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MICROSCOPIC DYNAMICS OF PEDESTRIAN EVACUATION IN HYPERMARKET

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ABSTRACT

Numerous evacuation models are developed since decade ago in order to offer an appropriate design to estimate the required time for evacuating from a variety of places with various conditions. Thus, high traffic buildings found in governmental or industrial are essential to accurately evaluate the require time for evacuation process in order to ensure the safety of pedestrians. Thus, in order to fulfill this requirement, various models in pedestrian dynamics system, either as a whole or only in psychological interaction among pedestrians is developed during the past decade until now. However, most of the existing model only discussed their application in a fix size square room with limited number of pedestrian and without the presence of obstacles in the room. Therefore, this paper presents a model that simulates a large-scale pedestrian evacuation process in a hypermarket with the presence of obstacles, and provides some recommendation for improving the evacuation flow and increase public safety. From the simulation results, it shows that our proposed design for the study area improved in both the evacuation times and flow.

Keywords: *Evacuation; Social force model; Obstacle; Hypermarket.*

1.0 INTRODUCTION

Pedestrian modelings are among the most interesting fields found in transportation science. Deepening the knowledge in pedestrian flows is the key to offer a helpful thought in designing or improving public places with aim to reduce the loss of life and properties during disasters. However, pedestrian evacuation process is a complex issue due to particular human behaviors such as awareness to danger and panic cause by incidents. Therefore, it is hard to capture a normal pedestrian flow during evacuation for study purposes. Furthermore, a real-world experiment on evacuation process is nearly impossible. This fact motivated researchers to carry out their studies in this field using different modeling methods in order to developed simulation systems for studying pedestrian behavior during evacuation process.

Recently, there are various literature reports found on modeling crowd movements that deal with unexpected disasters. Many researchers from variety of disciplines have been successfully used to study the problem on this area and obtained fruitful results. Such results are the key that help to reduce the loss of life and properties during disasters. A few of these are the particle flow model [1-3], Social Force Model (SFM) [4-8] and Cellular automata (CA) [9-15]. Particle flow and social force are using physical models to simulate movements. CA models divide the environments into cells to model the movements of pedestrians between cells. Every model mentioned has its own advantages and weaknesses. For example, social force model produces more smoother movements compare to CA models due to its continuous nature.

Kosinski and Grabowski [16] introduced an intelligent agents system using Langevin equation with additional SFM term to simulate the panic level during evacuation that taken the speed at exit area as decisive term. However, the model shows a less realistic pedestrian movement compared to SFM. Parisi and Dorso [17] presented their work on studies of different degree of panic with different exit width. However, this model is only used for simulating limited number of crowd approximately

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200 pedestrians and mainly focuses on exit width effect to panic level during evacuation process.

Currently, Frank and Dorso [18] reported their investigation finding on human behavior impact during evacuation process. This work shows the clogging and pedestrian cluster forming during the escape in a room with single exit with a fix location of obstacle. In fact, literature [18] also reported that the distance of obstacle from exit play an important role for crowd panic level as well as the evacuation flow. In panic condition, pedestrians tends to push each other to rush out from the room in the shortest time, by placing an obstacle may avoid congestion that close to the exit by taking up the pressure, and so, the effects from congestion are taken to an early phase [19-20]. It can be observed that majority of the existing models placing the assumption that pedestrians are uniformly distributed in a room with small number of pedestrians and only a limited number of models that discussed on the distribution of pedestrians around the exits area or in a room without obstacles.

For this work, we used the SFM to simulate a large-scale pedestrian evacuation process in a hypermarket with the presence of obstacles. The SFM [5] are well known for its ability to displayed a realistic move for simulating evacuation process by taking considers the discrete personality of the pedestrian flow that allows the setting of individual physical variables e.g. mass, shoulder width, desired velocity and target destination. The related problem in this work is where is the best location to place an exit in order to improve the evacuation times and flows. A Part of this problem have been reported in [21] on the optimal exit doors location and width in a room without obstacles that produced a minimal evacuation time. This paper aims to study the effects of exit placement during the evacuation process with the intention to provide a safer environment and reduces the amount of fatalities. Hence, the outlines of the are described as follows: Section 2 described briefly on the SFM model postulated by Helbing et al. [4] for determine pedestrian movement; the discussion on the results of simulations are provided in Section 3; Finally, we conclude our finding in Section 4.

2.0 SOCIAL FORCE MODEL

The Social Force Model verifies that pedestrian movement is resolve by their desire to arrive at destination location along with the effects of surroundings on them [4, 5]. The recent social force model is represents with social force and granular force while the prior model is only based on a force known as the desire force.

Suppose that a pedestrian is moving at a desire speed of v_d and with a given direction of $\vec{e}_d$. However, in actual situation, pedestrians are always walks a bit out of actual path toward the direction to destination place $\vec{e}_d$ and they never walks exactly at the desire speed v_d. Pedestrian actual speed $v(t)$ is mainly dependents to environmental factors (e.g. obstacles, exit size). Hence, pedestrian have to increase or decrease their speeds with the intention of reaching the destination location at desired speed v_d. This acceleration or deceleration are corresponds to the desire force as it come from their will and own motivation. Therefore, pedestrian i can be defined in mathematical term as

$$f_d^{(i)}(t) = \frac{v_d^{(i)}(t)\vec{e}_d^{(i)}(t) - v_i(t)}{\tau} \quad (1)$$

where all magnitudes are assumed as a functions of time, and τ represent the relaxation time required to achieve pedestrian desired speed. τ value is determined through experiment.

The pedestrians reactions to environmental stimulus are denote by social forces. Although there exist stimulus such as family member or friends that generates attraction, but it is not included in the proposed model, but the basic rule still applied on pedestrians for tendency to preserve their private space between other pedestrians [5]. When people get nearer to each other, eventually its repulsive force would turn stronger. In other words, the repulsive force strength is mainly depending on the inter-pedestrian distance d that can be modeled as an exponentially decaying function defined as follow,

$$f_s^{(ij)} = A_i n_{ij} e^{(r_{ij} - d_{ij})/B_i} \quad (2)$$

with i and j corresponds to any two pedestrians, d_{ij} is the distance between the center of mass for both pedestrians, $n_{ij} = \left(n_{ij}^{(1)}, n_{ij}^{(2)}\right)$ represents the unit vector in direction of $\vec{ji}$ and $r_{ij} = r_i + r_j$ is the sum of pedestrian radius for pedestrian i and j. The parameters A_i and B_i are fixed based on experimental findings [4].

In addition, Eq. (2) is applicable to environmental factor (e.g. obstacles). Hence, pedestrian tends to maintain a distance to separate from each other so they could avoid from getting injured. Hence, r_{ij} and d_{ij} in Eq. (2) must be substitute by r_i and d_i each corresponds to pedestrian radius and their distance to the wall respectively.

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The final term in SFM which expressed the sliding friction that appear between pedestrian that get in contact to each other and to the walls is known as the granular forces. Thus, by assuming pedestrians relative velocities as a linear function, its mathematical can now be expression as

$$f_g^{(ij)} = \kappa g(r_{ij} - d_{ij})\Delta v_{ij} \cdot t_{ij} \quad (3)$$

where $\Delta v_{ij} = v_j - v_i$ is the speed difference between pedestrian i and j. If pedestrian i get in contact to a wall, then v_j is adjust to be zero in Eq. (3). $t_{ij} = \left(-n_{ij}^{(2)}, n_{ij}^{(1)}\right)$ is the unit tangential vector, orthogonal to n_{ij}. κ is an experimental parameter. $g(.)$ function is set to zero when the argument value is negative (that is, $r_{ij} < d_{ij}$) and equals the argument value for any other case.

Extreme crowded surroundings may cause body compression effects [4]. However, as reported in [17], this body compression forces play no significant role during the evacuation process. Hence, it is not taking consider in the proposed model. A more details explanation on $f_s(t)$ and $f_g(t)$ can be found throughout the literature [4, 5, 17, 18]. Table 1 summarizes the most usual values for the experimental parameters appearing in Eqs. (6)–(8).

Consequently, both the desire and granular forces control the pedestrian dynamical characteristic by changing their speed. The equation for pedestrian i movement can be expressed by

$$\frac{dv_i}{dt}(t) = f_d^{(i)}(t) + \frac{1}{m_i}\left[\sum_{i \neq j} f_s^{(ij)}(t) + \sum_{i \neq j} f_g^{(ij)}(t)\right] \quad (4)$$

where m_i is the mass of pedestrian i. The subscript j represents all other pedestrians but excluding i and the environmental factors.

The magnitude for desire speed, v_d in Eq. (1) is correspond to the pedestrian motion in free-flow speed. Additionally, the pointing direction $\vec{e}_d$ set the anxiety for the pedestrian to reach that particular exit. An impatient pedestrian tends to rush their way out by changing their desired direction for nearest exit route available [21].

3.0 SIMULATION RESULTS

One of the interesting problems in the field of pedestrian evacuation study is finding the proper positions of the exits in order to reduce the evacuation time. Numerous existing models do not considered the crowd distribution in a room and they assumed that the pedestrians are uniformly distributed in a large room without obstacle. However, the existence of obstacles is an important parameter in gaining an accurate location for exit. In this section, we will first perform a simulation in order to test and validate our model in a room without obstacle with the fundamental diagram from Zhao et al. [21]. Next, the SFM model is applied to simulate the evacuation process in a hypermarket (see Section 3.2). The optimal locations of the exits that produce a minimal evacuation time are determined, and all the mentioned simulations work is discussed in the following section.

3.1 Room Without Obstacles

To test the proposed model, consider a room of 14 x 18 m^2 with N pedestrians is randomly distributed in the initial stage. The number of pedestrians and the room size are chosen to be equivalent to those reported in Zhao et al. [21]. The pedestrian body width is set to be 0.5 m. An exit door of width W is placed at the centre of the left wall (see Fig. 1(a)). The system is simulated, and the evacuation time is calculated for various values of W based on the average of 10 runs of simulation. For each run, the only differing is on the initial distribution of pedestrians.

Fig. 1(b) displayed the snapshot of occupant moving toward the exit and Fig. 2 is the plot of the evacuation time (in time steps units) against the exit width. From the plot, it shows that when W increases, the evacuation time decreases nonlinearly, and eventually it reach a saturation state ($W \approx 8$ m) where further increases in exit width have only minor effects on the evacuation time. Such effect are also depends on N in general. After performed the evaluation, we find that these results are consistent with Zhao et al. fundamental diagram in [21]. From the observation in simulation, it can be state that the significant increases in evacuation time when $W < 4$ are cause by the clogging and collisions that occurs at the exit area which increase the travel time of pedestrian. Furthermore, behavior such as the faster-is-slower and overtaking characteristics within the crowd can also be observed during the simulation of the evacuation process.

3.2 Simulation In Hypermarket

Consider a hypermarket of 50 x 80 m^2 with 777 pedestrians and 54 blocks. The blocks represent the obstacles in this case and the possible exit locations are place based on distance (in meter) from left

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lower corner to the right lower corner of hypermarket (see Fig. 3). There are total of 80 m length of distance from the starting point at the lower left corner. The obtained hypermarket floor at the initial step is as shown in Fig. 4(a). With the given geometry and placement of the hypermarket area, obstacles and exits, now the 777 persons are distributed in the area and the evacuation time can be calculated (see Fig. 4(a)).

For our evaluation purposes, we consider the case where there is one 10 m exit or two 5 m exit. Here, a 5 m (10 m) exit is defined such way that 10 (20) pedestrians can leave the room through it simultaneously. Next, a series of simulation on this system are performed by changing the position of exits in order to determine the optimal location.

In order to observe the effect of obstacles, these pedestrians are positioned in the same places even if there are no blocks. The effect of exit width located at the centre of the lower wall with the presence of obstacles is analyzed. Fig. 5 shows the results for evacuation times for the hypermarket area with and without obstacles along with the increase of exit width for SFM models. We observed that the further increase beyond critical width (10 m wide exit) would not contribute to much reduce in evacuation times with the presence of obstacles. The reason is that the clogging effect at exit area inflict constrain on pedestrians movement.

In addition, we also observed that both the cases for with and without obstacle in Fig. 5 have similar evacuation time (average error of s). This is because at the hypermarket exit area does not have any obstacles that could reduce the clogging effect or coordinates their movement, and this event similar to those reported in [22, 23]. Fig. 6(a) shows the evacuation times for the hypermarket area with obstacles for different 5 m exit door locations. The sharp transitions in the plot are cause by pedestrian distance (being nearer or farther) to the exit door. The other effect is the dip which forms when door are located in cells 38-43 m (see Fig. 6(a)) when most blocks are present. The presence of walkway at the centre area helps in decreases the evacuation times as it coordinates pedestrian movement and reduces interactions. The mentioned effect is similar to those in [22, 23].

The common setting in a hypermarket is to have 10 m doors which represent a door that capable to allow 20 persons go through simultaneously. Results for one 5 m door and one 10 m door are plotted in Fig. 6. We notice that similar minimal evacuation time occurs for both 5 m and 10 m exit cases at similar area where the exit door located at 38-43 or 36-46 for 5 m or 10 m exit. We observed that the worse situation (highest evacuation time) arise when the exit is located at the corner of the room for 5 m exit and 10 m exit which located at 72-77 and 68-78 areas respectively, and the optimal situation for 5 m and 10 m exits are when the exit is located nearby the centre of the area which consists of the most number of walkway nearby the exit area, which occupying cells 38-43 and 36-46 respectively. This is because the optimal exit door is located in the centre of the room which is the shortest distance for all the pedestrians that provided them the fastest way to reach the exit.

The best evacuation time for 5 m and 10 m exits are $101.60 \pm 5.08\,\mathrm{s}$ and $63.50 \pm 11.32\,\mathrm{s}$ (error estimated from the average deviation of data from the mean value) respectively. This corresponds error are less than 20 s are consider a reasonable result as stated by [23]. Next, the 10 m exit is replace by two 5 m exits. Fig. 7 illustrated the optimal locations of both the two 5 m exits that minimize the evacuation time. Therefore, the best results were when the doors are located nearby the walkway and at the side of the hypermarket area. Fig. 8 shows the comparison results for one 10 m exit and two 5 m exits in term of evacuation time. From Fig. 8, the best evacuation time obtained is 57.60 ± 5.08 located at 20-25 m and 50-55 m. The difference in evacuation time is about 5.90 s that equivalent to approximately 40 pedestrians evacuate from the hypermarket area (see Fig. 8). Thus, two 5 m exits are much better than one 10 m exit. Fig. 4(b) and Fig. 4(c) shows the snapshot of simulation after 18.5 s in the hypermarket area.

4.0 CONCLUSION

The overall results shown by the proposed model has inferred it capabilities that suits in performing a complex and crowded event simulation. We applied social force model to model the pedestrian movement and to study placement of exit effects in the evacuation process. The simulation from the proposed model shows that: (i) Evacuation time are effectively reduces using two 5 m exits compared to a single 10 m exit. (ii) The optimal positions for exit doors where the evacuation time is minimal, is located at the centre of the lower wall of hypermarket area. (iii) Further increase beyond critical width (10 m) for the hypermarket case would not contribute a significant reduces in evacuation times.

Indeed, the model still consists some improvable features to be considers. For instances,

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parameters such as age, physical ability, psychological behaviors and group formation are to be considered to improve the system realism and this is an attractive adjustment to the social force model itself. For future work, we intend to integrate some of the mentioned features into our model and apply it to other geometries such as hall, stadium, movie theaters and etc.

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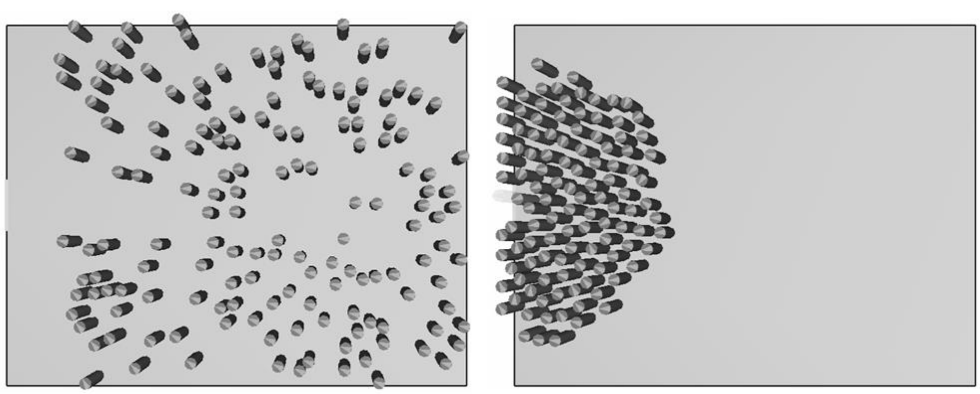
Table 1: Related variables apply for evacuation simulation

Parameter	Symbol	Value	Units
Force at $d_{ij} = r_{ij}$	A_i	2000	N
Characteristic Length	B_i	0.08	m
Pedestrian Mass	m_i	70	kg
Contact Distance	r_{ij}	0.5 ± 0.2	m
Acceleration Time	τ	0.5	s
Friction Coefficient	κ	2.4×10^5	Kg $m^{-1}s^{-1}$



(a) (b)

Fig. 1. (a) Illustration of 150 pedestrians randomly distributed in a 14 x 18 m^2 room with an exit at centre of left wall. (b) Snapshot of evacuation simulation when all pedestrians moving toward the exit.

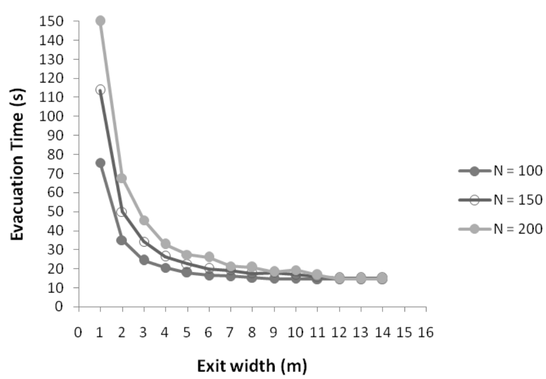


Fig. 2. Evacuation time versus exit width for 14 x 18 m2 room with an exit located as in Fig. 1(a). Each curve corresponds to N = 100, 150, 200 pedestrians initially distributed randomly.

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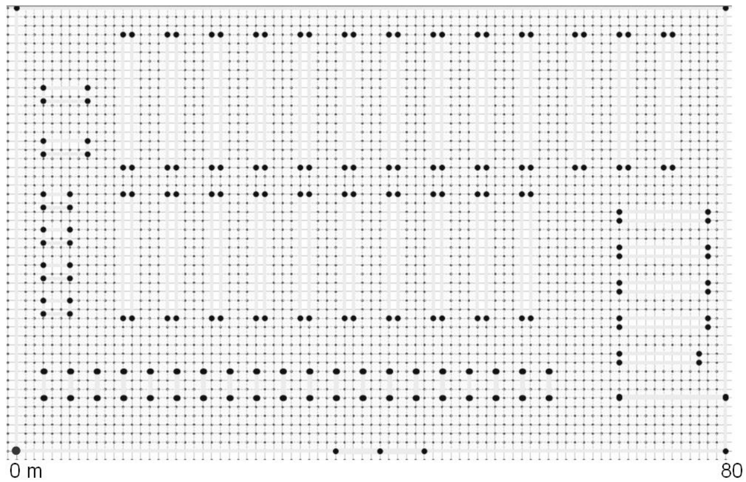

Fig. 3. Floor plan for all possible exit door locations in the hypermarket. The starting point (0 m) are mark in red dot.

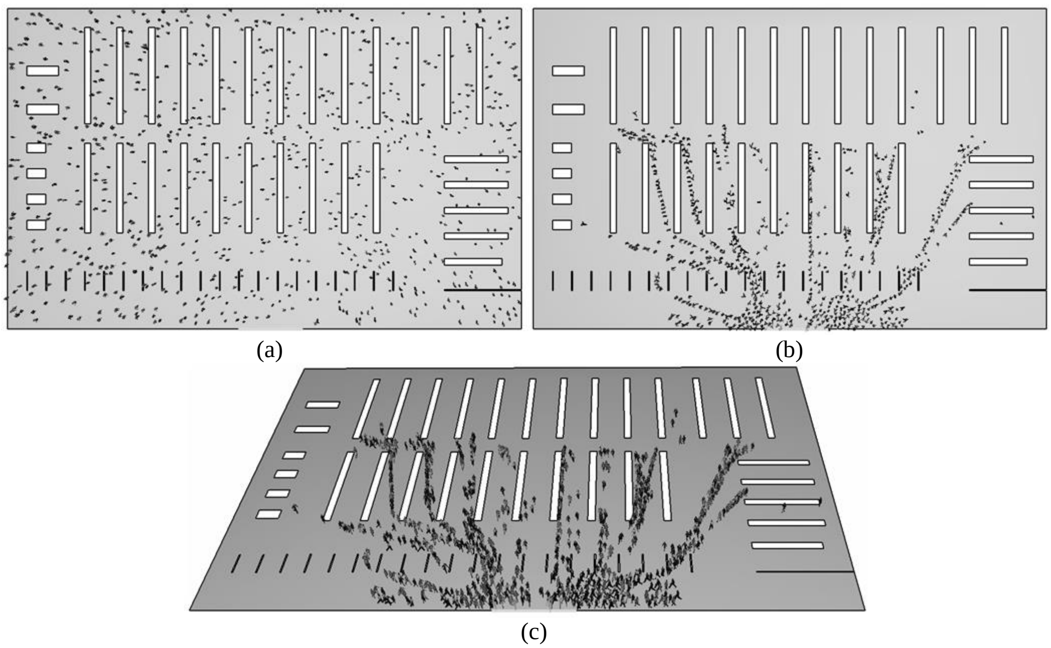

Fig. 4. (a) Hypermarket floor with 777 pedestrians initially distributed randomly. (b) 2-D snapshot of simulation after 22.5 s. (c) 3-D snapshot of (b).

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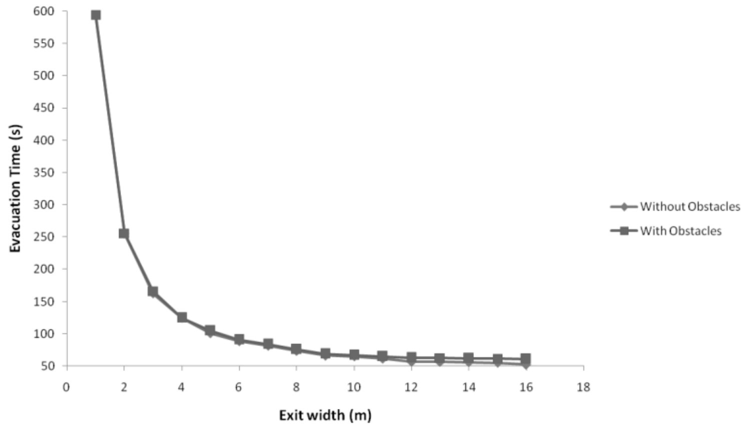

Fig. 5. Evacuation time with the increases exit width of the hypermarket area in Fig. 4(a).

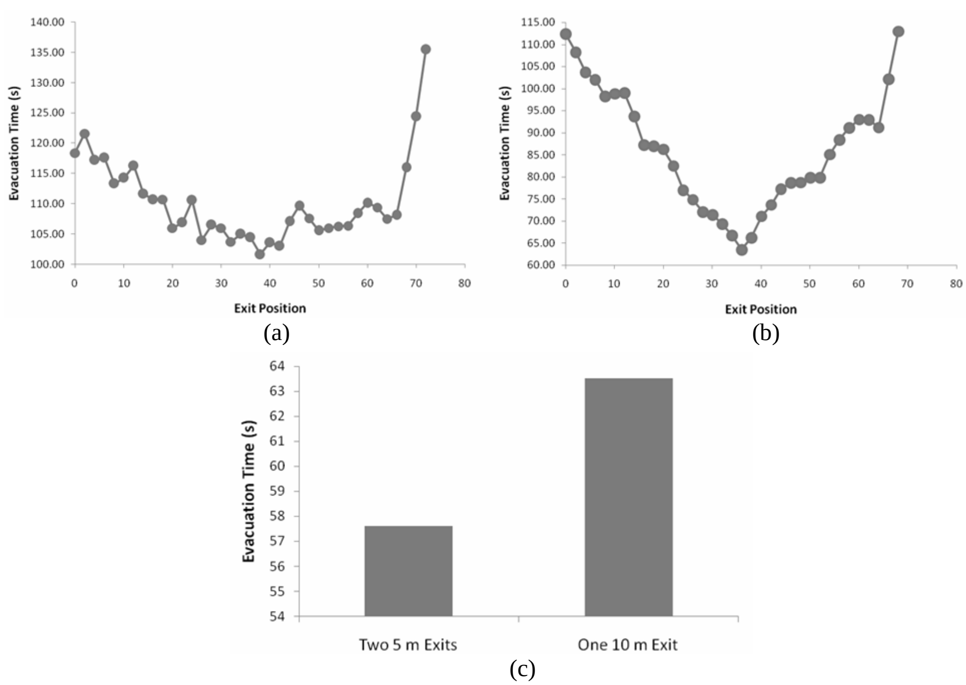

Fig. 6. Evacuation time versus exit position of hypermarket area for; (a) one 5 m exit; (b) one 10 m exit. A point with abscissa n corresponds to a exit location occupying distance n, $n+1$, $n+2$, …, $n+4$ m for case (a), and n, $n+1$, $n+2$, …, $n+9$ m for case (b). (c) Result of comparing the evacuation time for two 5 m exit and 10 m exit cases.

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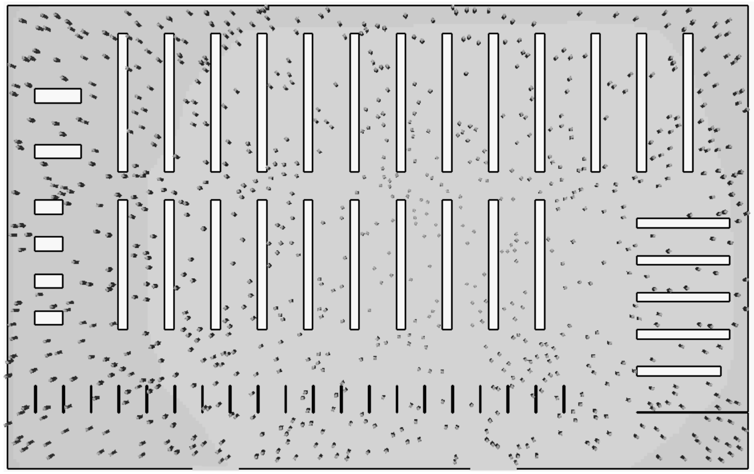
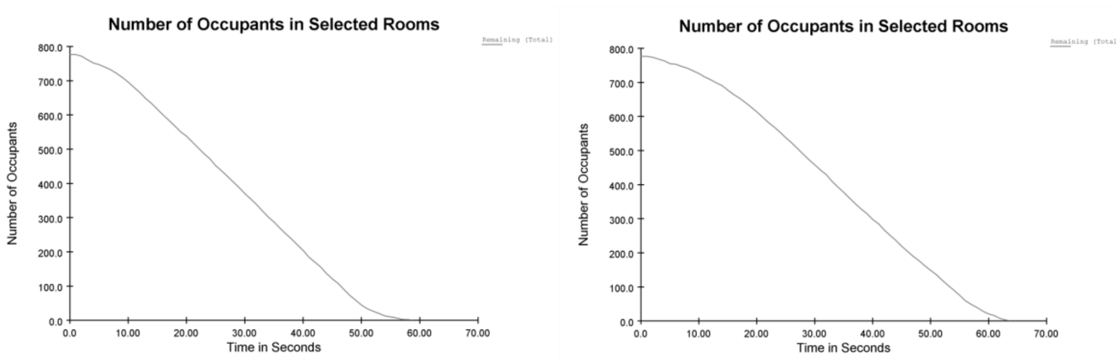


Fig. 7. Illustration of the optimal locations for two 5 m exits.



(a) (b)

Fig. 8. Evacuation time versus number of pedestrians (occupants) evacuates from the hypermarket for; (a) two 5 m exits; (b) one 10 m exit.