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Exploring the potential effectiveness of dynamic and static emergency exit signage in complex spaces through simulation

Lazaros Filippidis, Hui Xie, Edwin R. Galea *, Peter J. Lawrence

Fire Safety Engineering Group, University of Greenwich, Park Row, Greenwich, London, UK

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ABSTRACT

Emergency exit signs used in buildings aid occupant wayfinding during an emergency. However, research suggests that conventional signs lack the ability to attract people's attention in an emergency. This can result in the underuse of emergency exits and the overuse of main entrances with potentially fatal consequences. The effectiveness of signage depends on their ability to draw occupants' attention. A novel dynamic signage design, Active Dynamic Signage System (ADSS), was proposed to address this issue through incorporating flashing green LEDs into the arrow of conventional exit signs. Its effectiveness was tested in a series of experiments achieving a detection rate of up to 77% as opposed to 38% for conventional exit signs. In this paper, the signage model within the buildingEXODUS software was adapted to represent the ADSS and a series of simulations were run to investigate the potential effectiveness of the ADSS compared to conventional signs. The scenarios examined involved a supermarket geometry, 900 agents and three levels of signage configuration. The modelling results suggest that the ADSS can reduce total egress times for this structure by 18%, congestion by 36%, travel distances by 12%, resulting in a more efficient evacuation compared with that produced by conventional signage.

1. Introduction

Escape route signs and emergency exit signs are widely used in buildings to guide occupants to safety and away from danger in case of fire and other emergencies [1,2]. The directional and safety information conveyed by these signs is intended to reduce doubt in escape route or exit choice, especially where there is no direct visual access to emergency exits. Despite the required use of escape route signage, their effectiveness has often been questioned [3,4]. Furthermore, research has found that people tend not to notice or recall the location of emergency exit signs - an effect of 'learned irrelevance', where people continually exposed to escape route signs without using them are less likely to notice the signs when they are actually required [5,6]. The inefficiency of conventional signage systems in guiding occupants to a place of safety due to poor detectability has also been noted in several real disasters [7–10].

In order to gain an accurate estimation of the effectiveness of the signage systems and their impact on evacuees' route selection during building evacuation, the Fire Safety Engineering Group (FSEG) embarked on a series of research, including laboratory trials [11–13], online surveys [13,14] and large-scale evacuation trials [14,15]. These research activities investigated key aspects concerning how signage systems influence people's evacuation behaviour, including the effective visibility range of signage and the interaction between individuals and signage. A unique simulation capability to represent the interaction with signage in evacuation modelling was also developed in order to examine the effectiveness of signage within the built environment [11,12,16–18].

The visibility of signage is often defined through a maximum visibility distance in relation to the size of the elements on a sign, e.g., the height of text or graphical symbol in relevant signage standards [19–21]. However, this approach does not provide an explicit definition of the region from which a sign may influence people's wayfinding decision. To address this, FSEG introduced the concept of Visibility Catchment Area (VCA) [11,16] to define the region of floor area from where it is physically possible to discern information from the sign. When using the maximum visibility distance to describe the visibility of a sign, national and international regulatory authorities assumed that the VCA had a semi-circular representation centred on the sign with radius equal to the maximum viewing distance [19–22]. However, the actual region from where a sign is visible is also dependent on the angle of observation. When this is taken into consideration, the VCA is found to be circular in shape, with diameter equal to the maximum viewing

* Corresponding author.
E-mail address: e.r.galea@gre.ac.uk (E.R. Galea).

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distance and tangent to the surface of the sign (see Supplementary Material Section S1) [11]. A similar concept, known as the 'zone of influence', has been adopted by current ISO and British signage standard [23–25].

Of equal importance to the VCA concept, is determining whether people within the VCA tend to actually 'see' and perceive the sign, and consequently notice the indicated exit. Shields et al. [5] conducted unannounced evacuations in four large retail stores involving a total of 2073 customers and identified the under-use of emergency exits. McClintock et al. [6] surveyed 500 supermarket shoppers in an attempt to establish the psychological cause of the under-use of emergency exits observed in these evacuation experiments. McClintock found that while most people recognise and associate emergency exit signs with safety in an emergency, only 18% of those surveyed could recall seeing an emergency exit and, when presented with a store diagram, only 25% could mark the location of at least one emergency exit. McClintock argued that including additional lighting as a stimulus that is activated only during an emergency could improve signage conspicuity.

The effectiveness of conventional emergency exit signage was further investigated through a series of laboratory trials to examine individual wayfinding behaviour within an unfamiliar built environment under simulated emergency conditions [12]. It was demonstrated that most people have difficulty in perceiving and utilising the standard 'green running man' emergency exit sign, which was visually unobstructed and in the direct field of view of the participants. Only about 38% of people perceived the sign and used it to find their way out; while most of the others may look at the sign, but not actually perceive it [12]. The study also determined that of those who detected the sign, 97% followed the instruction of the sign [12]. These studies concluded that the conventional emergency signs are not as effective as they could be in providing wayfinding guidance. However, the effectiveness of the signs can be improved if their affordance, and therefore detectability, is improved, while at the same time ensuring that the information relayed is equally comprehensive.

Several experimental studies have been conducted to explore how the effectiveness of signage systems can be enhanced through the introduction of various forms of dynamic lighting. In one of the earliest studies, Jin et al. [26] measured the conspicuousness of both signs with flashing backlight and standard illuminated signs of the same size. Jin found that signs with flashing backlight were more conspicuous than the standard illuminated signs. However, no comprehension or evacuation test was conducted using the flashing signs. McClintock et al. [6] proposed several signage designs with various forms of lighting added to standard illuminated signs, including flashing backlight, external flashing light etc. They presented the signage options simultaneously to recruited participants and asked them to score them in terms of conspicuousness. The results suggested that the most favourable option was the sign with external blue flashing light. However, the various signage options were placed above doors that were clearly labelled 'emergency exit'. Thus, the trial methodology did not attempt to measure the test subjects' intuitive comprehension and association of the signage option with an emergency exit in realistic conditions. Nilsson et al. [27] questioned the appropriateness of associating the blue light with emergency exit signs, as green is normally used to signal "go" or safety and proceeded to test several signage options with different coloured flashing lights. They concluded that a green light is more likely to be associated with an emergency exit by people. In addition, Nilsson et al. [28] tested exit signs and exits augmented with external green flashing lights and found that they stood out and attracted more participants than standard signs during evacuation trials.

The studies described above [6,26–28] explored various methods of improving the conspicuousness of emergency exit signs through either introducing flashing backlights or external lights with the appearance of the signs remaining largely unchanged. Galea et al. [13–15] proposed an alternative and unique signage design concept which integrated LEDs into the arrow symbol of the standard 'green running man' emergency exit sign. When activated during an emergency, the LEDs flash in sequence and create an animation of a running arrow, effectively incorporating two types of dynamism, flashing (temporal changes) and animation (spatial changes), into the sign. This design reinforces both the conspicuity of the sign and the indicated direction of travel. These research findings informed the development of a new dynamic signage design concept, known as Active Dynamic Signage System (ADSS) [13–15]. The ADSS enhances the sign's affordance, i.e. the perceived and actual properties of the object (e.g. the sign) suggesting how the object should be used [29]. The lit component is only activated during an emergency, while the main characteristics of the ADSS such as size, colour and format of information relayed remain unchanged, thus maintaining maximum compliance with existing signage regulations and standards [23–25,30,31]. A series of laboratory trials [13] were conducted following the same procedure as the previous trials [12] that utilised the conventional signs to quantify the effectiveness of the new ADSS. The study concluded that, when exposed to the ADSS, participants achieved a successful detection rate of up to 77%, constituting an improvement of just over 100%. Furthermore, 100% of the participants who detected the ADSS followed the guidance conveyed by the sign.

The potential improvement in evacuation efficiency offered by the ADSS compared with the conventional signage was also tested through a series of full-scale evacuation trials in a small railway station in Spain, utilising different test populations of up to 171 naïve participants at a time [14,15]. These trials further confirmed the findings of the laboratory-scale trials that the ADSS was effective in directing a large proportion of the trial population (up to 66%) to appropriate targeted exits that were not their intuitive choice.

Based on the understanding of the interaction with signage obtained from the research, a signage model [11,12,16–18] was implemented within the buildingEXODUS evacuation simulation software - an agent-based microsimulation evacuation model [32–34]. The signage model calculates the VCA of signs within the geometry, taking into account the type and size of the signs, the presence of obstacles and the height of viewers [11,16–18]. When an agent is located within the VCA of a sign, the likelihood of the agent seeing and following the sign is determined, using the signage detection and acceptance probabilities obtained through the trials [12,13]. This allows the user to examine the effectiveness of a signage system designed and placed within a wide range of different buildings [12,17].

The work presented in this paper is a first attempt to demonstrate and quantify, through simulation, the potential improvement in evacuation performance of large complex spaces that may be achieved using dynamic rather than conventional signs. In contrast to previously conducted experimental trials, the simulated scenarios make use of a much larger target population consisting of 900 agents in a larger and more complex environment of a real supermarket geometry with multiple main and emergency exits, some of which are obscured by internal obstacles. The scenarios investigate three different signage implementations and compare the theoretical evacuation efficiency achieved by the ADSS to that of conventional exit signs within the examined building layout.

2. The signage model within the building EXODUS evacuation model

The core software used in this study is buildingEXODUS V6.3, an agent-based evacuation model. The basis of the model has frequently been described in other publications [12,17,18,32–34] and so will not be repeated here. Similarly, the concept of the buildingEXODUS signage model has been described previously [11,12,16–18] and so is only briefly described here to put the simulation predictions into context. A fuller description of the signage model can be found in the Supplementary Material Section S1.

Each sign has a circular VCA specified by the position of the sign (height above the floor), the location and height of obstructions in the vicinity of the sign, the maximum termination distance which is dependent on the height of lettering or graphical symbols and the observer's viewing angle [11]. The latter is defined by resolving the relative orientation between the agent (given by their travel vector) and the sign (defined by the normal to the sign). Due to peripheral vision and the likelihood that the agent may move their head or eyes, as they walk, the exposure of the sign to the agent varies from the maximum exposure (observation probability = 1.0) to the minimum exposure (observation probability = 0.0) as the observation angle increases from 0° to 180°. Thus, when the agent is facing the sign (0° observation angle) the agent has the maximum chance of seeing the sign (observation probability = 1.0) while when their back is towards the sign (180° observation angle) they have zero chance of seeing the sign (observation probability = 0.0). In this work it is assumed that identical sized conventional and dynamic signs produce the same VCAs and the same observation probability distribution.

Finally, the probability that the sign will be detected and comprehended, and the instructions followed, by the agent, is set by two experimentally determined parameters. Previous experimental research has shown that in ideal conditions (0° observation angle, no physical obstructions, and no visual noise) there is a 38% probability that a conventional sign will be detected, and once detected, there is a 97% compliance rate [12]. Similar experimental research using dynamic signs under identical conditions suggests that the detection rate is 77% with a 100% compliance rate [13]. While these rates are based on the results of two laboratory studies and thus represent the signage detection and compliance probabilities measured under the corresponding experimental conditions, they are used in this study to represent the likelihood of agents detecting and following a sign when they are able to observe the sign within the modelled supermarket environment. Thus, they represent detection rates under relatively ideal conditions. In reality, the detection rate within the supermarket environment, for both types of signs, is likely to be less than that suggested by the trials due to the presence of competing and distracting visual noise (see discussion in the limitations section).

Given the above considerations, this study primarily examines evacuation performance influenced by varying the wayfinding information conveyed by the signage system. Other factors, such the presence of fire hazards, staff intervention, and group behaviour etc. that can also influence people's evacuation behaviours, are not considered (see discussion in the limitations section).

3. The case study

The impact of both conventional emergency exit signage and the ADSS on evacuation efficiency is explored using a real, large, single storey supermarket geometry. The supermarket, constructed in 1999 and originally located in Greenwich (UK), was demolished in 2015. The cases examined consider eight distinct evacuation scenarios. In the first two scenarios (Scenarios A and B), no signage system is used. In Scenario A it is assumed that all agents have knowledge of only the main exits while in Scenario B, they have knowledge of all exits. These two scenarios represent base case scenarios for the purpose of comparison. In the other six scenarios, various configurations of signs in terms of number, location, and nature (conventional or ADSS) are used to guide the agents to the available exits. It is assumed that in all examined signage scenarios the agents initially have knowledge of all the main exits. However, as the agents attempt to evacuate from the structure, moving initially towards the main exits, they may encounter the signage system. In this case, some agents will perceive and follow the signs, thereby becoming aware of the previously unknown emergency exits and may choose to use these exits to leave the structure. It is important to note that the analysis described in this paper makes no attempt to identify the minimum signage distribution required to comply with regulatory requirements.

3.1. The geometry and population

The supermarket geometry used in this study is illustrated in Fig. 1. The geometry contains an array of internal shelving, tills and a café in the southern part of the geometry with five primary escape routes: four towards the four emergency exits (D1, D2, D7, D8) on the two sides of geometry and the main escape route via four entrances/exits (D3, D4, D5, D6) on the south side of the building (see Fig. 1a). The width of all exits is 2.5 m. The unit flow of all exits is assumed to be the same and is set to 1.33 p/m/sec. The height of the internal features is shown in Fig. 2b. All the remaining features are assumed to be at ceiling height. The total available free area where the agents can manoeuvre is approximately 2927 m^2 (excluding the space occupied by the shelving and other furnishings).

The supermarket is populated with 900 agents placed randomly within the shop floor area amongst the three shelving unit regions (see Fig. 1b). The agents are assigned an arbitrarily short response time ranging from 0 s to 30 s. Their travel speeds are randomly distributed between 1.2 m/s and 1.5 m/s. Both elements are selected to create the basis of an evacuation scenario with reasonable level of representative evacuee behaviour. The relatively small range of response times and walking speeds are deliberately imposed on the simulation to enable the direct impact of the signage to be more readily discernible while maintaining realistic and natural behaviours to be exhibited by the agents as they navigate and egress from the structure.

3.2. Scenario description

The eight scenarios examined are listed in Table 1, each representing different agent behaviours or signage configurations. Scenarios A and B are base case scenarios, which do not make use of the signage functionality and limit the exit availability to the main exits or the nearest exits, respectively. Three signage configurations, with gradually improved VCA coverage, are examined in this work. The initial signage distribution consists of signs located above each of the exits (normal or emergency), a common practice prior to adding a structure's furnishings. Two incremental improvements in terms of number and distribution of signs are also examined. These improvements aim to further demonstrate the exit utilisation by increasing the overall VCA coverage while considering the present furnishings within the structure. More specifically, for Scenarios C and D, a sign has been placed directly above each of the exits. The locations of these signs are highlighted in Fig. 2 as sign cluster 1. For Scenarios E and F two additional clusters, each with four signs, have been added to the shop floor at two key cross-aisle locations. The locations of these signs are highlighted in Fig. 2 as sign cluster 2. For Scenarios G and H two additional clusters, each with two signs, have been added to the shop floor at two key locations. The locations of these signs are highlighted in Fig. 2 as sign cluster 3. Note that Scenarios E and F also include the signs present in Scenarios C and D, and similarly Scenarios G and H also include the signs present in Scenarios E and F. The use of three sets of different signage configurations is to examine the impact that the gradually expanding signage system has on evacuation efficiency.

All the conventional and dynamic signs used in the scenarios are 10 cm in height and 30 cm in width, the same dimensions as the signs used in the laboratory trials [12,13] in which the detection and compliance probabilities were measured. The maximum viewing distance normal to the signs is calculated from the height of the graphical symbol on the sign (the green running man), i.e., 75 mm, multiplied by the appropriate distance factor [23,24]. For this study, the appropriate distance factor for calculating the viewing distance for externally illuminated escape route signs with vertical illumination of ≥400 lux at the sign is 200. This results in a maximum viewing distance of 15 m. However, given that standards employ an implicit safety factor of 2.0 when specifying distance factors [11,35], the signs used in this study can effectively be seen within a maximum distance of 30 m, by people with visual acuity of 1.0,

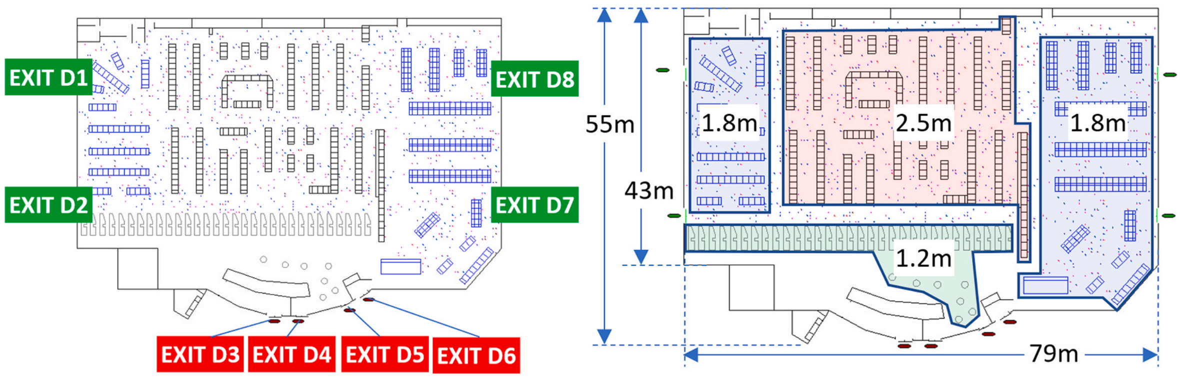
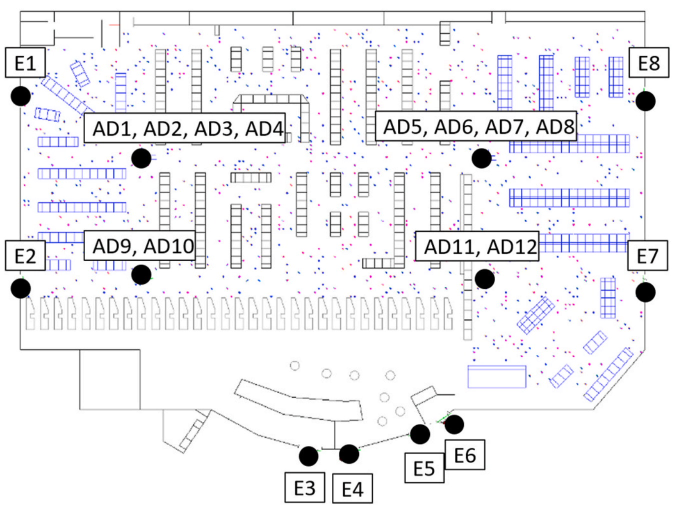


Fig. 1. The modelled supermarket layout, (a) showing the locations of the exits and shelving and (b) indicating the height of the various internal features and their size.



Sign cluster					
1		2		3	
Sign	Target exit	Sign	Target exit	Sign	Target exit
E1	D1	AD1	D1	AD9	E2
E2	D2	AD2	D3	AD10	E2
E3	D3	AD3	D2	AD11	E7
E4	D4	AD4	D1	AD12	E7
E5	D5	AD5	D5		
E6	D6	AD6	D8		
E7	D7	AD7	D7		
E8	D8	AD8	D8		

Fig. 2. Only cluster 1 signs are present in scenarios C and D. Cluster 1 and 2 signs are present in Scenarios E and F. Cluster 1, 2 and 3 signs are present in Scenarios G and H.

observed normal to the signs. Therefore, in this study the signs are assumed to have a VCA with a maximum termination distance of 30 m excluding the safety factor. All exit signage considered in this study is assumed to be mounted at a height of 2.2 m from floor level following the recommendation in Ref. [25]. The height of the sign, shelving and furnishings is considered when calculating the VCA of each sign.

The overall VCA coverage that is afforded by the three signage system configurations, i.e. for Scenarios C/D, E/F and G/H, are presented in Supplementary Material Section S2.

3.3. The simulations

Each scenario was run 100 times to take into consideration the natural stochastic variation within each simulation. Furthermore, for each simulation run, the population was randomly generated within the shopping area before the tills (see Fig. 1b). While the population for each simulation falls within a specific demographic profile, each time it is generated, new values are drawn from set ranges for the agents' physical and psychological characteristics. Also, their initial distribution within the populated zone varies each time the population is generated. Interaction with signage is especially sensitive to the agents' location and the direction they are facing. This is to reduce the influence that the agents' characteristics or location in the supermarket have on the outcome of the evacuation process. In the next section the simulation results produced by the eight scenarios are presented.

4. The results and discussion

Several simulation parameters that are used throughout the discussion of the simulation results are described below to aid in the interpretation of the scenario outcomes.

- **Total Evacuation Time** (TET) (seconds) is the predicted total evacuation time for the scenario, it represents the time for the last agent to exit the geometry.
- **Person Evacuation Time** (PET) (seconds) is the time for an individual agent to exit the geometry.
- **Distance Travelled** (D) (metres) is the distance travelled by an agent from their starting location to their point of exit.
- **Cumulative Wait Time** (CWT) (seconds) is a measure of the total time an agent is forced to travel at a speed less than their desired speed (maximum walk speed), including periods during which they are forced to wait in a queue, measured from after their response time has elapsed to the point of their exit. The CWT is therefore a measure of the overall congestion experienced by the agent during their evacuation. The greater the CWT, the greater the congestion experienced by the agent during the evacuation and so the less efficient is the evacuation for that agent.
- **Personal Evacuation Efficiency** (PEE) (%) is defined as (1 - CWT/PET) x100. It represents the complement of the proportion of the personal evacuation time for an agent wasted in congestion. A PEE of 100% suggests that the agent wasted no time in congestion, while a

Table 1
The examined evacuation scenarios.

Scenario	Description	Signage type
A	**Main exit:** A base case scenario with no utilisation of signage, agents are aware of only the main exits (D3, D4, D5, D6) and so only utilise these during the evacuation.	NA
B	**Nearest exit:** An ideal scenario in which all agents are aware of all exits and so utilise their nearest exit during the evacuation.	NA
C	**Conventional exit signage above exits (signage cluster 1 in Fig. 2):** Emergency exit signs are placed above each exit (signs in cluster 1 in Fig. 2). While initially agents are only aware of the main exits, during the evacuation, if they detect a sign above an emergency exit, they may choose to use that exit.	Conventional
D	**Dynamic exit signage above exits (signage cluster 1 in Fig. 2):** As Scenario C however, the conventional signs are replaced with dynamic signs.	Dynamic
E	**Conventional exit and floor signage (signage cluster 1 and 2 in Fig. 2):** As Scenario C with two clusters of four signs added to the shop floor at two key cross-aisle locations (signs in cluster 2 in Fig. 2).	Conventional
F	**Dynamic exit and floor signage (signage cluster 1 and 2 in Fig. 2):** As Scenario E however, the conventional signs are replaced with dynamic signs.	Dynamic
G	**Conventional exit and floor signage (signage cluster 1, 2 and 3 in Fig. 2):** As Scenario E with two clusters of two signs added to the shop floor at two key locations (signs in cluster 3 in Fig. 2).	Conventional
H	**Dynamic exit and floor signage (signage cluster 1, 2 and 3 in Fig. 2):** As Scenario G however, the conventional signs are replaced with dynamic signs.	Dynamic

PEE of 50% suggest that half of the agent's PET was spent caught in congestion. Clearly, the larger the PEE the more effective is the individual agent's evacuation.

- **Evacuation Efficiency** (EE) (%) is the average PEE for a simulation and represents the average PEE for the 900 agents.

As each scenario is repeated 100 times, an average of the TET, PET, D, CWT, and EE over all 100 simulations is produced to reduce the impact of stochastic variations associated with agent starting locations.

4.1. The base (Scenario A) and ideal (Scenario B) scenarios

The first case examined is the base case, Scenario A. In this scenario it is assumed that the agents only make use of the main exits, through which they entered the geometry and hence are most familiar with. As a result, it represents a case without the utilisation of signage and so represents the worst case. This is a credible worst case as it is well known that in real incidents people tend to use familiar routes and are generally reluctant in using unknown emergency exits, preferring to utilise familiar exits to leave a structure [5,36–38]. When compared to the other scenarios, Scenario A is expected to produce the longest evacuation times, the most unbalanced exit use (only half the exits are used), highest congestion and longest travelled distances (see Table 2).

Table 2
Achieved TET, PET, CWT, Distance travelled for all scenarios.

Scenario	Average TET (s) (SD)	Average PET (s) (SD)	Average CWT (s) (SD)	Average Distance (m) (SD)
A	173.0 (5.5)	83.5 (1.4)	24.9 (1.0)	55.0 (0.7)
B	99.4 (3.6)	45.3 (0.9)	9.4 (0.7)	25.4 (0.5)
C	164.4 (5.3)	78.2 (1.3)	21.6 (0.9)	52.4 (0.6)
D	153.4 (5.4)	71.9 (1.4)	17.7 (1.0)	49.3 (0.6)
E	146.1 (5.1)	68.8 (1.2)	15.9 (0.9)	47.5 (0.5)
F	125.9 (4.8)	59.7 (0.9)	11.0 (0.7)	42.3 (0.5)
G	126.9 (5.1)	61.5 (1.1)	11.5 (0.8)	43.9 (0.5)
H	104.3 (4.4)	53.4 (0.8)	7.4 (0.5)	38.8 (0.6)

In contrast to the worst-case scenario is Scenario B, an ideal case in which it is assumed that all the agents are fully aware of all the exits and know which is their closest. As a result, agents utilise their nearest exit. While, in reality, some occupants may be familiar with the emergency exits, it is highly unlikely that they all will be familiar with all exits, and at the same time be able to utilise the shortest paths to exit the structure [5,36–38]. This scenario will produce the shortest travel distances and potentially the shortest evacuation times and the least amount of congestion (see Tables 2 and 3). The results from Scenario A and B form a basis for comparison with the signage scenarios.

In comparing Scenario B with Scenario A, we note that all the main evacuation parameters have improved significantly, the average TET for Scenario B decreased by 43% (173 s to 99.4 s); PET decreased by 46% (83.5 s to 45.3 s); CWT decreased by 63% (24.9 s to 9.4 s) and distance travelled decreased by 54% (55.0 m to 25.4 m). The reason for the significant improvement in evacuation efficiency is due to the better usage of all available exits. Nevertheless, Scenario B produces an unbalanced exit usage as most of the agents use the emergency exits as these are closer to their starting locations. As a result, the main exits (D3, D4, D5 and D6) are underutilised while exits D1 and D8 are heavily used.

While Scenario A has elements of realistic and observed behaviours it constitutes a worst-case scenario. The actual evacuation performance of the supermarket is likely to be better than this, as the scenario does not consider procedural measures such as interaction with staff and signage. Scenario A therefore represents an upper limit on the expected evacuation performance. In contrast, Scenario B represents an ideal evacuation performance in which all agents exit via their nearest exit. Scenario B therefore represents a lower limit on the expected evacuation performance, despite the significantly skewed exit usage. However, while ideal it is unrealistic as it assumes perfect exit and layout knowledge by all agents. In reality, the expected evacuation performance for the supermarket is likely to be between these two extremes and it could be argued, more likely closer to Scenario A than Scenario B.

The average egress curves for Scenario A and B are presented in Fig. 3. This presents the average number of agents to exit at each specific time (over the 100 repeat simulations) for each scenario. The curves thus define an envelope of evacuation performance, with the actual evacuation curve (i.e., real evacuation) most likely falling between the two extremes. Furthermore, it is expected that the results for the other simulated scenarios to also fall between these two extremes.

4.2. Conventional signage scenarios (scenarios C, E and G)

In Scenarios C, E and G the number and distribution of conventional exit signs, and therefore the VCA coverage, are gradually increased in an attempt to improve the evacuation performance achieved in the base case, Scenario A. Increasing the VCA coverage is intended to increase the likelihood that the agents will be able to physically 'see' a sign and thereby follow the information it relays by moving towards a newly discovered emergency exit. The intent is to improve the evacuation efficiency of the structure (approaching that of Scenario B) while using a minimum number of signs.

In Scenario C, the conventional exit signs are only placed above each exit (see Fig. 2, sign cluster 1). The exit signs above the emergency exits offers a VCA coverage of 44% of the free floor space. However, of greater significance is that most agents intersect the VCA such that they have a large viewing angle to these signs (effectively walking near parallel to the signs' face), decreasing the probability that a sign will be within their field of view (and hence they are not able to physically 'see' the sign) as they make their way to the known main exits.

Example paths that demonstrate the behaviour of seven selected agents in Scenario C are presented and discussed in Supplementary Material Section S3. The analysis shows that the conventional emergency exit signs in Scenario C do not cover sufficient floor area and are placed in locations which tend to result in large viewing angles. These

Table 3
Average evacuation performance of Conventional (Scenario G) and Dynamic (Scenario H) signage compared with the Ideal scenario (Scenario B).

Simulation parameters	Ideal (Scenario B)	Conventional (Scenario G)	Dynamic (Scenario H)	% Diff btw Conventional and Ideal	% Diff btw Dynamic and Ideal	% Improvement Dynamic over Conventional
TET	99.4 s	126.9 s	104.3 s	27.6%	4.9%	17.8%
PET	45.3 s	61.5 s	53.4 s	35.7%	17.9%	13.1%
CWT	9.4 s	11.5 s	7.4 s	22.3%	−21.3%	35.7%
D	25.4 m	43.9 m	38.8 m	72.8%	52.8%	11.6%
EE	84%	85%	89%	1.2%	5.9%	4.7%

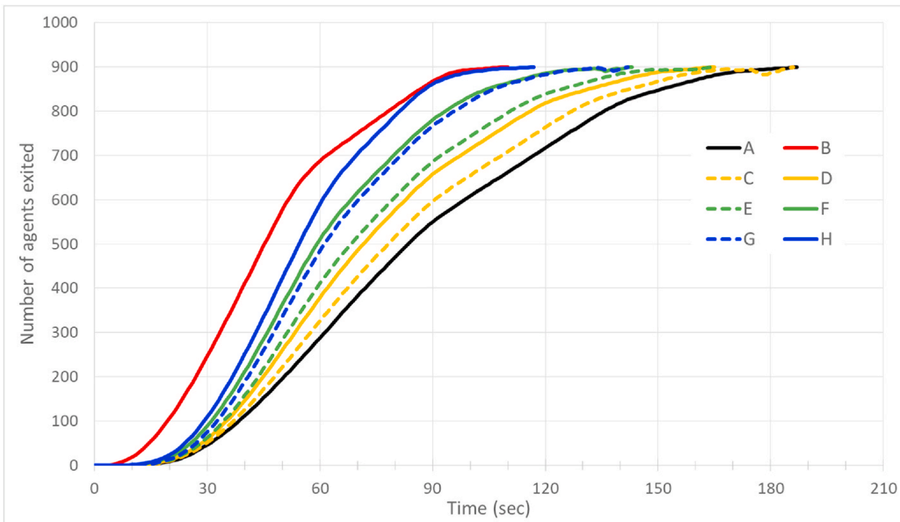


Fig. 3. Predicted evacuation performance showing the average number of agents to exit the structure over time for Scenarios A to H (dashed curves represent scenarios with conventional signs).

factors combined with the conventional signs' low detection probability result in only marginal improvements in evacuation performance compared to Scenario A. This is reflected in the modest improvement in TET (4.9% or 8.6 s), PET (6.3% or 5.3 s), CWT (13.3% or 3.3 s) and D (4.7% or 2.6 m) for Scenario C compared to Scenario A (see Table 2). This is further demonstrated by the average evacuation curve for Scenario C which is very close to that for Scenario A (see Fig. 3).

To address these deficiencies eight additional signs are introduced in Scenario E. These are positioned in two clusters of four at two key cross-aisle locations (see Fig. 2, sign cluster 2). Their purpose is twofold, first to increase the floor area covered by the VCA of the emergency signs and second to decrease the viewing angle for agents travelling from the back to the front and from left to right or right to left. The VCA floor coverage achieved by adding the two clusters of signs in Scenario E is 53% (VCA coverage of signs E1, E2, E7, E8, AD1 to AD8) compared to the previous coverage in Scenario C of 44% (VCA coverage of signs E1, E2, E7 and E8). The increase is not as large as may have been expected due to significant overlap of the VCA regions. However, the additional signage also provides greater opportunities for agents who enter the VCA to have a smaller viewing angle thereby increasing the probability that the sign will be physically 'seen' and hence increasing the overall signage detection probability. As a result, the enhanced signage coverage improves the overall evacuation efficiency and results in a further reduction in predicted evacuation times. This is reflected in the improvement in TET (15.5% or 26.9 s), PET (17.6% or 14.7 s), CWT (36.1% or 9 s) and D (13.6% or 7.5 m) for Scenario E compared to Scenario A (see Table 2). This is further demonstrated by the average evacuation curve for Scenario E which has moved closer to that for Scenario B (see Fig. 3).

However, many agents still failed to detect an exit sign and make use of an emergency exit. This is due to several factors; first conventional signs have a small detection probability even when viewed straight on. Secondly, while some agents may enter the VCA they did so for only a short period of time before they pass out of the VCA of the sign or increase their viewing angle. Thirdly, as some agents cross the VCA of the additional signs they are travelling almost parallel to the surface of the signs and so had a relatively large viewing angle (around 90°) and therefore low observation probability. Given the paths that these agents follow, they have a small window of opportunity to detect a sign.

To address the deficiencies identified in Scenario E, four additional emergency exit signs are introduced in Scenario G. These are positioned in two clusters of two at two key locations (see Fig. 2, sign cluster 3). The purpose of these signs is to "capture" agents that have progressed further away from the signs added in Scenario E, located at the top half of the geometry, and direct these agents to the two emergency exits located towards the front of the store (exits D2 and D7).

The VCA floor coverage achieved by adding the two clusters of two signs in Scenario G is 57% (VCA coverage of signs E1, E2, E7, E8, AD1 to AD12) compared to the previous coverage in Scenario E of 53% (VCA coverage of signs E1, E2, E7, E8, AD1 to AD8). The modest increase in VCA is again due to the significant overlap of the VCA regions. However, the additional signage provides even greater opportunities for agents who enter the VCA to achieve a small viewing angle for a greater period of time thereby increasing the likelihood of signage detection. As a result, the enhanced signage coverage improves the overall evacuation efficiency and results in a further reduction in predicted evacuation times. This is reflected in the improvement in TET (26.6% or 46 s), PET (26.3% or 22 s), CWT (53.8% or 13.4 s) and D (20.2% or 11.1 m) for Scenario G compared to Scenario A (see Table 2). Nevertheless, some agents still fail to detect an exit sign and so exit via the main exits.

As the number of conventional signs increase and hence the proportion of the free floor space covered by the signs' VCA, the predicted evacuation times (TET) decreases. Compared to the case with no signs (where everyone exits by the main entrances, Scenario A), adding conventional signs above each exit (eight signs, Scenario C) reduces the TET by 4.9% (or 8.6 s), including another eight strategically located signs (16 in total, Scenario E) reduces the TET by 15.5% (or 26.9 s) and including another four strategically located signs (20 in total, Scenario G) reduces the TET by 26.6% (or 46.1 s). The improvement in evacuation performance can be seen in Fig. 3, where the average evacuation curves for Scenarios C, E and G progressively move closer to that for the ideal case, Scenario B. However, the performance achieved in Scenario G is a long way short of the ideal, albeit unrealistic performance of Scenario B, which represents a 42.5% (73.6 s) reduction in TET. It is also noted that the average CWT achieved in the signage scenarios decreases with the increase in the number of emergency exit signs. This is due to the increase in the number of agents utilising the emergency exits, thus reducing congestion at the utilised exits. The average CWT in Scenario G is 11.5 s compared to 24.9 s in Scenario A, a reduction of 53.8% (13.4 s). However, in Scenario B, the average CWT is only 9.4 s representing a reduction of 62.2% (15.5 s) compared to Scenario A. This suggests that the exit usage in Scenario B is more optimal than in Scenario G and so some further improvement in the usage of the emergency exits is possible.

4.3. Dynamic signage scenarios (scenarios D, F and H)

One way of improving evacuation performance is to continue to add more emergency exit signs. This would have multiple benefits including, further increasing the VCA coverage and increasing the frequency and duration of exposure to signage. While this will increase the likelihood that a sign will be ‘seen’, these improvements do not address the key failing of conventional signage systems, i.e., their low detection probability. Thus, adding more conventional signs while gradually improving signage detection and hence exit usage, will significantly increase the cost of the system, and potentially provide an undesirable outcome of overloading the environment with emergency signage. The signs could also be increased in size, and consequently increasing the VCA coverage, which is likely to also increase the detection probability. However, the authors suggest that in many cases, building owners are likely to prefer to use the least number of the smallest signs that can be deemed to comply with guidelines or regulations.

An alternative is to utilise a more effective signage system that has a better detection rate such as the ADSS. To gauge the impact of dynamic signs, the previously examined signage Scenarios C, E and G are re-examined using the same assumptions but with dynamic signs replacing the conventional signs.

In Scenario D, dynamic signs are placed directly above each exit, replacing the conventional signs in Scenario C (see Fig. 2, sign cluster 1). The behaviour of agents in this scenario is similar to that observed in Scenario C (see Supplementary Material Section S3). As in Scenario C, the VCA of the dynamic exit signs in Scenario D do not cover sufficient floor area and are placed in locations (above the exits) which tend to create a large viewing angle. These negative factors are more significant than the improved detection probability of the dynamic signs, resulting in modest improvements in evacuation performance compared to Scenario A. This is reflected in the small improvement in TET (11.3% or 19.6 s), PET (13.9% or 11.6 s), CWT (28.9% or 7.2 s) and D (10.4% or 5.7 m) for Scenario D compared to Scenario A (see Table 2).

In Scenario F, dynamic signs replace the conventional signs of Scenario E (see Fig. 2, sign cluster 2). The VCA floor coverage achieved by the signs in Scenario F is the same as in Scenario E, i.e., 53% (VCA coverage of signs E1, E2, E7, E8, AD1 to AD8). As well as increasing the floor area covered by the VCA of an exit sign, the additional signage provides greater opportunities for agents who enter the VCA of a sign to have a smaller viewing angle and better detection probability thereby increasing the overall likelihood that the sign will be physically ‘seen’ and detected. As a result, the enhanced signage coverage improves the overall evacuation efficiency and results in a further reduction in predicted evacuation times. This is reflected in the improvement in TET (27.2% or 47.1 s), PET (28.5% or 23.8 s), CWT (55.8% or 13.9 s) and D (23.1% or 12.7 m) for Scenario F compared to Scenario A (see Table 2).

Within the simulation, many more agents are now able to detect the signs (due to the increased detection rate associated with the dynamic nature of the signs) and choose to redirect to emergency exits. Nevertheless, some agents still fail to detect an exit sign and make use of an emergency exit due to the same reasons identified when analysing the results of Scenario E (see Section 4.2). Furthermore, while the detection probability for dynamic signs is high, it is not 100% and so there is still a chance (23%) that some will not perceive a dynamic sign.

To address the identified deficiencies in Scenario F, four additional dynamic emergency exit signs are introduced in Scenario H. As in Scenario G, these are positioned in two clusters of two at two key locations (see Fig. 2, sign cluster 3), their purpose is to “capture” agents that have passed by the additional signage clusters introduced in Scenario F and direct these agents to the two emergency exits located towards the front of the store (exits D2 and D7).

As described in Scenario G, the VCA floor coverage is increased from 53% to 57%, the modest increase in VCA being due to a significant overlap of the VCA regions. However, the additional signage provides even greater opportunities for agents who enter the VCA of a sign to achieve a small viewing angle for a greater period of time thereby increasing the likelihood of signage detection. As a result, the enhanced signage coverage improves the overall evacuation efficiency and results in a further reduction in predicted evacuation times. This is reflected in the improvement in TET (39.7% or 68.7 s), PET (36% or 30.1 s), CWT (70.3% or 17.5 s) and D (29.5% or 16.2 m) for Scenario H compared to Scenario A (see Table 2). While some agents still fail to detect an exit sign, and therefore fail to make use of an emergency exit, a number of additional agents now detect one of the additional signs in Scenario H and thus manage to evacuate via one of the emergency exits.

As with the scenarios involving conventional signs (Scenarios C, E, G), as the number of dynamic signs increase through Scenarios D, F, H (and hence the proportion of the free floor space covered by the VCA), the TET decreases. Compared to Scenario A where everyone exits by the main entrances, adding eight dynamic signs in Scenario D above each exit reduces the TET by 11.3% (or 19.6 s), including another eight strategically located signs (16 in total, Scenario F) reduces the TET by 27.2% (or 47.1 s) and finally, including another four strategically located signs (20 in total, Scenario H) reduces the TET by 39.7% (or 68.7 s). Furthermore, the performance of Scenario H is also very close to the ideal, albeit unrealistic performance of Scenario B, producing a TET only 4.7% (or 4.9 s) greater than the TET of Scenario B (see Fig. 3).

The trend in average CWT are also similar to those scenarios involving conventional signs. As the number of emergency signs increases, the average CWT decreases. This is due to the increase in the number of agents utilising the emergency exits, thus reducing overall congestion during egress. The average CWT in Scenario H is 7.4 s compared to 24.9 s in Scenario A, a reduction of 70.2% (17.5 s). Furthermore, the average CWT produced in Scenario H is 21.3% (2 s) less than that in Scenario B. This suggests that the exit usage in Scenario H is more optimal than in Scenario B. However, agents travel an average of 38.8 m to exit in Scenario H compared to 25.4 m in Scenario B. Thus, agents in Scenario H travel 52.8% (13.4 m) further and hence take longer on average to exit, with their PET being 17.9% (8.1 s) more than in the optimal scenario, despite wasting 21.2% less time in congestion. A summary of these results is presented in Table 2.

4.4. Comparing the performance achieved by conventional and dynamic signs

Experimental analysis has demonstrated that dynamic signs have a significantly greater affordance than conventional emergency exit signs. In this section, the improvement that dynamic signs offer, over conventional signs, on evacuation performance, within a complex built environment, is examined through the two most optimal simulated scenarios, G and H that utilise the two types of signs, respectively.

From the analysis in Section 4.2 and 4.3 it is evident that the emergency exit signage can favourably impact evacuation performance, and that the number and positioning of emergency exit signs are important influencing factors in determining evacuation efficiency. While it is obviously important to have exit signs located above each exit point, in large complex spaces where occupants may not be familiar with the layout and where obstructions may limit the visibility of signs, these alone are insufficient to attract occupants located far from the emergency exits. The most efficient signage Scenarios investigaed (G and H), involved 20 signs, with 8 signs located above the emergency and normal exits and 12 signs strategically located within the floor space. Scenario G involved conventional signs while Scenario H involved dynamic signs.

The average exit curves for Scenarios A, B, G and H, generated from the 100 repeat simulations, can be seen in Fig. 3. As stated in Section 4.1, Scenario A and Scenario B define an envelope of evacuation performance, of which the evacuation curves for Scenario G and H fall between these two extremes. As can be seen the entire exit curve for Scenario H is shifted to the left of the curve for Scenario G, and so is considerably closer to the ideal case (Scenario B), suggesting that the evacuation using the dynamic signs is not only faster but also closer to the ideal case than the evacuation using the conventional signs. Significantly, it is not only the TET in Scenario H that is less than that for Scenario G, but the time for each agent to evacuate. This means that the entire evacuation process using the dynamic signs is more efficient, requiring less time than the evacuation using conventional signs. This is seen more clearly by examining the PET frequency distribution for Scenarios A, B, G and H (see Fig. 4). As can be seen, the PET distribution for Scenario H closely resembles that for Scenario B and demonstrates that a higher proportion of agents in Scenario H have shorter evacuation times than those in Scenario G. Furthermore, for Scenario A (worst case), the median PET is 78 s (50% of the population have a PET less than 78 s) while for Scenario B (ideal case), the median PET is 42 s. When the dynamic signs are used (in Scenario H), the median PET is 52 s while in contrast when conventional signs are used (in Scenario G) the median PET is 58 s. Thus, in these scenarios the dynamic signs tend to result in lower personal evacuation times for the population than conventional signs.

Presented in Table 3 is a summary of the main findings of the cross comparison between the conventional signage (Scenario G), the dynamic signage (Scenario H) and the ideal scenario (Scenaro B). The identified evacuation performance is averaged over 100 repeat simulations. Compared to the conventional signage, the dynamic signage offers a 17.8% (22.6 s) reduction in average total evacuation times, a 13.1% (8.1 s) reduction in average personal evacuation times, a 35.7% (4.1 s) reduction in average time wasted in congestion, a 11.6% (5.1 m) reduction in average distance travelled and a 4.7% improvement in evacuation efficiency (from 85% to 89%). In terms of overall performance, the average total evacuation time achieved using the dynamic signs is only 4.9% (4.9 s) greater than that achieved in the ideal case while the average personal evacuation time is only 17.9% (8.1 s) greater. With the exception of the average distance travelled, the evacuation performance achieved using the dynamic signage system is close to ideal. Not only does the dynamic signage offer an appreciable improvement in evacuation performance over that achieved by the conventional signs, the differences in the key simulation parameters between the conventional (Scenario G) and dynamic (Scenario H) signage were also found to be statistically significant. Using two independent sample T-test (Pooled), the differences in all the simulation parameters for the two scenarios were found to be statistically significant at $p < .01$ ($p < .00001$).

It is noted that the EE (evacuation efficiency) for Scenario G (conventional signs) is 85% while for Scenario H it is 89%. Not only is the EE for Scenario H better than that for Scenario G, but it is also better than the EE generated by Scenario B (ideal scenario) (84%). Indeed, in Scenario H, 70% of the population have a PEE greater than 85%, while in Scenario G this falls to 57% and in Scenario B it is only 54%. The higher proportion of agents with high PEE in Scenario H is a result of reduced congestion at the exits for this scenario. This suggests that the dynamic signs in Scenario H result in the least amount of time wasted in congestion and is even considerably better than the ideal scenario. To explain the EE results, consider the exit usage for Scenarios B, G and H. In Scenario B agents make use of their nearest exits. As all the agents start the simulation on the shop floor side of the tills, most agents will make use of the emergency exits (D1, D2, D7 and D8), with exits D1 and D8 being most heavily used 29% and 26% agent exit usage, respectively.

Thus, while agents in Scenario B experience the shortest travel distances, they incur significant congestion, especially as they attempt to use the most heavily used exits D1 and D8 and hence the low PEE. In contrast, in Scenarios G and H, most agents make use of the main exits i. e. D3, D4, D5 and D6, with 76% of the agents using these exits in Scenario G and 62% in Scenario H. However, as agents using the main exits are travelling from all over the geometry, even from the opposite end of the geometry, this staggers their approach to the main exits reducing the levels of congestion that would otherwise have been experienced at these exits. As a result, the average CWT experienced in Scenario H (dynamic signs) is less than that experienced in Scenario B which in turn produces better PEEs. This also explains why the average distance travelled in Scenarios G (43.9 m) and H (38.8 m) are 72.8% and 52.8% greater than those in Scenario B (25.4 m), respectively. However, the average distance travelled in Scenario H are 11.6% shorter than those in Scenario G because the dynamic signs are more effective than the

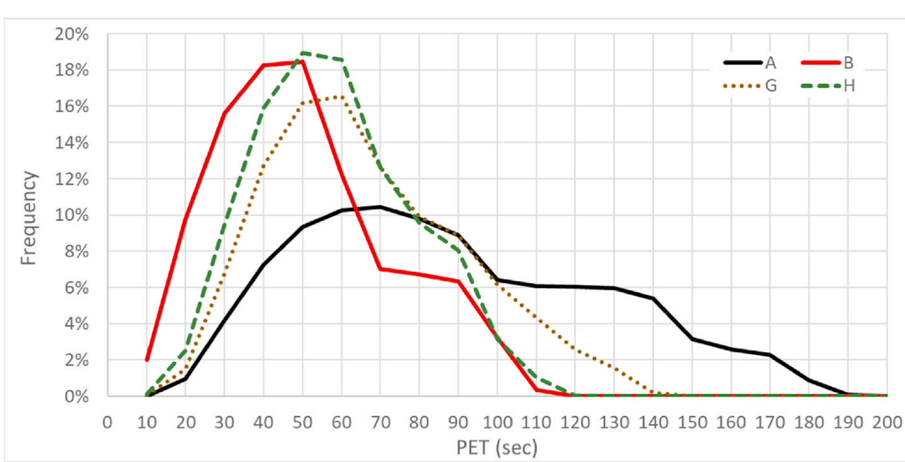


Fig. 4. Average PET distributions for Scenarios A, B, G, H over 100 simulations.

conventional signs in redirecting the agents to the emergency exits.

As with any modelling analysis, the findings and general conclusions derived from this study are subject to the identified scenario specifications and modelling limitations (see Section 4.5). It also remains to be seen if similar levels of enhanced evacuation performance could be achieved in reality by conducting full-scale unannounced evacuation trials in similar large complex spaces. Furthermore, while the findings and general conclusions derived from this study apply to the specific supermarket layout studied in this paper, the nature of the geometry, its size, layout, arrangement and size of internal obstacles, location and number of exits, is representative of this general type of building. Thus, while it remains to be demonstrated that dynamic signage could achieve similar evacuation performance enhancements in buildings with similar layouts and constraints, the authors hypothesise that it is reasonable to assume that some level of enhanced evacuation performance would be expected.

4.5. Analysis limitations

There are a number of limitations associated with this work which should be considered when reviewing the results. The primary intention of these simulations was to explore the potential impact that signage can have on evacuation performance and so complicating and competing factors such as the presence of staff, group behaviour or the impact of smoke were deliberately excluded. The analysis thus focused on the impact of number, location, and type of signs on evacuation performance. The following limitations are identified and discussed:

1. The detection rates used for both types of sign were not collected within a supermarket geometry but under ideal laboratory conditions. However, there is some evidence supporting the use of these values [5,6,14,15]. The low detection rate used to represent conventional signage, in particular within a retail environment, is supported by Refs. [5,6]. In Ref. [5] Shields et al. undertook unannounced evacuation trials from four retail premises. One of the retail premises (Marks & Spencer Culverhouse Cross store) involved a large single floor retail space in which there was minimal staff intervention in directing 409 customers to exits – only 13.4% of customers reporting their exit choice was influenced by a staff member. In this evacuation, which closely resembles the scenario and environment used in the present study, only 15.5% of customers utilised emergency exits. Furthermore, in a survey study concerning evacuation from retail premises [6], only 18% of surveyed shoppers could recall seeing an emergency exit in the retail store they had just exited and, when presented with a store diagram, only 25% could mark the location of at least one emergency exit. These numbers are consistent with the detection rate for conventional signs of 38% used in this study. The detection rate for the ADSS (77%) is also supported by full-scale evacuation trials conducted in a railway station [14,15], in which up to 66% of participants were successfully redirected to remote emergency exits through the use of the ADSS.
2. Group behaviour is not considered in the simulations. Individuals within a crowd may follow others to an emergency exit that they are unaware of, thereby increasing the number of people using the emergency exits. Similarly, they may follow individuals who have bypassed an emergency exit while others may simply ignore the movement of the crowd [14,39,40]. Thus, the impact of crowd behaviour on exit usage is complex. However, the high shelving bays within the simulated physical environment reduce visual access and the likelihood that agents located throughout the bulk of the store will be able to observe and hence follow much exiting behaviour.
3. Occupants within a supermarket are likely to be carrying baskets or pushing shopping carts. The movement of these occupants is likely to be slower than if unencumbered however, this aspect has not been included within this analysis. This expected reduction in travel speeds would have impacted all the scenarios equally and so the comparative analysis should not be impacted. However, by excluding these behaviours, the absolute predicted evacuation times may be underestimated.
4. The response time data used in the analysis is not based on real data but is arbitrary and extends from 0 s to a maximum of 30 s. The purpose of the response time data was to ensure that not all agents started the evacuation at the same time but did so in a staggered way, consistent with established expectations. In reality, it is possible that some occupants may take slightly longer to react than represented in these simulations however, the difference is not expected to be significant (e.g., in four announced drills within Marks and Spencer retail premises in the UK, mean response times of 25 s, 25 s, 30 s and 37 s were recorded [41]). However, this will have impacted all the scenarios equally and so the comparative analysis should not be impacted.

5. Conclusions

This work has employed agent-based evacuation modelling to explore the potential impact of emergency exit signage on evacuation efficiency in a complex geometry. The geometry selected for analysis consisted of a real supermarket with four main exits, four emergency exits, and a number of high bay shelving units typically found within supermarkets. The layout of the supermarket was challenging as the shelving units significantly reduced the visual access of agents to emergency exits. As a result, signage is required to direct agents to unfamiliar emergency exits, otherwise the agents would naturally attempt to exit via the known exits, i.e. the main exits. As with any modelling analysis, the findings and general conclusions derived from this study are subject to the identified scenario specifications and modelling limitations. It also remains to be demonstrated that similar evacuation performance enhancements may be achievable in buildings with similar layouts and constraints.

The simulation results are complex with incremental improvements in terms of the number of signs used, their location and the type of sign used (conventional or dynamic) resulting in improvements in overall evacuation performance. The main findings of the simulation results relating to the supermarket geometry can be summarised as follows:

- Locating exit signs (conventional or dynamic) only above the emergency exits (located on the side walls) has limited impact on evacuation performance (reducing evacuation times by only 5% and 11%, respectively) as visual access is severally compromised by the high bay shelving throughout the store. Furthermore, the predominant movement of the agents will be towards the main exits located in the front of the store. As a result, the movement of the population will be predominately parallel to the signs producing large observation angles resulting in low likelihood that signs will be visible.
- Evacuation performance improves as the number of conventional signs deployed increases. However, evacuation performance is not only dependent on the number of signs, but on their strategic positioning. According to the model assumptions and with the number of signs deployed increased from eight at two strategic locations to 12 at four strategic locations, the evacuation time is decreased by 16% and 27%, respectively. If the conventional signs are replaced by dynamic signs, evacuation performance improves further, with evacuation times decreased by 27% and 40%, respectively. The improvement in evacuation performance with the number and location of signs is due to the increase in the proportion of the floor space covered by the signs' VCA and increasing the chance of agents experiencing small observation angles when encountering a sign. Both of which increase the likelihood that signs will be physically visible to the agents. The better performance of dynamic compared to conventional signs in these simulations is due to their higher detection rate, 77% compared to 38% for conventional signs as determined through laboratory studies.

- The most significant level of improvement in evacuation performance was achieved by replacing the conventional signs with dynamic signs. Under the model assumptions, compared to conventional signage, dynamic signage was shown to reduce total egress times by 18%, congestion by 36% and travel distances by 12%. Furthermore, the system of dynamic signs resulted in an evacuation time that was only 5% greater than the ideal scenario in which all agents are assumed to know the location of all the exits and so utilise their nearest exit.

The significance of this modelling analysis is three-fold:

- It supports the premise that it is not only the number but the strategic positioning of emergency exit signs that is required to reduce evacuation times in a structure with a complex internal layout.
- It quantifies the potential advantage of dynamic signs over conventional signs for the identified structure with complex layout,
- It presents an iterative and incremental modelling methodology to assess the required number and positioning of emergency exit signage within complex spaces to achieve desired evacuation performance.

Finally, it is suggested that the proposed modelling methodology enables engineers to rationally plan the signage system layout in complex spaces and determine the likely impact that signage will have on the evacuation performance. This in turn allows engineers to provide an improved estimate of the likely lower limit of evacuation performance rather than simply assuming this is defined using the unrealistic and over optimistic assumption that nearest exits will be used.

CRediT authorship contribution statement

Lazaros Filippidis: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Hui Xie:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Edwin R. Galea:** Conceptualization, Funding acquisition, Supervision, Methodology, Writing – review & editing. **Peter J. Lawrence:** Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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