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Research Article

Modelling of Crowd Evacuation with Communication Strategy Using Social Force Model

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Abstract

Mobile crowd steering application has received much attention nowadays to steer crowds during fire or disaster evacuation. As reported in many studies, real drill experiments have been conducted to validate the mobile crowd steering application. However, simulations have also been undertaken to overcome the limitation of practical drill experiments when testing the application. Although there are algorithms reported for agent-based mobile crowd simulations, not many studies have adopted the social notion during mobile crowd steering simulations. As mobile crowd steering applications require user interaction during fire evacuation, we have foreseen a gap in current simulation algorithms, which leads to unrealistic simulation. This paper introduced a new insight into the agent-based crowd simulation through integration of communication strategy into the state of the art of social force for crowd management. The model was presented, formulated, and validated through a fire evacuation simulation. From the simulation results, the proposed model can reduce evacuation time and crowd density at the door opening area as compared to the original Social Force Model in a similar experimental setup.

***Keywords*:** Social force model; crowd evacuation simulation; NetLogo; microscopic simulation

1. Introduction

Mobile crowd steering application is an application to guide users to exit during a disaster. To date, various mobile crowd steering applications have been developed to ensure user safety during an emergency. For example, smart technology for positioning, such as beacons (Atila et al., 2018), augmented reality (Ahn & Han, 2011), and Internet of Things (Yan et al., 2019; Ryu, 2015; Khan et al., 2018) was developed to provide evacuation guidance to users during a disaster. The application will send an evacuation path to a user's mobile phone, retrieve current user position, recalculate the optimal route, and resend the optimal path information or next movement's instruction. The optimal evacuation path is crucial to ensure high rate of evacuation within a specific time range. The optimal evacuation path could be the path that has the shortest distance from user location to the exit door, or the path with fewer users using it at that time.

To validate the mobile crowd steering application, a real drill needs to be conducted. In a real drill experiment conducted by Zhu and Shi (2016), each person recorded their finish time upon arriving at the final destination. Multiple video cameras were also installed at different locations of the building to mark the evacuation process.

Due to uncertainties during a disaster, unexpected events can occur. This leads to the dilemma of testing the efficiency of mobile crowd steering application. Hence, simulation needs to be conducted. From a previous study (Merkel, 2014), a simulation can access and analyse the implications of following a specific evacuation instruction derived from an evacuation planning algorithm. This study was needed to evaluate the whole evacuation process and develop strategies for improvement as conducted by Merkel (2014), to ensure the mobile application is fully functional in any situation and ready to be distributed to users.

In the simulation study, we can observe the simulation results by changing some parameters. For example, increasing the number of users requesting the evacuation information simultaneously, limiting the number of available corridors or stairs to use, and changing the walking speed of the crowds (Iizuka & Iizuka, 2015). In other words, the simulator can investigate the effectiveness of the mobile application in terms of its ability to deliver the evacuation information within a specific time, recalculate evacuation paths after having some parameters changed (e.g., the position of user), and generate evacuation paths that are reliable and safe for users. The simulation results are needed to ensure the availability of the application in a time-critical situation in which each second matters to save lives. The simulation study is also needed to test the reliability of the generated evacuation path algorithm in various scenarios.

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Although various simulations have been conducted, we have foreseen a gap in those simulations. We argue that humans perform social interactions during an emergency evacuation by communicating with each other to pass information and assist others. For this reason, it is essential to add this element in the simulation study even though the users can access the evacuation guidelines on their smartphones. Social interaction among the evacuees is a critical element to produce a realistic simulation result. Active social interaction will provide a more realistic simulation results such as group formation (indicates the grouping of people having the same knowledge or goal) and leader-following behaviour.

This paper introduced a new insight into the agent-based crowd simulation through integrating communication strategy into the state of the art of social force for crowd management. The model was presented, formulated, and validated through a fire evacuation simulation. The model was based on the claim that the evacuees will interact with each other in terms of sharing evacuation information or following other evacuees to evacuate. From the simulation results, the proposed model can reduce evacuation time and crowd density at the door opening area as compared to the original Social Force Model in a similar experimental setup.

In this research, the model was developed and extended based on the well-known Social Force Model (SFM). SFM is widely used to address the local movement of a crowd during a steering process. It pertains to how pedestrians interact with each other during the move. Interaction between pedestrians affects their next movement. SFM also involves contact between a pedestrian and a static object, such as walls, to avoid collision.

As for the remaining of this paper, Section 2 describes related works of mobile crowd evacuation applications and SFM. The SFM formulation and communication model are presented in Section 3. Section 4 presents our simulation settings, results, and discussion while Section 5 presents the conclusion.

2. Related Works

Several studies have been introduced to develop mobile crowd evacuation applications during a disaster as shown in GPS-based evacuation guidance application (Wada & Takahashi, 2013), GoFast guiding application (Chen et al., 2015), CLOTHO: IoT-based evacuation planning system (Xu et al., 2018), and personalised alert notification (Aedo et al., 2012).

To validate this technology, real field testing needs to be conducted. Practical field testing involves the cooperation of participants such as walking fast to simulate a real emergency scenario. In a real drill experiment conducted by Zhu and Shi (2016), each individual recorded their finish time upon arriving at the final destination. Multiple video cameras were also installed at different locations of the building to mark the evacuation process. However, there are many limitations in real field testing. Hence, simulation is introduced to validate the mobile crowd evacuation application. Simulation aims to determine multiple conditions such as receiving messages, receiving no messages while calculating the evacuation time and total number of people, and recalculating the evacuation route. Simulation supports pre-emergency scenarios such as designing a safe evacuation route based on congestion or damage predictions (Inoue et al., 2008).

However, some insufficiencies have been detected on current simulation algorithms. Simulation studies are also limited (Ahn & Han, 2011; Iizuka & Iizuka, 2015; Wada & Takahashi, 2013; Chen et al., 2015; Xu et al., 2018; Aedo et al., 2012; Nakajima et al., 2007). Various algorithms have been used for simulations of mobile crowd steering applications. For example, An and Han (2011) used the optimal exit path algorithm to calculate the path that produces less evacuation time, while Iizuka dan Iizuka (2015) used the distributed stochastic search algorithm to simulate evacuation from a campus building. Among the current simulation studies, SFM is a promising algorithm.

SFM simulates the microscopic movement of pedestrians described as a particle. Helbing and Molnár in 1995 (Helbing & Molnar, 1998) developed this model to design pedestrian movement in line with the forces of society (psychological forces), which encourages it to move to the target. In this model, the pedestrian retains a certain distance from other pedestrians (repulsion forces) as well as obstacles such as wall and other static objects. SFM is focused on forces of communication that define the psychological intentions of the pedestrian. The building blocks of social forces consist of driving, repulsion, and attractive forces. Repulsion and attractive forces are grouped as an interaction force. Driving force reflects the motivation of people moving towards a target at a desired speed, while interaction force is the force that forms interactions between people and objects, including socio-psychological and physical interactions. These forces are formulated to determine the next position of each pedestrian at a specific time.

SFM is a standard model in simulations, defining the dynamics of pedestrian crowds as their desired speeds given the objectives of simulated pedestrians encoded. The model has many advantages, such as a rigorous and universal mathematical formula, an excellent ability to self-organise, and the influencing factors of a comprehensive and realistic simulation effect. As a result, it is widely favoured by researchers simulating crowd movements for various purposes of building evacuation such as grouping behaviour (Zhang et al., 2020; Du et al., 2018), leader-following (Rinke et al., 2017), awaiting pedestrians (Johansson et al., 2015), narrow stairs (Wu et al., 2013), and escalators (Li et al., 2015). Social relationships and social interactions among group members influence crowd dynamics greatly (Moussaïd et al., 2016). Some works employed SFM for collision handling (Hao et al., 2018), with the aims to control agents' territorial behaviour and ensure a realistic simulation.

Several adaptations and improvements for SFM have been introduced to overcome the limitations of the original model. From the review, one recent trend in SFM modifications is to calculate the pedestrian motion through grouping technique. This technique helps to reduce complexity during computation. Table 1 summarises the latest studies of improved SFM.

Table 1
SFM extensions.

Modified SFM	Authors	Added/ Modified Force and Parameters	Added Parameters
Momentum equation	Juan et al. (2020)	Disturbance fluctuation force	Momentum of pedestrian flow
Dynamic Navigation field	Jiang et al. (2019)	Generalised cost	Local walking cost per unit distance, strength tendency value of avoiding high-density region
Grouping SFM	Du et al. (2018)	Desired direction	Distance-dependent parameter, leader radius, square root total team leaders, average team radius
	Liu et al. (2018)	Group force	Weight of relationship between pedestrians, strength of attractive force, the least safe distance between pedestrians, the direction of attractive force
	Zhang et al. (2018)	Leader force	Leader fitness function, position of group leader
	Huang et al. (2018)	Group avoidance force, interaction force for subgroup	Radius of group, radius of furthest member of group P, distance of P to the centre of mass, walking direction of a group, average direction of all members
Vision factor	Wang and Cao (2018)	Repulsive force + relative velocity factor	Vision field factor, relative velocity factor
Headed SFM	Farina et al. (2017)	Optional force (modelling pedestrians in groups)	Pedestrian heading
Evacuation indicator	Yuan et al. (2017)	Driving force	Priority evacuation indicator.
Transmission information	Han et al. (2017)	Driving and attractive force	Reserving factor, post-spread reserved exit information, number of information transmission, pedestrian confidence in choosing neighbours.

Although the algorithms have been improved, we argue that adopting SFM in mobile crowd steering application simulations is not straightforward. SFM suffers from a modelling situation in which users carry mobile phones, receive, and send messages during a disaster. Hence, we argue that there is a need to introduce an extended SFM for mobile crowd steering simulations.

3. The Model

3.1. The social force model

The Social Force Model proposed by Helbing et al. (2000) consists of three forces: driving force, other pedestrians' repulsion force, and wall repulsion force. Each pedestrian, i having a mass, m_i aims to move at a certain desired speed, v_i^0 to a certain direction, e_i^0. Each pedestrian adapts their actual velocity, v_i with a characteristic time, T_i . The equation to calculate each pedestrian's new speed and direction for the movement as described in the work of Helbing et al. (2000) is:

$$m_i \frac{dv_i}{dt} = m_i \frac{v_i^0\,(t) e_i^0 - v_i(t)}{T_i} + \sum_{j \neq i} f_{ij} + \sum_{w} f_{iw}$$

The second part of the equation is to calculate the interaction force between pedestrians i and j as shown in Equation (2).

$$\overrightarrow{F_{ij}} = \{A_i exp\,((r_{ij} - d_{ij})\,/\,B_i) \;+\; kg\,(r_{ij} - d_{ij})\}n_{ij} \\ +\; \kappa g(r_{ij} - d_{ij})\Delta\, v_i^t\, t_{ij}$$

In Equation (2), A_i and B_i are constants, d_{ij} is the distance between the centre of a pedestrian's mass. The additional body forces are $kg\,(r_{ij} - d_{ij})\}n_{ij}$ which is to counteract body compression and $\kappa g(r_{ij} - d_{ij})\Delta\, v_i^t\, t_{ij}$ which is a sliding force impeding relative tangential motion if pedestrians *i* and *j* are too close. The k and κ represent large constants

The third part is Equation (3), to calculate the repulsive force from obstacles such as walls. The definition parameters are similar to Equation (2), where *w* represents the wall. The detailed model definition including the definition of the parameters is available in the work of Helbing et al. (2000).

$$\overrightarrow{F_{iw}} = \{A_i exp\,((r_i - d_{iw})\,/\,B_i) \;+\; kg\,(r_i - d_{iw})\}n_{iw} \\ +\; \kappa g(r_i - d_{iw})(v_i\,.\,t_{iw})\,t_{iw}$$

The existing SFM modifications emphasise the modification of the pedestrian's driving force, where the calculation of force is done by group to minimise computation costs (Du et al., 2018), and some works created a new type of force to accommodate specific scenarios (Liu et al., 2018; Farina et al., 2017; Han & Liu, 2017; Huang et al., 2018). Modified SFM results normally show more realistic and collective crowd behaviours such as self-organised patterns.

3.2 The communication strategy model

We developed the communication strategy model and integrated the model into the basic SFM. The communication strategy serves to allow evacuation in a more structured way to reduce congestion at the door opening area. We designed the communication strategy as in Algorithm 1. The two types of agents or people that we used were marked with pink and blue colours. Pink-coloured individuals were equipped with the message while the blue-coloured individuals were without the message. The algorithm is described as follows:

Step 1: Any individuals within a radius of three from the first person who has the message will also receive the message. The patch colour will change to red, and the person's colour also changes to pink.

Step 2: Individuals with the message start to move. As the pink-coloured individuals move, they will pass the message to other individuals they encounter. The blue-coloured individuals nearby will change to pink and start to move.

Algorithm 1 Message passing between people

```
if any? neighbours in-radius 3 then
    pass message
else
    keep moving towards the exit door
end if
```

The flowchart in Figure 1 describes the communication strategy integrated into the SFM evacuation model. The number of people receiving the message depends on the distribution of their position in the room. If the room occupation is high (e.g., more than 300 people), the chances that everyone will receive the message are high.

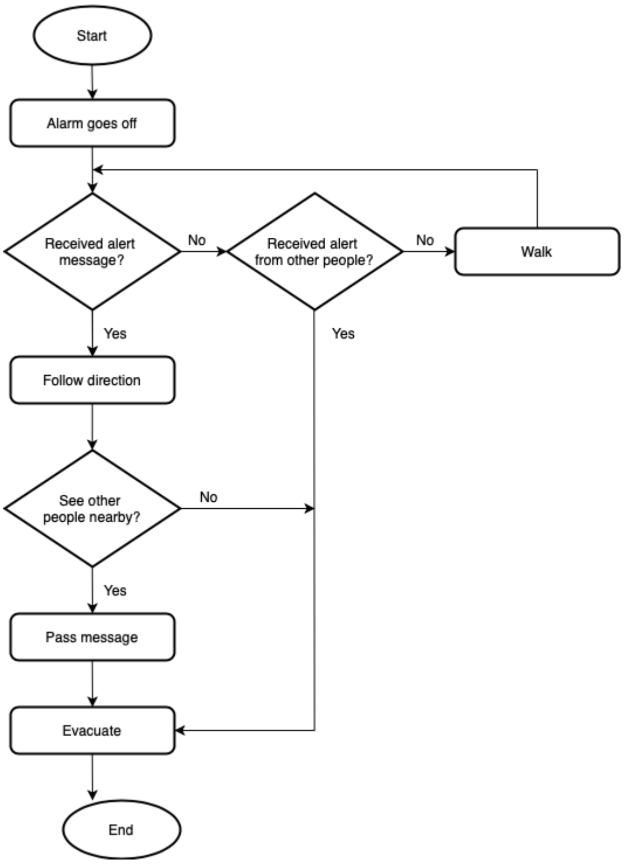


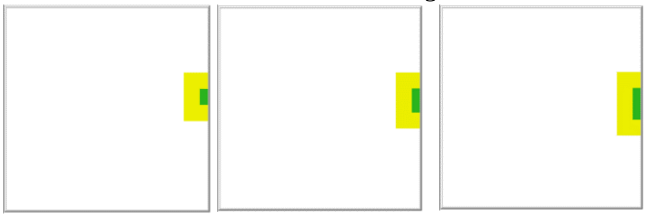
Fig. 1. Flowchart of the communication strategy in the evacuation process.

4. Simulation Experiment Settings

4.1. Experiment settings

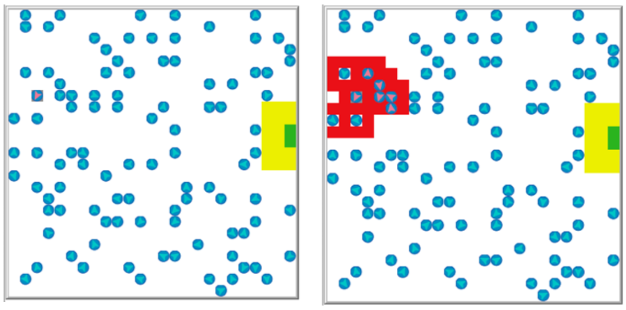
We conducted three experiments, each consisting of three scenarios, to evaluate how long it takes for a group of people to evacuate a building during an emergency. We compared three experiment settings: 1) the original SFM algorithm, 2) no specific algorithm, and 3) the communication strategy with the SFM algorithm. We used NetLogo as our simulation tool and designed the simulation environment using 25×25 patches. The three simulation scenarios were: 1) using two patches of door width, 2) using three patches of door width, and 3) using four patches of door width. We ran the simulation using 100, 200, 300, 400, and 500 people for each scenario.

We evaluated the performance of our algorithm (Experiment 3) using the original SFM as a benchmark. For Experiment 3, we integrated the communication strategy and improved it in terms of people's movement patterns during evacuation, to reduce crowd density at the door opening area. We designed the rooms for the experiments, as shown in Figure 2. The door was coloured green, and the area near the door opening was coloured yellow. The door opening was designed to observe the density at the door opening during evacuation. The door opening area was different in size for each door width. Three types of door width were created to investigate its effect on evacuation time. In this simulation model, the evacuation started when the alarm sound went off. A few assumptions were made: 1) No visible fire or smoke in the room, and 2) Everyone will evacuate the room when the alarm goes off.



(a) (b) (c)

Fig. 2. The design of room for the three experiments: (a) Door width = 2-patch, (b) Door width = 3-patch, and (c) Door width = 4-patch.



(a) (b)

Fig. 3. Experiment 3 set up: (a) Random position of a person having the message, and (b) People within radius of 3 will receive the message.

We designed Experiment 3 to show the effect of communication strategy during an evacuation process. In this experiment, pink represented individuals with the message, while cyan represented individuals without the message. The first person having the message (pink-coloured) was randomly positioned in the walkable area (white patches). Any individuals within a radius of 3 (red patches) received the message as well.

To describe agent behaviour in Experiment 3, we categorised the agents into two types: leader and followers. Leader agent was the first to receive the message to evacuate the room. Leader agent spread the message to its nearby agents. They spread the message to the other agents as they moved towards the exit door. The follower agents represented people who did not receive the message first. They received the message from their nearby agents.

Follower agents started moving when they received the message.

4.2. Parameter settings

The specification for the SFM models followed the work done by Helbing et al. (2000). Under panic condition, the velocity (desired speed) of people leaving the room could increase from 1 to 1.5 ms^{-1}. The parameters were A = 1.0, B = 0.5, k = 2.4 x 10^5kg $m^{-1}s^{-1}$, Tr = 1.0, $V0$ = 1, and dt = 0.05.

5. Results and Discussion

We developed a simulation model and ran a series of evacuation experiments. The experiments were performed using Intel Core i5 3.1 GHz CPU with 8 GB RAM. We used the NetLogo simulation tool as our simulation platform. We measured the total evacuation time using tick value. Tick is a time unit used in NetLogo tool. For Experiment 1 using 2-patch door width, as the number of people in the room increased, the total time for evacuation was also increased. For the 3-patch door width, the evacuation time was increased, as shown in Figure 4. For Experiment 2, the evacuation time for all three door width settings was higher compared to Experiment 1. The increased evacuation time was from 98% to 100% as compared to Experiment 1. For Experiment 3, the evacuation time was slightly higher than Experiment 1. This is due to the second-phase movement of people during the evacuation. The first-phase movement involved the people who received the message from people nearby having the message. Once the first-phase movement was concluded, the second-phase movement started. The increase in evacuation time varied from 30 to 300 ticks, while the decrease in evacuation time ranged from 30 to 50 ticks.

Experiment 1 used the original SFM and generated minimum evacuation time for all three experiments except the 2-patch door width with 200, 400, and 500 people. For these three scenarios, Experiment 3 produced the lowest evacuation time, with time differences ranging from 20 to 70 ticks.

Experiment 2 used no specific algorithm and generated the highest evacuation time for all three door widths. In this experiment, the mean speed of people was the highest compared to other experiments. However, the evacuation process took extended time.

Experiment 3 used the communication strategy with the SFM algorithm, conducted to observe the effect of its usage with SFM during evacuation. In certain scenarios, while the evacuation time is higher than in experiment 1, the tick gap range is between 30 and 300. The evacuation time was slightly higher because of the delay between first-phase and second-phase movements. The evacuation time was reduced for the 2-patch scenario involving 200, 400, and 500 people, while the scenario of 300 people showed an increase of only 37 ticks. For all the 15 scenarios in Experiment 3, eight scenarios showed lower crowd density at the door opening area, as shown in Figure 8. The mean speed of people was also reduced during the evacuation, as shown in Figure 7. Our algorithm was able to shorten the evacuation time by three out of a total of 15 scenarios compared to experiment 1 and reduced the crowd density at the door opening area by eight scenarios.

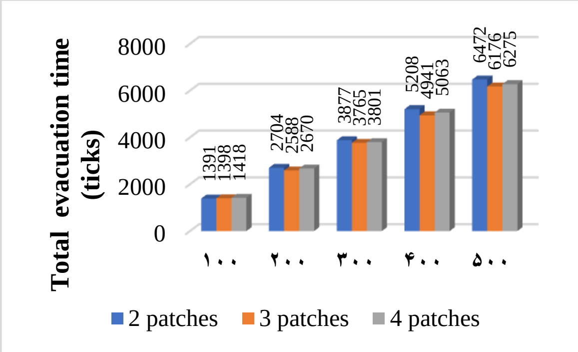


Fig. 4. The evacuation time (ticks) for each scenario in Experiment 1.

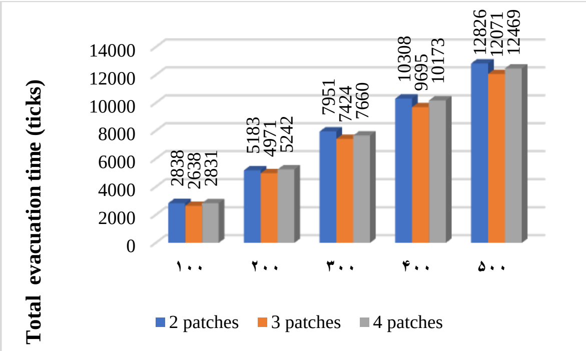


Fig. 5. The evacuation time (ticks) for each scenario in Experiment 2.

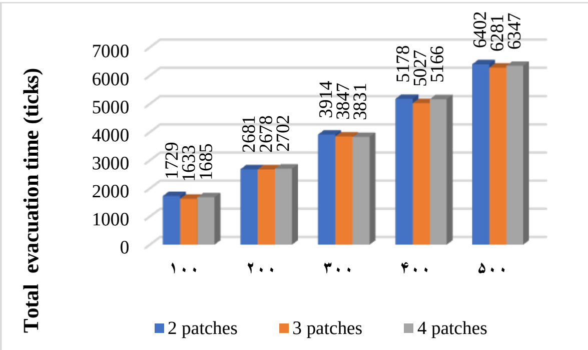
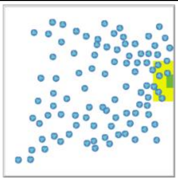
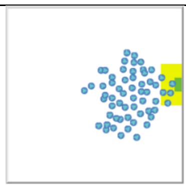
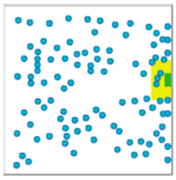
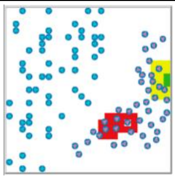
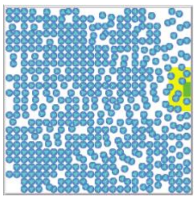
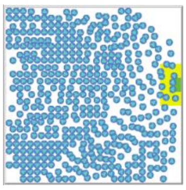
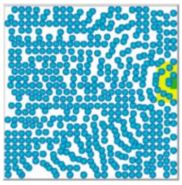
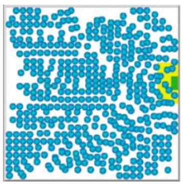
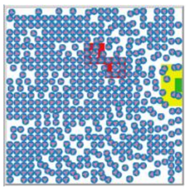
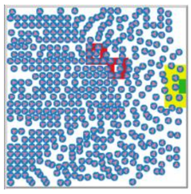
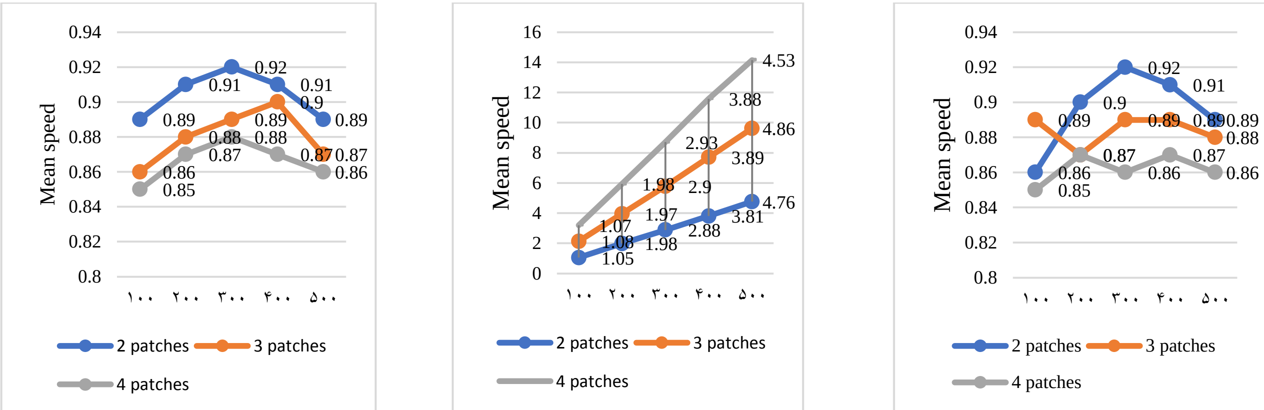


Fig. 6. The evacuation time (ticks) for each scenario in Experiment 3.

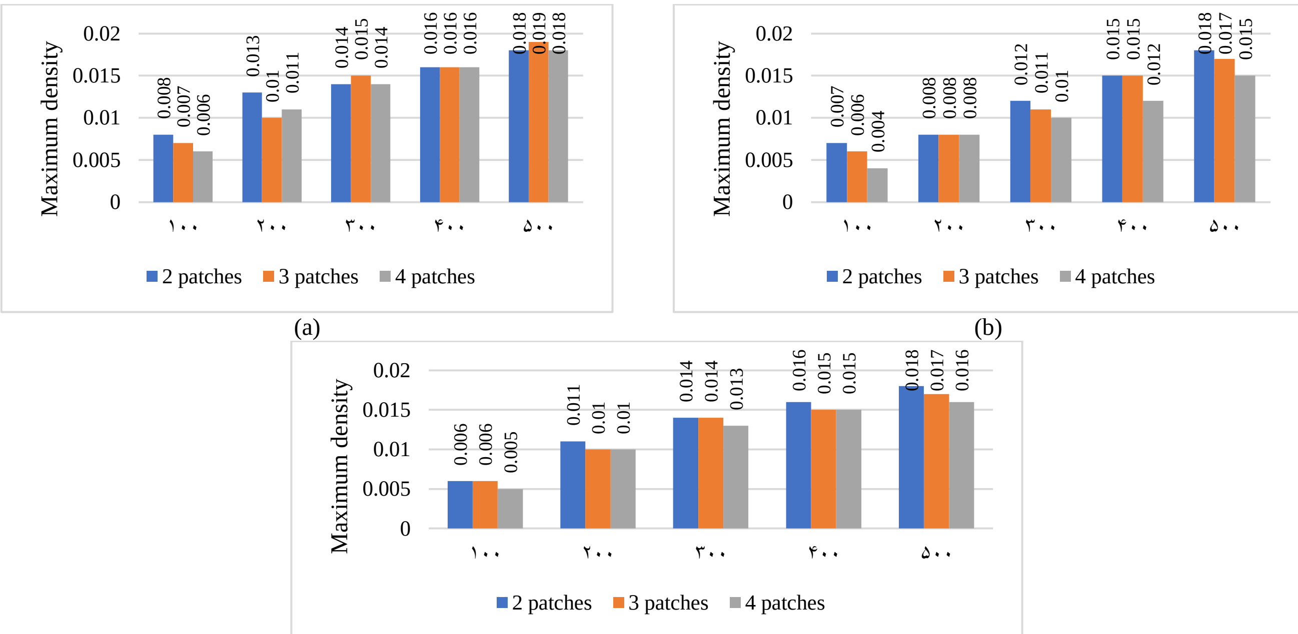
Table 2
Screenshot of simulations at ticks = 100 and ticks = 500 for the three experiments.

	Experiment 1		Experiment 2		Experiment 3	
Number of people	Ticks = 100	Ticks = 500	Ticks = 100	Ticks = 500	Ticks = 100	Ticks = 500
100						
500						



(a) (b) (c)

Fig. 7. The mean speed of people for each scenario: (a) Mean speed in Experiment 1, (b) Mean speed in Experiment 2, and (c) Mean speed in Experiment 3.



(a) (b)

(c)

Fig. 8. The maximum density at the area of door opening: (a) Maximum density for Experiment 1, (b) Maximum density for Experiment 2, and (c) Maximum density for Experiment 3.

Table 3
The evacuation time and the number people receiving the first-hand message for Experiment 3.

	Number of people received the first-hand message			Total Evacuation Time (Ticks)		
	Door width (patches)			Door width (patches)		
Number of people	2	3	4	2	3	4
100	4	4	4	1729	1633	1685
200	6	5	7	2681	2678	2702
300	10	9	9	3914	3847	3831
400	14	11	14	5178	5027	5166
500	18	14	15	6402	6281	6347

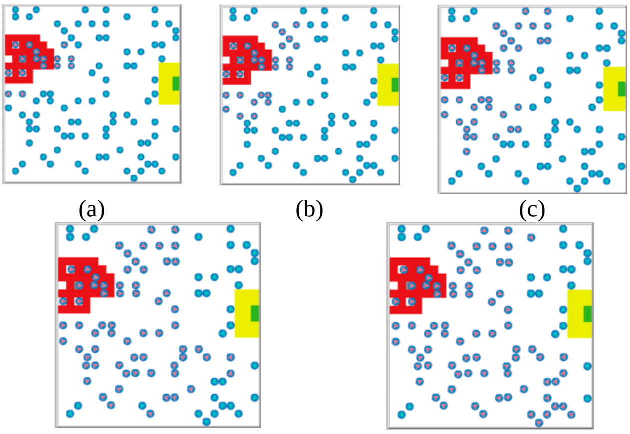


Fig. 9. Message spreading for 200 people set up: (a) tick = 2, (b) tick = 4, (c) tick = 6, (d) tick = 12, and (e) tick = 16.

To investigate the effect of communication strategy on crowd evacuation in a room, we randomly positioned the first agent carrying the message. The message-carrying agent passed the message to the other agents during the movement towards the exit door. Any agent located within a specified radius of the message-carrying agent received the message and started to evacuate the room. As shown in Figure 9, the first group of agents that received the message (determined by the red patch) started spreading the message to the other nearby agents. The higher population in the room would help spread the message more rapidly. Thus, the scenario with more people yielded a substantial outcome, which reduced the overall evacuation time and the maximum density in the door opening area. As a result of the simulation, experiment 3 was able to generate less crowd density in the door opening area. Table 3 indicates the evacuation time and the number of people who received the first-hand message for Experiment 3. However, evacuation time is also affected by the distance of the first group of people receiving the alert to the exit door. In future research, we would like to explore this relationship.

6. Conclusion

During evacuation, communication strategy is essential to allow message spreading among individuals, to minimise evacuation time. This paper presented the communication strategy used with the SFM algorithm to simulate mobile technology use during an indoor emergency evacuation. The model calculates the shortest path to exit by considering each person's mobile elements such as current position, walking speed, and heading. This algorithm was developed as a preliminary study to design a platform to support the evaluation of existing mobile crowd evacuation applications. By incorporating communication strategy into SFM in the mobile application evaluation simulation, we showed how our algorithm simulated the emergency to support evacuation. We simulated how individuals with the message could spread it to individuals nearby to allow them to evacuate. The experimental results showed that the integration of communication strategy with SFM is a practical and suitable option for simulating crowd evacuation. The model includes interaction between individuals with mobile phones and without mobile phones. The evacuation time using the communication strategy with SFM was slightly higher compared to the original SFM model because of the delay between first-phase and second-phase movements. This phenomenon could be reduced by increasing the number of radius of people receiving the message for the first time. For our future works, we will investigate the effect of the number of people having the message first-hand on evacuation time and the distance to the exit door. We plan to design the room with multiple exits to observe the exit-selection strategy among individuals. We will also conduct a thorough model comparison with other existing works.

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