit choice. There are pedestrians who are unaccustomed to the evacuation process, and they may panic and rush toward the nearest exit. Pedestrians do not usually consider the crowding and the width of the exits and thus cause an imbalance when evacuating multi-exit facilities in terms of exit utilization (Liao et al., 2017). In such situations, the nearest exit becomes the most crowded, and few people think of going to exits that are more distant. This inevitably increases the evacuation times while reducing the efficiency of evacuation (Hao et al., 2014). On the other hand, the optimal or time-based strategy intends to ensure that the shortest possible time will be required for evacuating pedestrians (Ng & Chow, 2006). This strategy focuses on pedestrians moving toward exits that are the least crowded and observable in a normal as well as logical evacuation situation. It also considers the size of the crowd as well as the exit layouts and widths, thus resulting in reduced evacuation times and improving evacuation efficiency. The evacuation time is largely based on the number of pedestrians and the number and width of the exits (Hao et al., 2014).

Research in the area of emergency evacuation can roughly be categorized into three distinct research streams (Vermuyten, Beliën, De Boeck, Reniers, & Wauters, 2016). The first stream empirically studies the behavior of pedestrians and crowd dynamics. The second stream utilizes mathematical models to simulate and describe the behaviors of pedestrians during evacuations. The third stream of research on emergency evacuations develops models that aid in the determination of the optimal evacuation plan or design solutions (Abdelghany, Abdelghany, Mahmassani, & Alhalabi, 2014; Akopov & Beklaryan, 2015; Al Qhtani, Al Shammari, & Kurdi, 2017; Ding, 2011; Wagner & Agrawal, 2014). In the current literature, the majority of the research belongs to the first two streams, e.g., Liu, Yang, Fang, and Li (2009), Ren-Yong and Hai-Jun (2010), Cao, Song, Lv, and Fang (2015), Zheng, Li, and Guan (2010), Abdelghany, Abdelghany, Mahmassani, Al-Ahmadi, and Alhalabi (2010), Ji, Lu, Jin, Wei, and Ni (2018), Yue, Guan, Shao, and Zhang (2011), Yuksel (2018). The proposed algorithm, on the other hand, introduces an optimization that ensure the balanced evacuation of pedestrians that reduces congestion and over-crowding around exits.

The present study is based on previous work that has assessed how evacuation plans are affected by exit placement (Kurdi et al., 2018). Well-known algorithms, such as simulated annealing (SA) and depth-first search (DFS), representing optimal and nearest-exit strategies, respectively, have been used to examine how the placement of exits (adjacent, opposite, or all sides) affects the efficiency of the evacuation plans (Kurdi et al., 2018). Moreover, an evacuation model has been devised for evaluating the percentage of crowds as well as evacuation times at every exit. According to the results, exit placement is crucial in ensuring an evacuation plan's efficiency. It was also noted that SA is more efficient than DFS in ensuring that pedestrians are distributed in a balanced manner among the various exit placements. DFS also suffers long evacuation times, particularly concerning emergency exits that were adjacent.

This paper attempts to resolve the problem of over-crowding and congestion around exits in emergency evacuation situations by introducing a balanced evacuation algorithm that can be applied to multiple-exit facilities (BEME). For this, the evacuation time at every exit as well as the distance that every pedestrian must travel are reduced by equally distributing pedestrians between all exits. The solution presented in this paper can contribute to existing literature in three major ways. First, since few studies have focused on pedestrians being evacuated during emergency situations in a balanced manner among multiple exits, the BEME design and implementation can close this gap. Second, this study involved the development of a purpose-built simulator for conducting a comparative evaluation of the proposed balanced approach's performance when compared to two recognized artificial intelligence (AI) techniques: SA and DFS. The results affirm the importance of a balanced evacuation that includes exits having various spatial placements when pedestrians evacuate a multi-exit facility. Third, it is possible to use BEME as an integrated evacuation system's central element. It can be employed as a cell phone application that can steer pedestrians toward an appropriate exit so that pedestrians can be equally distributed across the exits, thus enhancing safety and minimizing life-threatening risks.

The remainder of this paper is organized as follows. In Section 2, the related work section reviews existing work devising models for facilities with multiple exits. Next, in Section 3, the proposed BEME algorithm is presented. A numerical scenario is presented in Section 4. In Section 5, the performance of BEME is comparatively assessed against well-established AI algorithms with varying number of exits, pedestrians, and exit placements. The experimental findings are described and discussed in Section 6. Finally, Section 7 summarizes and concludes the paper and briefly discusses future directions.

2. Related work

This work is framed within the existing literature via a thorough review of evacuation simulations and models for facilities that have multiple exists. This means, models are devised for facilities consisting of a single level with several exits; a good reflection of the modelled real life, where the layout of multiple exists will affect the pedestrian evacuation process. Thus, the exit selection strategy is the basic rule underpinning the evacuation simulation.

Research addressing the evacuation problem can roughly be classified as simulation- and optimization-oriented approaches. In the former approach, factors and parameters influencing the evacuation process are examined to analyse its impact on the procedure. The latter approach proposes optimal solutions to ensure the safe evacuation of pedestrians (Vermuyten et al., 2016). The proposed solution is a novel optimization-oriented approach that balances the distribution of pedestrians among points of egress to support efficient evacuations.

Pedestrian behavior has long been explored in various exit selection phenomenon. In a classroom setting comprised of two-door exists, various scenarios were considered to understand the evacuation behaviour of students (Liu et al., 2009). The findings confirmed the importance of wider exits (i.e. two doors open) for total evacuation time and clogging. Evacuees' choices was similarly examined using a logit-based discrete choice model given pedestrians' exit preferences, congestion and width of the exit (Ren-Yong & Hai-Jun, 2010). The findings show that evacuation time is determined by the number of evacuees that choose each exit and that an emergency guide sign can impact the exit selection.

Cellular automata models are popularly utilised in evacuation simulation literature. One such model was developed to study the impact of multi-partition single-exit selection and social forces on evacuee movement (Zheng et al., 2010). Potential fields were availed as an environmental model, and the impact of the 'excess politeness' social force and exit choice were examined. It was found that the length of the partition had a direct impact on total evacuation time and congestion. For multiple exits, another model considered several behavioral components, including the choice of exit, the frequency of update of exit gate and the pedestrians' congestion perception and tolerance (Abdelghany et al., 2010). Using a simulation model fo the Masa'a facility at the Great Mosque of Mecca, Saudi Arabia, it was noted that evacuation performance improves when pedestrians are able to weight their choice of exits based on nearness and crowding. Thus, pedestrians' exit decisions and their impact on evacuation performance can be improved by learning about better exit opportunities. A more recent study developed an evacuation model based on cellular automata that id divided into triangular grids to increase pedestrians' movement directions from 8 to 14 (Ji et al., 2018). This novel model proved more efficient than rectangular grid evacuation models.

An agent model was developed that considers crowd behavior under grave conditions, such as crowd crushing and turbulence, as well as confining external situations (Akopov & Beklaryan, 2015). A program simulator was designed to model various system parameters with the absence and presence of obstacles that determines the effect of crowd turbulence and crushing. The findings affirm that the layout of pillars in an enclosed area minimizes the effects of crowding. This effect is only matched with the introduction of a large number of additional exits. An agent-based evacuation model was implemented to simulate pedestrian evacuation behavior during emergencies (Yuksel, 2018). The agent-based model is developed by applying neuroevolution, which uses evolutionary algorithms to generate artificial neural networks. Simulations were conducted to determine the feasibility of the proposed model and found that the agents were able to perform their tasks efficiently and find their way to exits.

A simulation-optimization modeling framework was developed to determine the optimal evacuation plan for crowded multi-exit facilities (Abdelghany et al., 2014). The framework integrates a genetic algorithm with a microscopic crowd simulation model (cellular automata) to iteratively search for an optimal evacuation plan. The framework's performance was assessed through a hypothetical pedestrian facility evacuation. The assessment results show that the developed framework results in a superior evacuation plan within a reasonable number of iterations. These results were also found to outperform the conventional nearest-exit evacuation plans. The genetic algorithms was also utilized in a more recent work, where an evacuation plan generator was proposed to guide pedestrians efficiently to exits and safety (Al Qhtani et al., 2017). The near optimal evacuation plan utilized the genetic algorithm due to the non-linearity of the evacuation problem. The findings show that the developed model was able to optimize the evacuation of pedestrians by effectively reducing the evacuation time.

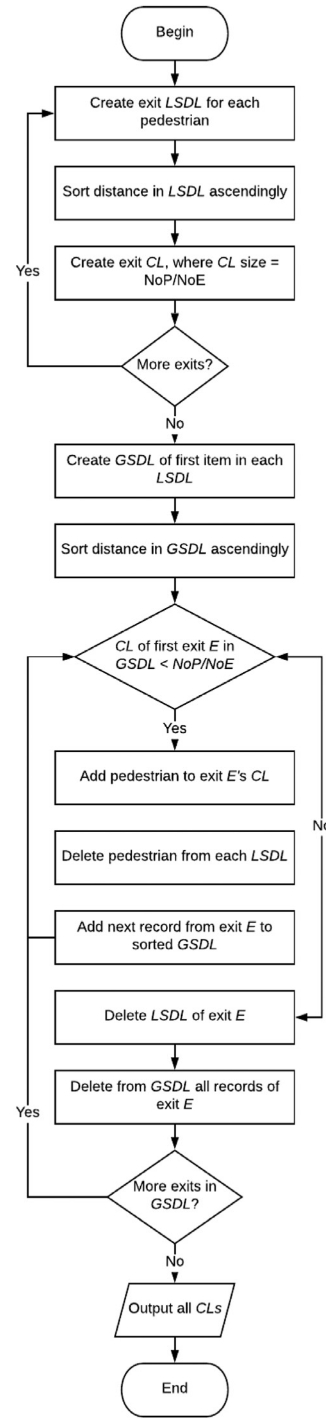


Fig. 1. The flowchart of the BEME algorithm.

3. Balanced evacuation algorithm for multiple exits

The framework of the new BEME algorithm, which attempts to balance the number of evacuees against the number of exits in a facility to overcome clogging and over-crowding around points of egress, is illustrated in Fig. 1.

The number of pedestrians (*NoP*) and number of exits (*NoE*) in the facility are received by the algorithm as input to produce an evacuation path to a suitable point of egress for each pedestrian. The algorithm employs three types of lists: two local lists for each exit in the facility and a global list. The first local list is the local shortest distance list (*LSDL*). The *LSDL* is maintained at each exit as a list of shortest distances between each pedestrian in the facility and this exit. The exit capacity list (*CL*) is the second locally stored list, which is also maintained at each exit; this is a list of pedestrians that will egress from this exit. The global shortest distance list (*GSDL*) maintains a global list consisting of the shortest distances in each of the locally maintained *LSDLs*.

The algorithm runs in two main phases. In the first phase, an *LSDL* is generated for each exit in the facility intended for evacuation. The generated *LSDLs* maintain a list of all pedestrians to be evacuated and the shortest distances to each one of the exits. Next, each *LSDL* is sorted in ascending order. An empty local *CL* is then created for each exit; the size of the *CL* is equal to *NoP*/*NoE* for

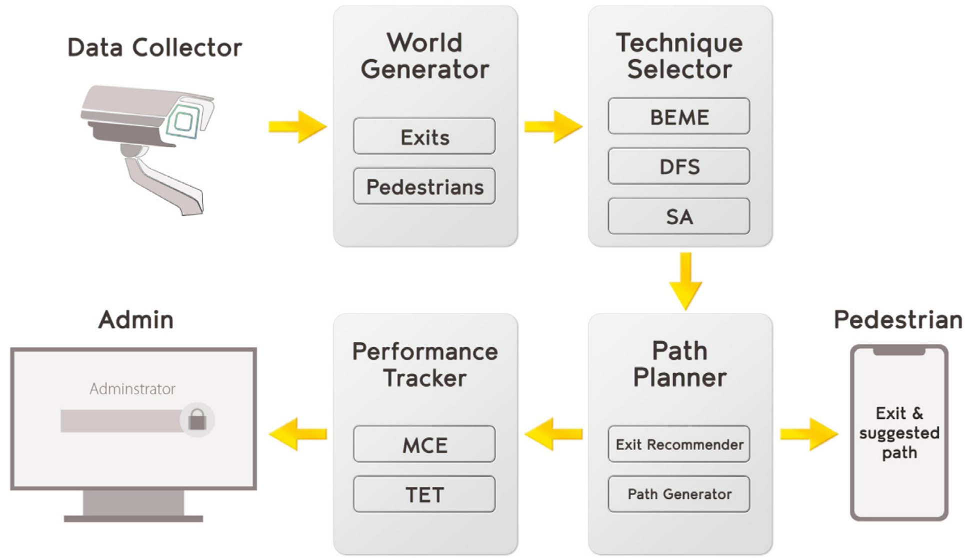


Fig. 2. Abstract system overview.

each exit. In the second phase of the algorithm, pedestrians under evacuation are distributed evenly between points of egress by considering the shortest distances to each exit. This is possible with the generation of a *GSDL*, which consists of the shortest distances recorded in each *LSDL*. The *GSDL* is then sorted in ascending order by distance to resolve any conflict between pedestrians. Subsequently, the algorithm determines whether the *CL* of the exit reported as the first item in the *GSDL* is less than *NoP*/*NoE*. If this condition is true, then the first item's pedestrian is inserted into the exit's *CL* and removed from all other *LSDLs*. The *GSDL* is then updated with a new record from the exit's *LSDL* while maintaining the order of the list. The algorithm continues its examination of the first items in the *GSDL* and updates the *CLs* and *LSDLs* of each exit until the condition is no longer satisfied.

The architectural design of the system is illustrated in Fig. 2. The system is divided into the following five components:

- *Data collector:* This component is required when the system is deployed in a real-life scenario. It consists of multiple sensors and cameras that periodically collect data about the placement of exits and locations of pedestrians based on real-world coordinates. These data are then passed on to the *world generator*.
- *World generator:* In a simulated scenario, this component randomly generates locations for a finite number of pedestrians and exits. When deployed in a real-life scenario, this component maps the placement of exits and locations of pedestrians based on real-world coordinates to the simulated word coordinates.
- *Technique selector:* This component is used to select one of three path techniques: BEME, DFS, and SA. BEME considers a path that balances the number of evacuees against the number of exits, DFS selects a nearest-exit path, and SA considers an optimal path.
- *Path planner:* This component consists of an *exit recommender* and a *path generator*. The *exit recommender* produces an exit recommendation for each pedestrian. The *path generator* then creates an evacuation path based on the technique selected. In a real-life scenario, this information would be transmitted to each pedestrian to guide their evacuation.
- *Performance tracker:* This component tracks and registers the output generated by the system. In a real-world context, the performance measures are dynamically tracked to monitor the deviation between the planned and real-life evacuations. This enables instantaneous corrective measures or future planning. The tracked performance measures include the following:
  - Maximum crowd at exit (*MCE*): This metric computes the number of pedestrians evacuating from each exit and determines the maximum values.
  - Total evacuation time (*TET*): This metric is the duration from the time the first pedestrian passes through an exit to the time the last pedestrian evacuates the facility (Fry & Binner, 2016). This performance measure is calculated as $n_i/K_i + J_i$, where n_i is the number of pedestrians evacuating from exit i, K_i is the width of exit i, and J_i is the speed of the pedestrians.

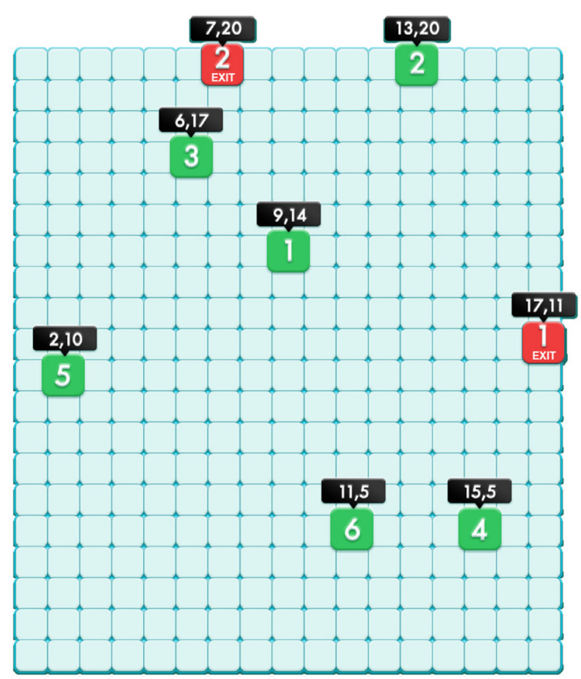


Fig. 3. The initial state of the evacuation room in the numerical scenario.

Table 1
Exit 1's LSDL.

Pedestrian	Distance
1	8
2	9
3	11
4	6
5	15
6	6

Table 2
Exit 2's LSDL.

Pedestrian	Distance
1	6
2	6
3	3
4	15
5	10
6	15

Table 3
Exit 1's LSDL sorted in ascending order.

Pedestrian	Distance
4	6
6	6
1	3
2	15
3	10
5	15

Table 4
Exit 2's LSDL sorted in ascending order.

Pedestrian	Distance
3	3
1	6
2	6
5	10
4	15
6	15

Table 5
GSDL at the start of the algorithm.

Exit	Pedestrian	Distance
2	3	3
1	4	6

4. Numerical scenario

A numerical scenario is presented to demonstrate the proposed algorithm's performance. The examples assume a two-dimensional grid of $x \times y$ cells representing a room with six pedestrians ($NoE = 6$) and two exits ($NoE = 2$). The two exits are laid out on adjacent sides of the room, and the pedestrians are randomly distributed across the room. Fig. 3 illustrates the initial state of the presented example.

In the first phase of BEME, an LSDL is generated for the two exits. These two lists maintain a catalog of all six pedestrians and the shortest distance to Exits 1 and 2 (see Tables 1 and 2, respectively). For instance, Pedestrian 1's distance to Exit 1 is 8 (see Fig. 4) and that to Exit 2 is 6. The populated LSDLs are then sorted in ascending order to reflect the distance of the pedestrians from closest to furthest (see Tables 3 and 4). Next, a local CL is created for each exit. The CL size is equal to NoP/NoE for each exit to equally distribute the pedestrians across exits. In other words, two CLs of size 3 are created for Exits 1 and 2. The CLs will be used to show the pedestrians that are assigned to depart from the designated exit.

In the second phase of BEME, a GSDL is generated to maintain a global list of shortest distances obtained from the LSDLs. In the examples, the GSDL is populated with the first two rows from the LSDS of Exits 1 and 2 and then placed in ascending order (see Table 5). At this point, the algorithm will determine whether the number of elements in the CL of the exit reported as the first item

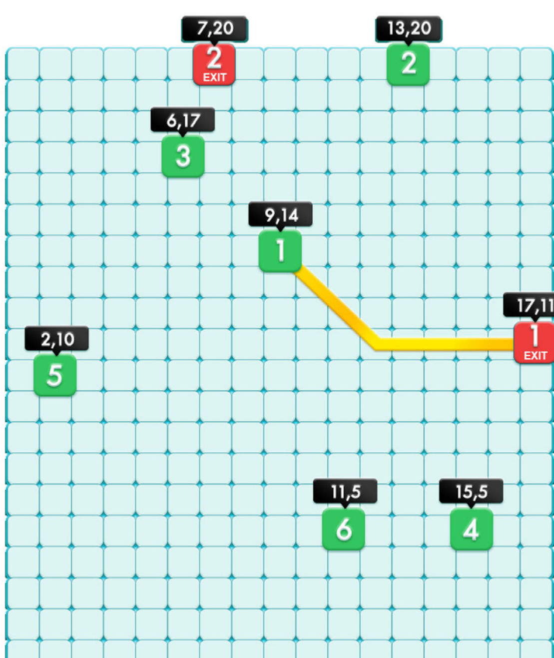


Fig. 4. The distance between Pedestrian 1 and Exit 1 in the numerical scenario.

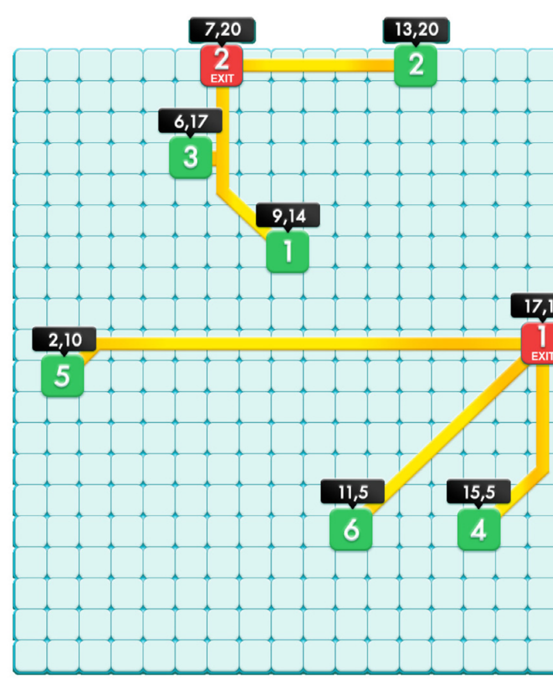
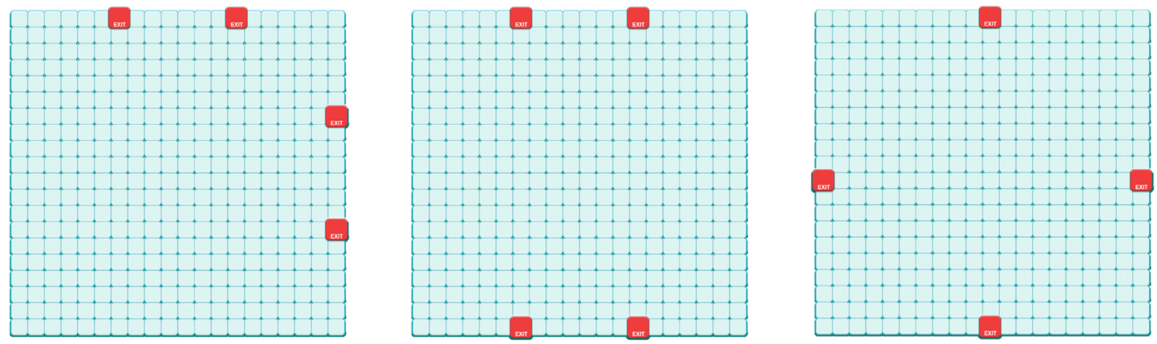
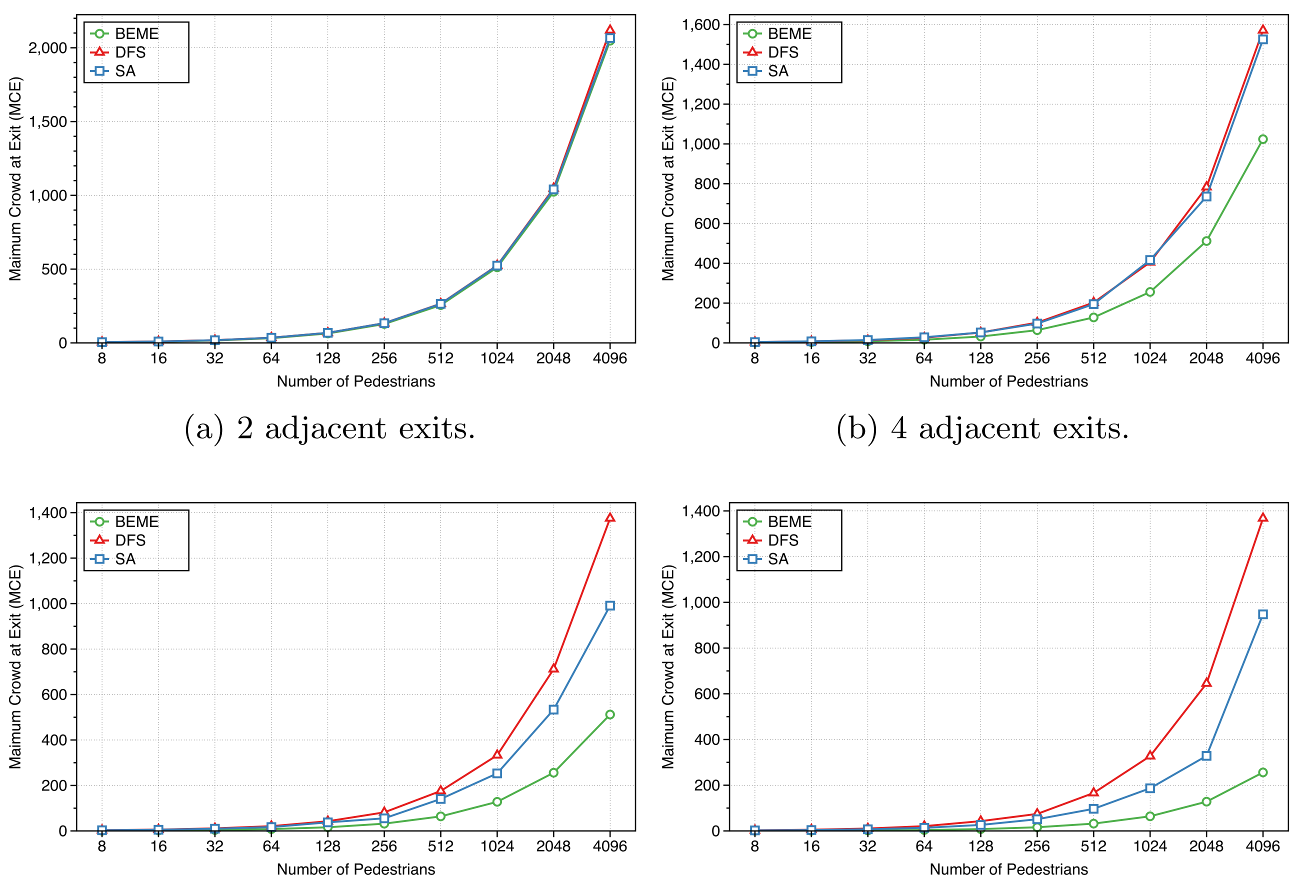


Fig. 5. The final state of the algorithm that illustrates the balanced assignment of pedestrians to exits.



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

Fig. 6. The varied exit placements when $NoE = 4$.



(a) 2 adjacent exits. (b) 4 adjacent exits.

(c) 8 adjacent exits. (d) 16 adjacent exits.

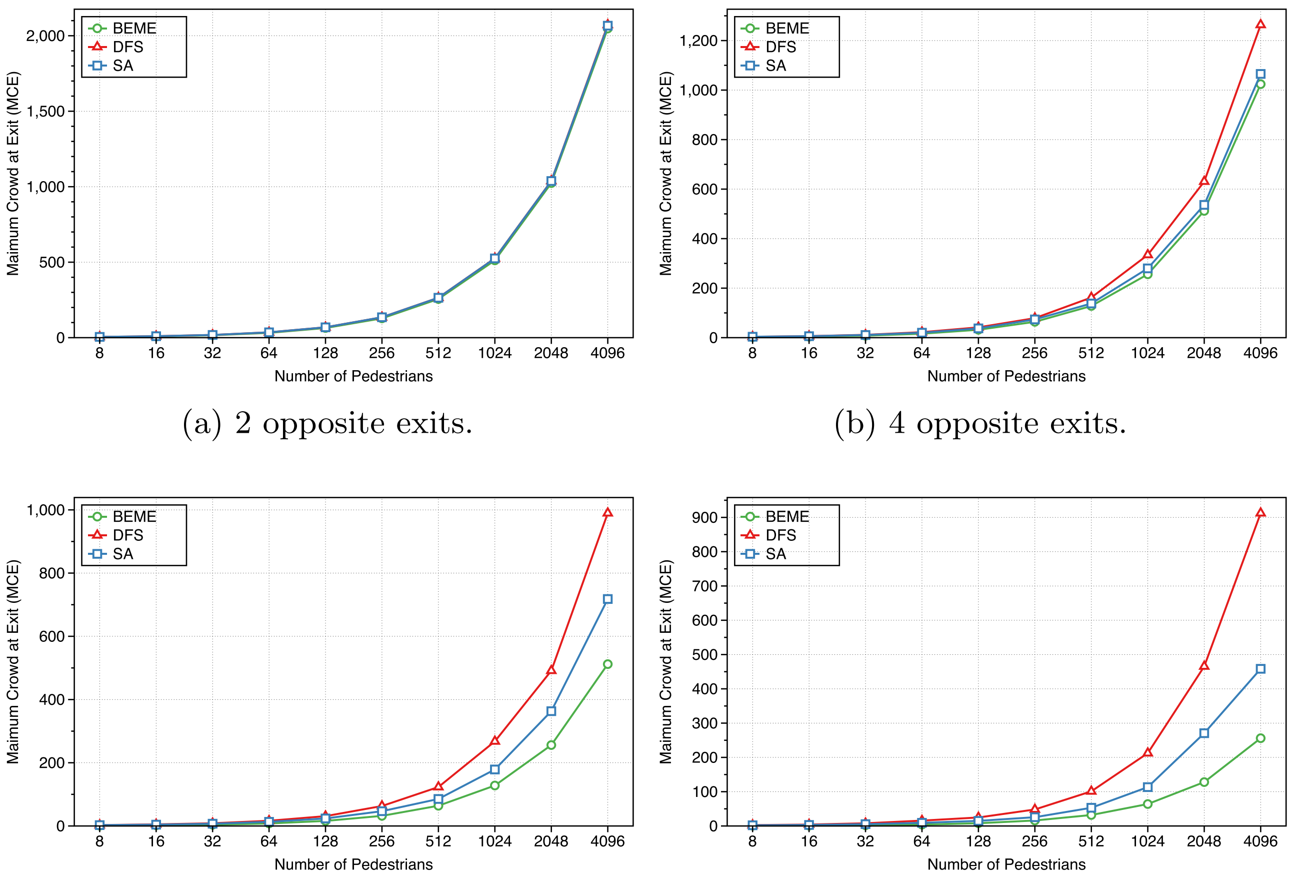
Fig. 7. Max crowd at exit (MCE) as the number of pedestrians (*NoP*) increases from 2 to 4,096 in a room with adjacent exits.

in the GSDL is less than *NoP*/*NoE*. In the numerical scenario, the number of elements in Exit 2's CL is zero, which is less than three. This means that Pedestrian 3 will be assigned to egress via Exit 2 and thus is added to Exit 2's CL. Afterward, Pedestrian 3's records are removed from the locally maintained lists, i.e., LSDLs for Exits 1 and 2, and the GSDL. Consequently, the next record from Exit 2's LSDL is entered into the GSDL, as shown in Table 6.

The algorithm continues its progress as it assigns Pedestrian 1 to Exit 2 (i.e., entered in Exit 2's CL), and the pedestrian is subsequently removed from the two exits' LSDLs and the GSDL. Pedestrians are continually added to the CL of Exit 1 or 2 until one of the lists is full. When one of the CLs is full and the exit is at risk of congestion, the algorithm eliminates the LSDL of the CL's exit and removes all its records from the GSDL. The algorithm returns a balanced assignment of pedestrians to exits maintained in the CL. This final assignment for the given scenarios is illustrated in Fig. 5.

Table 6
GSDL after Pedestrian 3 assignment.

Exit	Pedestrian	Distance
2	1	6
1	4	6



(a) 2 opposite exits.

(b) 4 opposite exits.

(c) 8 opposite exits.

(d) 16 opposite exits.

Fig. 8. Max crowd at exit (MCE) as the number of pedestrians (*NoP*) increases from 2 to 4,096 in a room with exits on opposite sides.

5. Experiment

A Java-based environment simulator was developed based on a previously built simulator (Kurdi et al., 2018) to examine the performance of the proposed algorithm and benchmarks with regard to the efficiency of evacuation plans. The simulator consists of a two-dimensional grid of $x \times y$ cells representing a facility with a finite *NoP* and a finite *NoE*. Each cell can either be empty or occupied by a single agent (i.e., a pedestrian or an exit). A pedestrian occupying a cell can move in one of eight directions: North, North East, East, South East, South, South West, West, and North West. At each time step in the simulation, the pedestrian can move from its current position to an adjacent position, but back stepping is prohibited (Wang, Ma, Wang, Qin, & Jia, 2014). Several exit placements are also investigated in this paper, including exits on adjacent sides of the room, opposite sides, and all sides (Fig. 6).

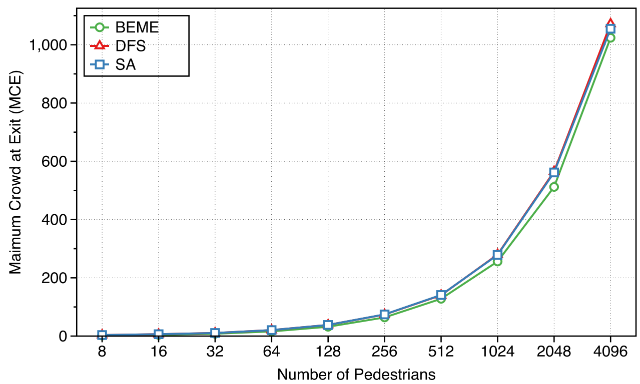
The evaluation framework considers representative samples of evacuation scenarios with varying numbers of pedestrians and exits to assess the performance of the proposed and benchmark algorithms. These parameters are as follows:

- The number of pedestrians *NoP*: ten different scales for *NoP* were considered to illustrate the performance of the algorithms: $2\hat{k},\ k = 3, \ldots 12$ pedestrians.
- The number of exits *NoE*: four values for the number of exits were considered: $2\hat{k},\ k = 1, \ldots, 4$. For each scale, various exit placements were considered, including adjacent exits, opposite exits, and exits placed on all sides of the room (Kurdi et al., 2018).

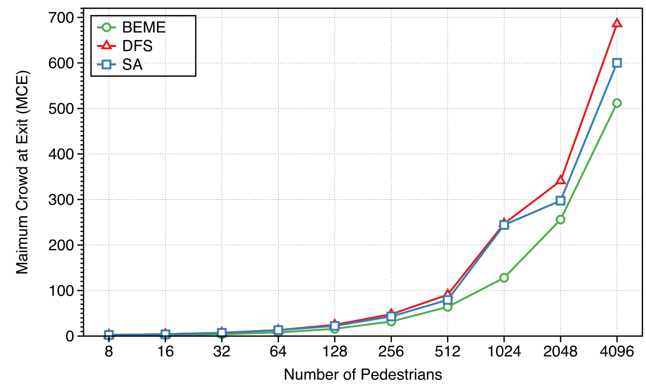
Two well-established AI techniques were used to evaluate the BEME algorithm. The two techniques, SA (Kirkpatrick, Gelatt, & Vecchi, 1983) and DFS (Tarjan, 1972), differ in their objectives. The former searches for an optimal evacuation strategy, while the latter attempts to find the nearest exit for evacuation.

SA is a probabilistic search heuristic technique that mathematically mirrors the cooling of a set of atoms to a state of minimum energy (Kirkpatrick et al., 1983). This technique draws an analogy between the cooling of a material (i.e., searching for minimum energy state) and the solving of an optimization problem. Unlike traditional optimization techniques, this approach is not restricted to a local optimum. In the case of pedestrian evacuations, the initial temperature is high, and it is slowly lowered during successive iterations. The process should be slow enough to allow the state to reach equilibrium at each temperature (Kurdi et al., 2018).

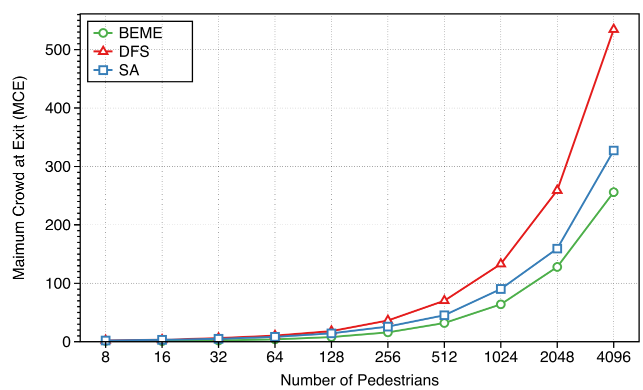
The DFS technique for finding the nearest exit requires that the position of each pedestrian be identified as (x, y) on a board (Tarjan, 1972). Then, it weighs all board points by checking every point on the board against its neighbors (forward, backward, left, and right) until a destination or an obstacle is reached. After generating the distances and sorting them in an array, the distance between each pedestrian and the various exits is 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 found (Kurdi et al., 2018).



(a) 4 exits on all sides.



(b) 8 exits on all sides.



(c) 16 exits on all sides.

Fig. 9. Max crowd at exit (MCE) as the number of pedestrians (*NoP*) increases from 2 to 4096 in a room with exits on all sides.

Table 7
Simulation parameters and assigned values.

Parameter	Assigned value
Room size	100×100 square meters
Number of exits	2, 4, 8, and 16
Number of pedestrians	8, 16, 32, 64, 128, 256, 512, 1,024, 2,048, and 4,096
Pedestrian speed	1 meter per second
Exit width	1 meter
Exit placement	Adjacent, opposite, and all sides layouts

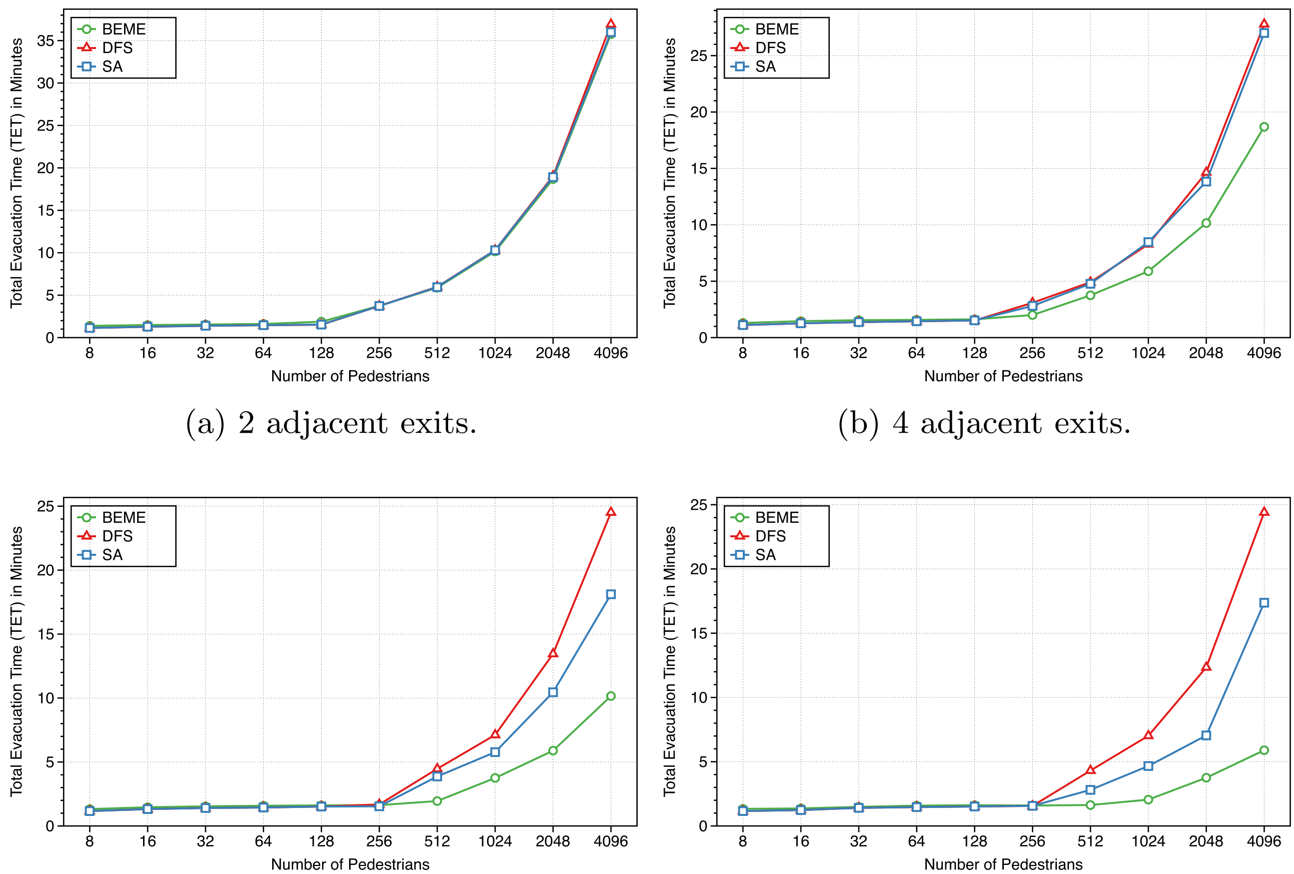
In the simulation, the following performance metrics were computed for each scenario: maximum crowd at any exit (MCE) and total evacuation time (TET). Exits are assumed to be identical, and for simplicity, only one pedestrian egresses per second.

The simulations were conducted in a 100×100 m room. The number and positions of pedestrians were randomized but identical for each test case. The width of the exits was set at 1 m, as is typically adopted in evacuation scenarios (Cristiani & Peri, 2017; Heliövaara et al., 2012; Xiong, Tang, & Zhao, 2013). The pedestrian speed was set at 1 metre per second (Fry & Binner, 2016). The simulation considered ten different scales for the number of pedestrians, ranging from 2 to 4096, as described previously, and four different scales for the number of exits, ranging from 2 to 16. Exit placements were varied as noted above to examine the impact of placement on the evacuation efficiency, including exits placed on adjacent sides of the room, exits placed on opposite sides of the room, and exits placed on all four sides of the room. Table 7 lists the parameters utilized in the simulation and their assigned values. A total of 100 test cases were performed, and the average MCE and TET were then computed.

6. Results and discussion

The maximum crowds at exits (*MCE*) is computed as the maximum number of pedestrians evacuating at each exit. The number of pedestrians at each exit is first calculated, and then, the exit evacuating the largest number of pedestrians is taken as *MCE*. The measure was plotted for each number of exits as they increased exponentially (2 to 16 exits) against the number of pedestrians in lin-log graphs. Figs. 7–9 illustrate the *MCE* when exits are adjacent, opposite, or on all sides of the room, respectively. In contrast to Figs. 7 and 8, only 4, 8, and 16 exits were considered when exits were positioned on all sides (see Fig. 9) as the room in the model is square.

Fig. 7 shows the performance of BEME and the benchmark algorithms DFS and SA as the number of pedestrians increases from 2 to 4096 in a room with adjacent exits. Given only two exits on adjacent sides of the room (Fig. 7a), the performance of the BEME algorithm is similar to that of DFS and SA. Of the two benchmark algorithms, the simulation values produced by SA were close to those produced by BEME. As the number of exits is increased to four on adjacent sides (Fig. 7b), BEME begins to clearly outperform the benchmark algorithms, with a lower maximum number of pedestrians egressing at each exit. This reduces overcrowding and clogging at points of egress. There was a slight variation between the performances of the DFS and SA techniques, particularly as the number of pedestrians increased to thousands. These variations between the benchmark algorithms became more evident as the number of exits increased to 8 and 16 (Figs. 7c and 7 d, respectively). In these instances, the SA technique outperforms DFS, as it



(a) 2 adjacent exits.

(b) 4 adjacent exits.

(c) 8 adjacent exits.

(d) 16 adjacent exits.

Fig. 10. Total exit time (TET) as the number of pedestrians (*NoP*) increases from 2 to 4096 in a room with adjacent exits.

tends to distribute pedestrians across exits more evenly. Overall, BEME showed superior performance compared to the benchmark techniques, with a significant reduction in the number of pedestrians at exits.

The performance of the proposed algorithm and the benchmarks is further illustrated in Fig. 8, which shows the results obtained with exits placed on opposite sides of the room. Analogous to what was previously observed in Fig. 7a with the adjacent placement of two exits, the performance is similar among the three algorithms when there are only two points of egress (Fig. 8a). With four exits placed on opposite sides of the room (Fig. 8b), the performance of BEME and SA improved compared to the DFS technique. The better SA performance is in contrast to the performance observed for exits placed adjacently in Fig. 7b. Moreover, the MCE numbers are significantly reduced for the benchmark algorithms when exits are placed opposite each other. For instance, with 4,096 pedestrians evacuating the premises, the MCE for the SA technique for the opposing exit placement is 1065 pedestrians, compared to 1525 pedestrians for adjacently placed exits. Consequently, the adjacent placement of exits raises the risk of overcrowding and injury at the exits. With 8 and 16 exits, the performance of BEME notably improved compared to the performance of the benchmark techniques, as is evident from Figs. 8c and 8 d, respectively. In these instances, the SA performance differed from DFS, producing lower MCE numbers.

The effect of exit placement on the performance of the proposed and benchmark techniques is further demonstrated in Fig. 9, which shows the performance for placements of 4, 8, and 16 exits on all sides of the room. With four points of egress distributed on all sides, the performance of all three algorithms was quite similar (Fig. 9a). While this is in contrast to the results illustrated in Figs. 7b and 8 b, it was anticipated, as the distribution of exits encourages relatively equal distributions of pedestrians to those exits across the BEME, DFS, and SA algorithms. Variations in the performance of each algorithm became evident as the number of exits increased to 8 and 16 (Figs. 9b and 9 c, respectively). With eight exits distributed equally across all four sides of the room, the variations between the three algorithms are relatively small, with BEME outperforming the benchmark algorithms (Fig. 9b). The differences between BEME and the benchmark techniques increase as the number of exits increases to 16 points of egress (Fig. 9c). In comparison to Figs. 7 and 8, the value of MCE for the DFS and SA algorithms decreases significantly.

The performance was also measured via total exit time, the duration from when the first pedestrian evacuates to when the last pedestrian egresses from the facility. The results for the TET for BEME and the benchmark algorithms are given in Figs. 10–12. The results as the number of exits increased exponentially from 2 to 16 against the increasing number of pedestrians (2 to 4,096 pedestrians) are plotted in lin-log graphs. The three figures, Figs. 10–12, demonstrate the impact of the exit placement on the reported measure. Fig. 12 only shows the impact of the exit placement on all sides for 4, 8, and 16 exits due to the geometric constraints of the four-sided room.

Fig. 10 shows the performance in terms of THE TET for BEME and the benchmark algorithms when exits are placed on adjacent sides of the room. With only two exits, the total exit time is similar for all three algorithms (Fig. 11a). This was anticipated,

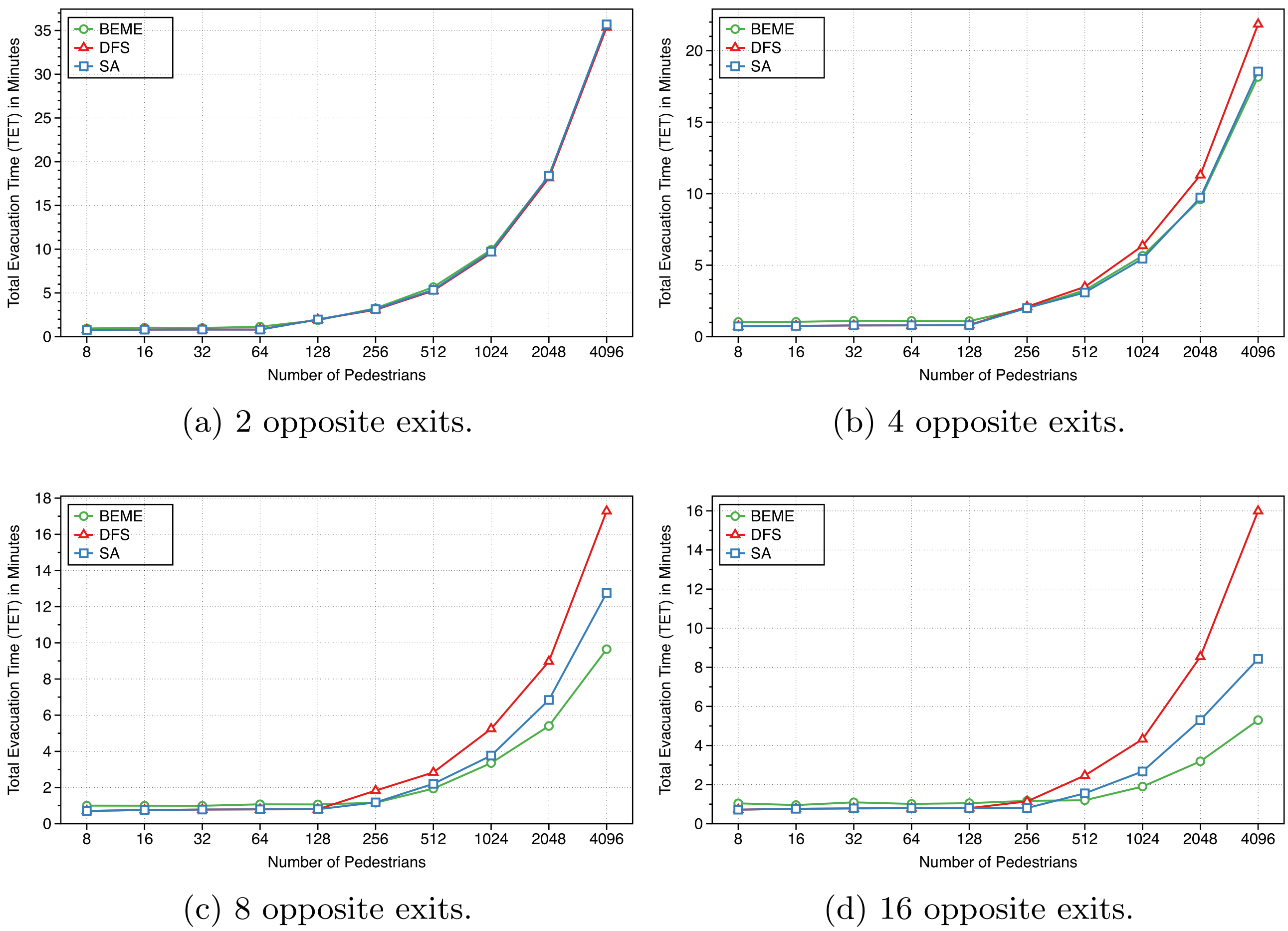


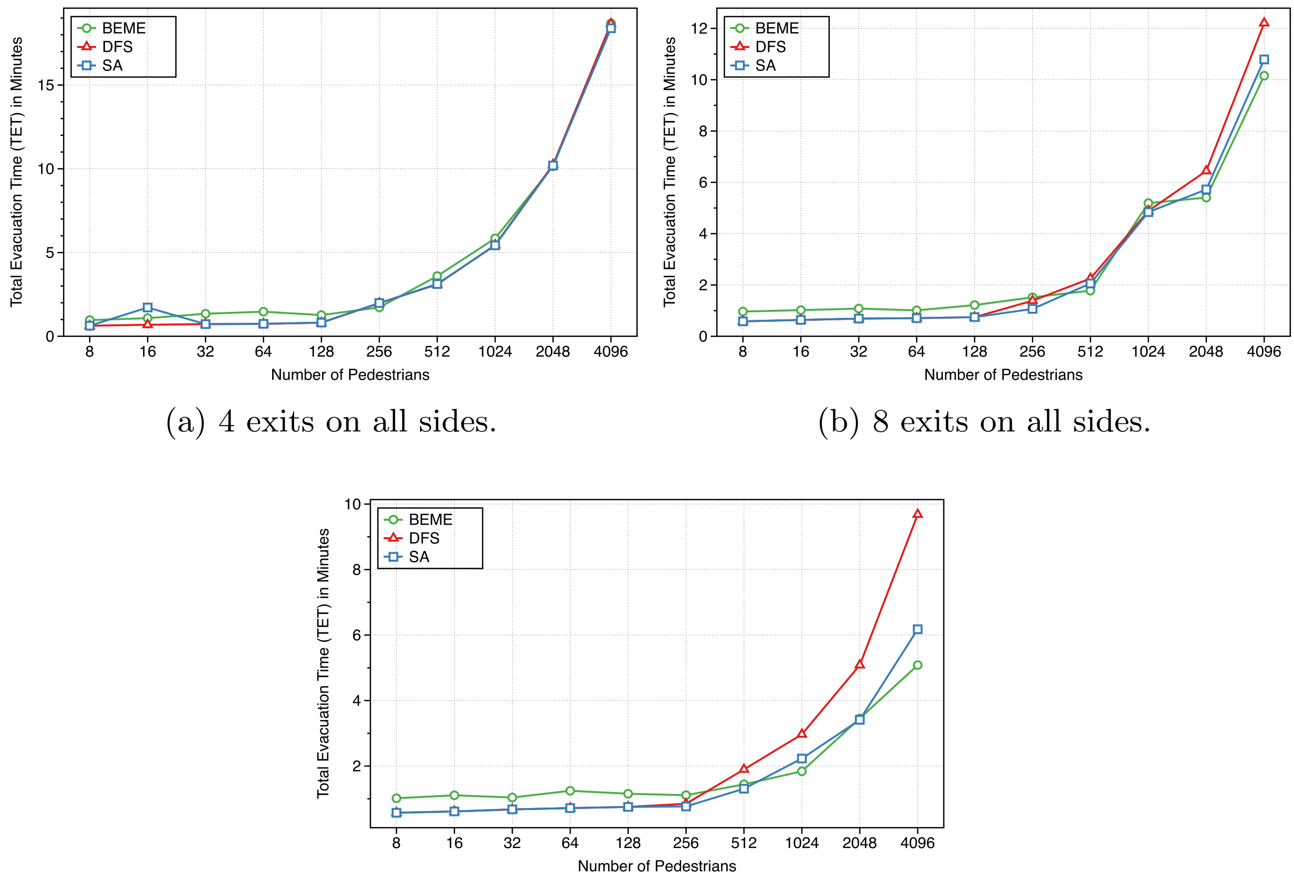
Fig. 11. Total exit time (TET) as the number of pedestrians (*NoP*) increases from 2 to 4096 in a room with exits on opposite sides.

as the limited number of exits does not present the algorithms with many options for pedestrian distribution. The better performance of BEME becomes more evident as the number of exits is increased (4, 8, and 16) and as the number of pedestrians is increased. The TET for BEME when exits are placed on adjacent sides for 4,096 pedestrians is 18 minutes, compared to approximately 27 minutes for both the DFS and SA techniques (Fig. 11b). The variations between the algorithms in terms of the TET performance become even more evident with 8 and 16 exits, as shown in Figs. 11c and 11 d, respectively. In these instances, the performance of the BEME algorithm proved superior to that of the benchmark algorithms. The variations between the two benchmark algorithms also become apparent with 8 and 16 adjacent exits. Of these two benchmark algorithms, the SA technique resulted in faster evacuations (lower TET).

The TET performance of BEME, SA, and DFS was also observed for exits placed on opposite sides of the room (Fig. 11). With only two opposing exits, the TET results for the three algorithms are similar to the times and variations observed in the adjacent placement, as shown in Fig. 10a. Conversely, the similarities between the algorithms dissipate as the number of exits increases. At four exits on opposite sides, the performances of BEME and SA remain similar, with both algorithms outperforming the DFS technique in terms of TET (Fig. 11b). The disparity between BEME and the benchmark algorithms continues to grow as the number of exits increases to 8 and 16 exits (Figs. 11c and 11 d, respectively). In these two instances, the DFS algorithm required the longest time to evacuate all pedestrians, followed by the SA algorithm. BEME, in contrast, had the shortest TET, with 4,096 pedestrians evacuating an eight-exit facility in less than 5.5 minutes. However, the BEME technique exhibited a slightly longer TET when there were fewer than 256 pedestrians regardless of the number of exits. Nevertheless, the margin between the performance of BEME and that of the benchmarks did not exceed 30 seconds.

The TET performance of the proposed algorithm and the benchmark algorithms is further illustrated in Fig. 12 for 4, 8, and 16 exits placed on all sides of the room. The performances of the three algorithms are similar when there are only four points of egress positioned on all sides (Fig. 12a). The TET obtained for BEME was slightly worse than those obtained for the benchmark algorithms when the number of pedestrians exiting the facility was fewer than 2,048. Still, the difference in TET was less than 45 seconds for all instances. This variance was also discernible as the number of exits was increased to 8 and 16 (Figs. 12b and 12 c, respectively). The performance of the DFS technique falls as the number of exits increases to 8 and 16 when the number of pedestrians is above 256. SA produced similar results to those of BEME when the number of exiting pedestrians surpassed 256. Notwithstanding, the TET results are best viewed in tandem with the MCE, for which the performance of BEME surpassed that of the benchmark algorithms by reducing clogging at points of egress.

The conducted simulations reported in this paper examined the impact of exit placement, number of exits, and number of pedestrians on the MCE and TET performance metrics for BME, SA, and DFS. The MCE performance of BEME was balanced when both varying the number of exits and varying the exit placement. However, the MCE performance of the BEME algorithm did not falter across the three placement variations. This indicates the value of



(a) 4 exits on all sides.

(b) 8 exits on all sides.

(c) 16 exits on all sides.

Fig. 12. Total exit time (TET) as the number of pedestrians (*NoP*) increases from 2 to 4096 in a room with exits on all sides.

the proposed algorithm for evacuation infrastructure, where it can be utilized despite the inefficient spatial placement of the exits. Although similar MCE performances for all three techniques can be observed with only two adjacent exits and for exits placed on all sides of the room, variations across the three techniques appear as the number of exits is increased to 8 and 16. Of the two benchmark algorithms, SA proved superior to DFS, resulting in a reduced MCE across the varying conditions. The best performance for both DFS and SA was for exits placed on all sides of a room. These results are consistent with previous findings investigating the impact of exit placement on performance (Kurdi et al., 2018). The TET performance of BEME for adjacent exit placement was similar to that of the benchmarks for fewer than 256 pedestrians; however, differences become apparent as the number of pedestrians increases. For opposite and all-side exit layouts, the TET results for the BEME algorithm are slightly worse (30 and 45 second difference, respectively) than those of the benchmarks for fewer than 256 pedestrians. Still, when viewed in tandem with the MCE results, the findings show that the BEME performance eclipses that of SA and DFS given the reduced over-crowding at exits.

7. Conclusions and future work

The presented work proposes an evacuation algorithm, BEME, that attempts to resolve the problem of overcrowding and congestion around exits during emergency evacuations from multiple-exit facilities. The algorithm optimizes the evacuation process and reduces evacuation time by equally distributing pedestrians between all exits. A purpose-build simulator was developed to compare the performances of the proposed approach against two well-established AI algorithms: SA and DFS. A variable number of pedestrians and exits were considered, as well as varied exit placements. The findings affirm the benefit of the proposed approach for the optimization of the evacuation process, where the MCE was clearly reduced despite the varying exit layouts considered. The total evacuation time (TET) was similarly impacted, particularly with a greater number of pedestrians evacuating. When viewed in tandem, the results of the MCE and TET highlight the superior performance of BEME over the benchmarks.

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

- A new balanced evacuation algorithm, BEME, is proposed to ensure the timely and guided evacuation of pedestrians in a way that avoids overcrowding and congestion.
- A well-controlled simulation framework for evaluating BEME is developed.
- A thorough investigation of BEME's performance against well-established AI techniques with varying numbers of pedestrians and exits and varying layouts is conducted.

For future work, the proposed optimization model will be improved and extend by considering various factors. The following improvements are presently under consideration:

- Extend BEME to consider variable factors such as the size and shape of a facility. Obstacles, such as pillars, are also to be considered.
- Compare BEME's performance against other well-established algorithms such as A* and the Dijkstra algorithm.

Please cite this article as: H. Kurdi, A. Almulifi and S. Al-Megren et al., A balanced evacuation algorithm for facilities with multiple exits, European Journal of Operational Research, https://doi.org/10.1016/j.ejor.2020.07.012

- Improve BEME by considering individual and group behaviors of pedestrians, such as altruism (Chen, Li, Jiang, & Hu, 2018) and leading (Xiao-Lu, Wei, & Xiao-Ping, 2015) behaviors. The model should also consider the varied abilities of pedestrians (Kim, Ahn, & Lee, 2018).

Acknowledgment

This work was supported by Saudi Aramco, under the “Saudi Aramco Ibn Khaldun Fellowship for Saudi Women”, in partnership with the Center for Clean Water and Clean Energy at MIT, and the International Scientific Partnership Program ISPP at King Saud University.

References

Abdelghany, A., Abdelghany, K., Mahmassani, H., Al-Ahmadi, H., & Alhalabi, W. (2010). Modeling the evacuation of large-scale crowded pedestrian facilities. *Transportation Research Record: Journal of the Transportation Research Board, 2198*(1), 152–160.
Abdelghany, A., Abdelghany, K., Mahmassani, H., & Alhalabi, W. (2014). Modeling framework for optimal evacuation of large-scale crowded pedestrian facilities. *European Journal of Operational Research, 237*(3), 1105–1118.
Afandizadeh, S., Jahangiri, A., & Kalantari, N. (2009). Determination of the optimal network configuration for emergency evacuation by simulated annealing algorithm. In *Proceedings of the second WSEAS international conference on natural hazards (NAHA'09): 65*.
Akopov, A. S., & Beklaryan, L. A. (2015). An agent model of crowd behavior in emergencies. *Automation and Remote Control, 76*(10), 1817–1827.
Al Qhtani, A. S., Al Shammari, A. S., & Kurdi, H. A. (2017). A fast genetic algorithm-based evacuation plan generator. *Procedia Computer Science, 109*, 994–998.
Assouline, M., Bastien, M., Brenot, J., Dumas, M., & Parmentier, N. (1987). Economic consequences of evacuation in industrialised urban areas. *Radiation Protection Dosimetry, 21*(1–3), 165–169.
Bode, N. W., Miller, J., O'Gorman, R., & Codling, E. A. (2015). Increased costs reduce reciprocal helping behaviour of humans in a virtual evacuation experiment. *Scientific Reports, 5*, 15896.
Cao, S., Song, W., Lv, W., & Fang, Z. (2015). A multi-grid model for pedestrian evacuation in a room without visibility. *Physica A: Statistical Mechanics and its Applications, 436*, 45–61.
Chen, Y.-Z., Li, M., Jiang, R., & Hu, M.-B. (2018). Evacuation flow of pedestrians considering compassion effect. *Chinese Physics B, 27*(8), 088901.
Chiu, Y.-P., Shiau, Y.-C., & Lai, Y.-H. (2018). Study on evacuation simulation under crowd-diversion condition. *Advances in Mechanical Engineering, 10*(7). 1687814018785092.
Cristiani, E., & Peri, D. (2017). Handling obstacles in pedestrian simulations: Models and optimization. *Applied Mathematical Modelling, 45*, 285–302.
Davidich, M., & Köster, G. (2012). Towards automatic and robust adjustment of human behavioral parameters in a pedestrian stream model to measured data. *Safety Science, 50*(5), 1253–1260.
Desai, S. P., Harris, C. A., & Gordon, J. (2019). The economic impact of hurricane evacuations on a Coastal Georgia hospital: A case study. *Frontiers in Public Health, 7*, 149.
Dhamala, T. N. (2015). A survey on models and algorithms for discrete evacuation planning network problems. *Journal of Industrial & Management Optimization, 11*(1), 265–289.
Ding, A. W. (2011). Implementing real-time grouping for fast egress in emergency. *Safety Science, 49*(10), 1404–1411.
Formolo, D., & van der Wal, C. N. (2017). Simulating collective evacuations with social elements. In *Proceedings of the conference on computational collective intelligence technologies and applications* (pp. 160–171). Springer.
Fry, J., & Binner, J. M. (2016). Elementary modelling and behavioural analysis for emergency evacuations using social media. *European Journal of Operational Research, 249*(3), 1014–1023.
Hao, Y., Bin-Ya, Z., Chun-Fu, S., & Yan, X. (2014). Exit selection strategy in pedestrian evacuation simulation with multi-exits. *Chinese Physics B, 23*(5), 050512.
Heliövaara, S., Kuusinen, J.-M., Rinne, T., Korhonen, T., & Ehtamo, H. (2012). Pedestrian behavior and exit selection in evacuation of a corridor–an experimental study. *Safety Science, 50*(2), 221–227.
Hu, J., You, L., Zhang, H., Wei, J., & Guo, Y. (2018). Study on queueing behavior in pedestrian evacuation by extended cellular automata model. *Physica A: Statistical Mechanics and its Applications, 489*, 112–127.
Huang, K., & Zheng, X. (2017). A weighted evolving network model for pedestrian evacuation. *Applied Mathematics and Computation, 298*, 57–64.
Ji, J., Lu, L., Jin, Z., Wei, S., & Ni, L. (2018). A cellular automata model for high-density crowd evacuation using triangle grids. *Physica A: Statistical Mechanics and its Applications, 509*, 1034–1045.
Kim, J., Ahn, C., & Lee, S. (2018). Modeling handicapped pedestrians considering physical characteristics using cellular automaton. *Physica A: Statistical Mechanics and its Applications, 510*, 507–517.
Kirkpatrick, S., Gelatt, C. D., & Vecchi, M. P. (1983). Optimization by simulated annealing. *Science, 220*(4598), 671–680.
Kurdi, H. A., Al-Megren, S., Althunyan, R., & Almulifi, A. (2018). Effect of exit placement on evacuation plans. *European Journal of Operational Research, 269*(2), 749–759.
Lee, M., Nam, H., & Jun, C. (2017). Multiple exits evacuation algorithm for real-time evacuation guidance. *Spatial Information Research, 25*(2), 261–270.
Liao, W., Wagoum, A. U. K., & Bode, N. W. (2017). Route choice in pedestrians: Determinants for initial choices and revising decisions. *Journal of The Royal Society Interface, 14*(127), 20160684.
Liu, S., Yang, L., Fang, T., & Li, J. (2009). Evacuation from a classroom considering the occupant density around exits. *Physica A: Statistical Mechanics and its Applications, 388*(9), 1921–1928.
Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M. L., & Di Ruocco, A. (2012). Basic principles of multi-risk assessment: A case study in italy. *Natural Hazards, 62*(2), 551–573.
Ng, C. M., & Chow, W. (2006). A brief review on the time line concept in evacuation. *International Journal on Architectural Science, 7*(1), 1–13.
Oh, H., & Park, J. (2017). Main factor causing ?faster-is-slower? Phenomenon during evacuation: rodent experiment and simulation. *Scientific Reports, 7*(1), 13724.
Pan, X., Han, C. S., Dauber, K., & Law, K. H. (2006). Human and social behavior in computational modeling and analysis of egress. *Automation in Construction, 15*(4), 448–461.
Patel, N., Min, M., & Lim, S. (2016). Accurate evacuation route planning using forward-backward shortest paths.. In *Proceedings of the SYSCON* (pp. 1–6).
Poulos, A., de la Llera, J. C., & Mitrani-Reiser, J. (2017). Earthquake risk assessment of buildings accounting for human evacuation. *Earthquake Engineering & Structural Dynamics, 46*(4), 561–583.
Ren-Yong, G., & Hai-Jun, H. (2010). Logit-based exit choice model of evacuation in rooms with internal obstacles and multiple exits. *Chinese Physics B, 19*(3), 030501.
Tarjan, R. (1972). Depth-first search and linear graph algorithms. *SIAM Journal on Computing, 1*(2), 146–160.
Vermuyten, H., Beliën, J., De Boeck, L., Reniers, G., & Wauters, T. (2016). A review of optimisation models for pedestrian evacuation and design problems. *Safety Science, 87*, 167–178.
Wagner, N., & Agrawal, V. (2014). An agent-based simulation system for concert venue crowd evacuation modeling in the presence of a fire disaster. *Expert Systems with Applications, 41*(6), 2807–2815.
Wang, Z., Ma, J., Wang, H., Qin, Y., & Jia, L. (2014). Effect of interaction among same-direction pedestrians. *Transportation Research Procedia, 2*, 353–358.
Wu, Y., Kang, J., & Wang, C. (2018). A crowd route choice evacuation model in large indoor building spaces. *Frontiers of Architectural Research, 7*(2), 135–150.
Xiao-Lu, W., Wei, G., & Xiao-Ping, Z. (2015). Effects of evacuation assistant's leading behavior on the evacuation efficiency: Information transmission approach. *Chinese Physics B, 24*(7), 070504.
Xiong, M., Tang, S., & Zhao, D. (2013). A hybrid model for simulating crowd evacuation. *New Generation Computing, 31*(3), 211–235.
Yue, H., Guan, H., Shao, C., & Zhang, X. (2011). Simulation of pedestrian evacuation with asymmetrical exits layout. *Physica A: Statistical Mechanics and its Applications, 390*(2), 198–207.
Yuksel, M. E. (2018). Agent-based evacuation modeling with multiple exits using neuroevolution of augmenting topologies. *Advanced Engineering Informatics, 35*, 30–55.
Zhao, X., Ren, G., & Huang, Z.-f. (2016). Optimizing one-way traffic network reconfiguration and lane-based non-diversion routing for evacuation. *Journal of Advanced Transportation, 50*(4), 589–607.
Zheng, X., Li, W., & Guan, C. (2010). Simulation of evacuation processes in a square with a partition wall using a cellular automaton model for pedestrian dynamics. *Physica A: Statistical Mechanics and its Applications, 389*(11), 2177–2188.
Zhu, N., Jia, B., & Shao, C.-F. (2012). Pedestrian evacuation with the obstacles based on cellular automata. In *Proceedings of the 2012 fifth international joint conference on computational sciences and optimization (CSO)* (pp. 448–452). IEEE.