Emergency Evacuation from a Multi-floor Building using Agent-based Modeling

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ABSTRACT

This paper presents an overview of the ongoing research into the development of an agent-based model to enable simulations to be performed of agents evacuating from a multi-floor building with a complex layout, including staircases. Specifically, a flow field of navigation objects is constructed pre-computation, which stores the directions and shortest distances to all exits and staircases. Using the flow field, a navigation method is proposed for agents familiar with the environment to identify and follow the shortest route to a chosen exit. Preliminary simulations have been performed to investigate the effect on evacuation time of (i) exit configurations and (ii) familiarity of agents with the building layout. In assessing the effect of exit configurations, results show that the location of the main entrance has a significant influence on evacuation time. In addition, having more exits does not necessarily lead to a shorter evacuation time. In terms of the effect of familiarity of agents, having more agents with a greater level of familiarity does not significantly reduce evacuation time in most cases.

Keywords

Emergency Evacuation, Agent-based Modeling and Simulation, Multi-floor Building.

INTRODUCTION

Frequent natural and human-made disasters occur in which emergency evacuation from buildings is an important life-saving action (Makinoshima et al., 2017). However, in many instances, injuries or fatalities are not caused by fire, explosions, or other hazards in a building, but by the evacuees' behavior (Helbing et al., 2005). Hsieh et al. (2009) summarized a total of 215 human stampede events from 1980 to 2007 resulting in 7069 deaths and at least 14078 injuries. Thus, how to improve evacuation efficiency from buildings and ensure the safety of people in such situations has been and continues to be the focus of much research.

Although real-life studies based on experiments and drills can be used to collect evacuation data, there are issues related to ethical and safety concerns. It has been recognized that computational models could be used to complement these real-life studies (Bernardini, 2017) as well as expanding the number of scenarios able to be examined (Gwynne et al., 2016). Agent-based modeling and simulation (ABMS) is a computational methodology that has gained increasing attention (Macal and North, 2007) because it provides a natural and real-world description of a system (Aguirre et al., 2011). Although ABMS has been used in much research, scope remains for emergency evacuation to be improved in terms of the interaction between agents and consideration of more complex environments.

The ongoing research reported in this paper focuses on the development of an agent-based model for emergency evacuation of a multi-floor building with a complex layout including stairs. In the agent-based model, a navigation method is proposed, which can imitate more realistic human movement. The agent-based model

provides a foundation for more individual and social human evacuation behaviors to be considered in the future.

RELATED WORK

In emergency evacuation agent-based models, an agent's arrival at an exit marks its successful evacuation, after which it is removed from the environment. An evacuation simulation ends when all agents arrive at exits. The selection of an exit by agents has been discussed in many agent-based evacuation models. For example, the FDS+Evac model (Korhonen, 2018; Korhonen and Heliovaara, 2011) considers three types of agents: (1) *conservative agents* that prefer familiar exits; (2) *active agents* that observe their environment to find the exit which will lead to the fastest evacuation; (3) *herding agents* that tend to use the exit which the majority of agents choose. Chu (2015) proposed that agents choose exits based on emergency cues, knowledge (of the location of exits), group members with whom they have pre-existing relationships, movement of the majority of the agents, or instructions given by the authorities. In the majority of agent-based evacuation models, navigation is not explicitly discussed and refers to how agents determine the evacuation route to take from their initial location to an exit in a building. This may be in part attributable to the relatively simple spatial environments considered in those models, in which it is easy for an agent to find a way to an exit (Ben et al., 2013; Tan et al., 2014; Wagner and Agrawal, 2014; Zhang et al., 2017). In its simplest form, with a model containing only one room with and without obstacles, agents move towards the chosen exit or slightly adjust their directions in order to avoid other agents and/or obstacles (Ben et al., 2013). In some agent-based models, agents have intermediate targets before arriving at their final targets (Tan et al., 2014; Wagner and Agrawal, 2014; Zhang et al., 2017). For example, Wagner and Agrawal (2014) and Zhang et al. (2017) developed an agent-based model for evacuation from a concert venue and a lecture theatre respectively. In both models, agents move from seating areas to pathways and then to exits. In Tan et al. (2014), the route planning module decides which exit an agents is to evacuate from and generates the corresponding escape route, which consists of a series of targets to move to. However, in multi-floor buildings with complex layouts, there are numerous intermediate targets (internal doors, staircases, corridors, openings, and so on). Thus, in such buildings, it is a challenge for agents to determine a route to an exit. Chu (2015) proposed a wayfinding strategy by introducing navigation points where visibility is locally maximal area-wise. That is, the visible region of a navigation point is greater than that of all of its adjacent points. The agent can choose a navigation point to move to, which is nearest to an exit or is selected randomly. A limitation of this wayfinding method is that it may lead to a bottleneck effect around some navigation points, which are not real objects in the environment. Also, the method to calculate the distance between a navigation point and the exit is not stated explicitly.

PRELIMINARY AGENT-BASED MODEL

In this paper, a preliminary agent-based model has been developed involving agents evacuating from a multi-floor building with staircases. The model has been developed using Repast Simphony, which has been described as a sophisticated modeling environment that makes it easy for users to program code, visualize models and analyze data simultaneously (Barnes and Chu, 2015). This section first describes agent representation and movement within the preliminary model followed by an explanation of how a flow field is constructed and the description of the navigation method used in the agent-based model.

Agent Representation and Movement

Agent Shape

In existing agent-based models related to human movement scenarios, including evacuation, the projection of a person's body is usually approximated by either a circle (von Sivers et al., 2016), an ellipse (Chraibia et al., 2016), or a set of three circles (one for main body and two for shoulders) (Thompson and Marchant, 1995). In terms of representing a person's body, it is claimed that three-circles is the best approximation since it has some geometrical and computational advantages (Qu et al., 2014). For example, in real life, the shoulder width of a person is typically greater than their lateral width, a feature which is not represented by a single circle. Figure 1 illustrates the central 'torso' circle with radius r_t, the two shoulder circles with radius r_s, and the half width of the whole body r_w.

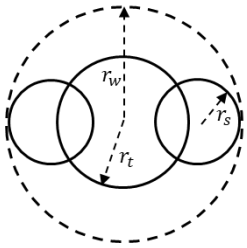

Figure 1. Three-circles Representing the Projection of a Person's Body

Agent Attributes

For the agent-based model presented in this paper, three agent attributes are used: *body size*; *speed*; *familiarity*.

In relation to body size, three dimensions are considered, namely r_t, r_s, and r_w (see Figure 1). These dimensions are used to govern the movement of agents in close proximity to one another, and that between agents and obstacles. The body size used is the adult size presented in Korhonen (2018), as shown in Table 1, which was first introduced by Thompson et al. (1997).

Table 1. Body Size

	r_w (m)	r_t/r_w	r_s/r_w
Size	0.255 ± 0.035	0.5882	0.3725

Agent movement is based on unimpeded walking speed, s_u, which is dependent on age and gender (Willis et al., 2004). This speed of 16 - 50 year olds, including males and females, is taken as 1.5 ± 0.28 m/s from a speed survey conducted in the UK involving 2613 people (Willis et al., 2004). According to the UK Higher Education Data and Analysis for 2013/14, the age of approximately 98% of people, i.e. staff and students, involved in higher education falls within this range (HESA, 2015, 2019).

Agents have different levels of familiarity within the spatial layout of an environment. Thus, an agent's familiarity parameter, F, is used to represent an agent's knowledge of building exits (from this point onward referred to as exits) and staircases. In this research, the familiarity level of each agent is modeled by assigning them with one of two values:

- F = 1 indicates that an agent has knowledge of the location from which it entered the building, namely the main entrance/exit, and all staircases.
- F = 2 indicates that the agent has knowledge of all exits and all staircases.

Note that both values indicate that agents are aware of all staircases as the focus of the research presented in this paper is on the effect of exits on evacuation.

Agent Movement

In reality, people take individual steps to move forward rather than gliding along smooth trajectories as in force-based models or hopping from cell to cell as in cellular automata (von Sivers et al., 2016). Thus, the basis of agent movement in this model is the 'stride' concept, which was first proposed in the Optimal Steps Model (Seitz and Köster, 2012). At a particular time step, an agent searches for the possible next point p_l^i to move to, based on its moving direction 'i' and stride length 'l'. The center of the agent moves to point p_l^i and its body occupies an area $a_{p_l^i}$. As shown in Figure 2, there are thirteen possible directions (i = 0, 1, 2,…, 12) in which an agent can move. Further, the radius of the semi-circle equals the stride length l of an agent, and direction $i = 0$ is the preferred direction of the agent.

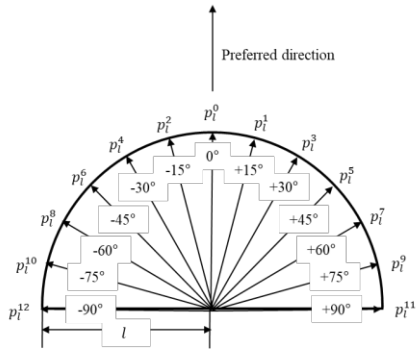

Figure 2. Possible Next Point for an Agent to Move to

Figure 3 indicates how an agent chooses the point p_l^i it will move to each time step. In Figure 3, 'k' is an integer between 0 and $(\lfloor l_m/0.1 \rfloor - 1)$, where l_m is the maximum stride length of the agent. The value of l_m is determined according to the empirical findings of Seitz and Köster (2012), who suggested that stride length has a strong dependence on an agent's speed. Equation (1) is used to calculate the maximum stride length,

$$l_m = 0.462 + (0.235 \times s_u) \tag{1}$$

At each particular time step, the agent first checks if it can move to point p_l^0 as indicated in Figure 2, which corresponds with the agent moving its maximum stride length in its preferred direction. If the agent cannot find a point to move to after completing the process indicated in Figure 3, the agent will stay at the same location for a time step and re-apply the process in Figure 3 at the next time step.

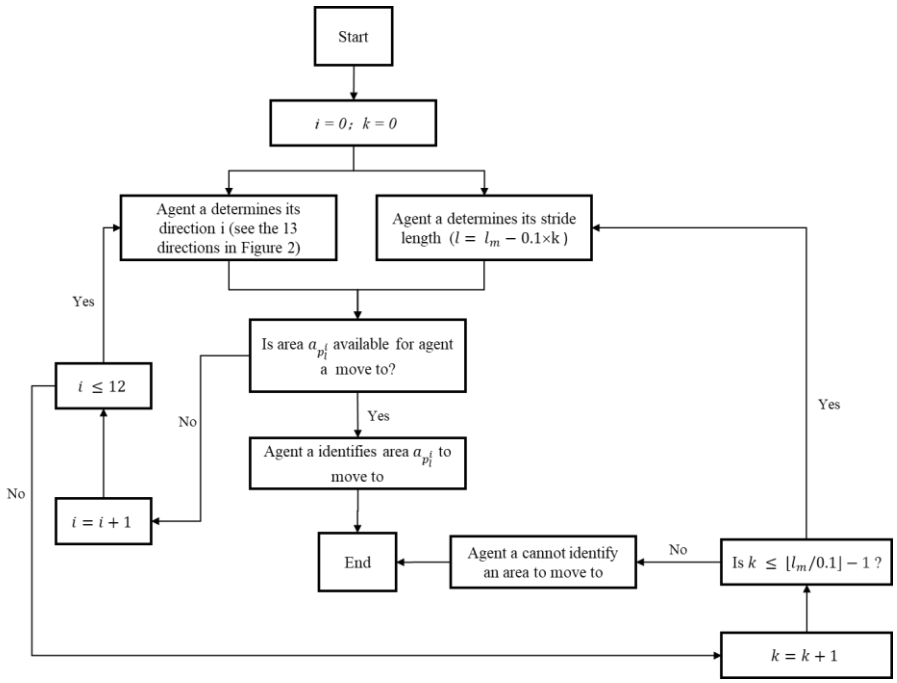

Figure 3. How an Agent Determines the Next Possible Point to Move to

Construction of a Flow Field

A flow field is constructed using navigation points, which are virtual points located at regular grid locations in open areas on each floor of a building. Each navigation point (NP) holds information regarding the direction and shortest distance to all building exits and staircases located on that floor of the building. Based on the flow field of NPs, which includes internal doors, agents can be directed to an exit or a staircase on that floor of the building. For computational efficiency, the flow field is pre-computed and re-used unless the building layout is changed.

Navigation

Initially, each agent selects the exit it will use to evacuate the building from those it has knowledge of and its closest to its location. Subsequently, the navigation method is applied by each agent to decide each move as it progresses to its chosen exit. The evacuation route to be taken by an agent includes a final target (exit) and may include intermediate targets (internal doors and staircases) en-route to the final target. Figure 4 shows the navigation method employed by an agent to find a way to its chosen exit. From Figure 4, if an agent is (not) located on the same floor as its chosen exit, the agent will move directly to that exit (staircase) if a straight line between them does not intersect with any walls. However, for cases where a straight line between them does intersect with a wall, the agent selects an internal door to move to. If the agent cannot locate an internal door, it will use the direction information held by the NP closest to its location. That is, the agent attempts to move in the direction given by the NP, rather than move towards the NP. Thus, it is not possible for congestions to occur around NPs, which would be unrealistic given they are virtual points.

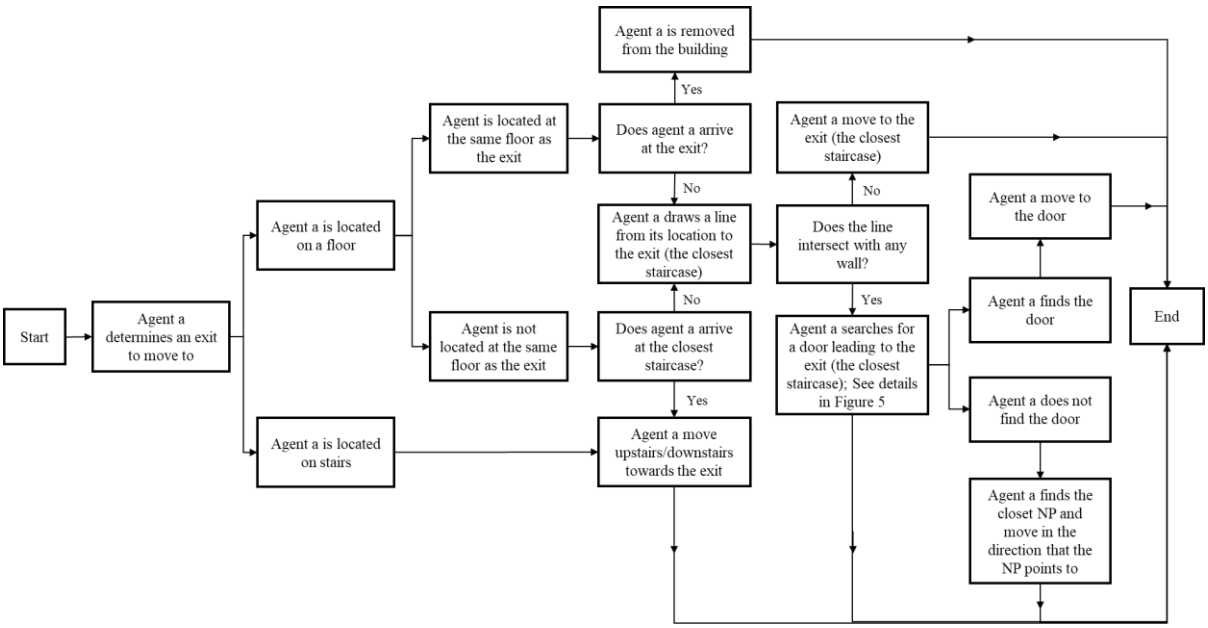

Figure 4. Navigation Method to an Exit

Figure 5 describes how an agent selects an internal door to move to, in which $d_a^{to\_door}$ indicates the distance from agent a to an internal door and $d_{door}^{to\_e/s}$ is the distance between an internal door to an exit (staircase). As indicated in Figure 5, the internal doors that an agent may choose are required to satisfy three conditions.

1) A straight line between the agent and the internal door must not intersect any walls.
2) The difference between angles θ_1 and θ_2 is not greater than 90 degrees, where θ_1 and θ_2 represent the angle of the direction from the agent to the internal door, and the angle of the direction from the internal door to the exit (or staircase) respectively.
3) The difference between angles θ_1 and θ_3 is not greater than 90 degrees, where θ_3 is the angle of the direction that an agent's closet NP directs it to the exit (or staircase).

By using θ_3, the agent will not miss potential internal doors, which are blocked by walls but lead to shorter routes. If the agent finds at least one internal door that satisfies the three conditions, it will choose the one with shortest route from its location to the exit (or staircase).

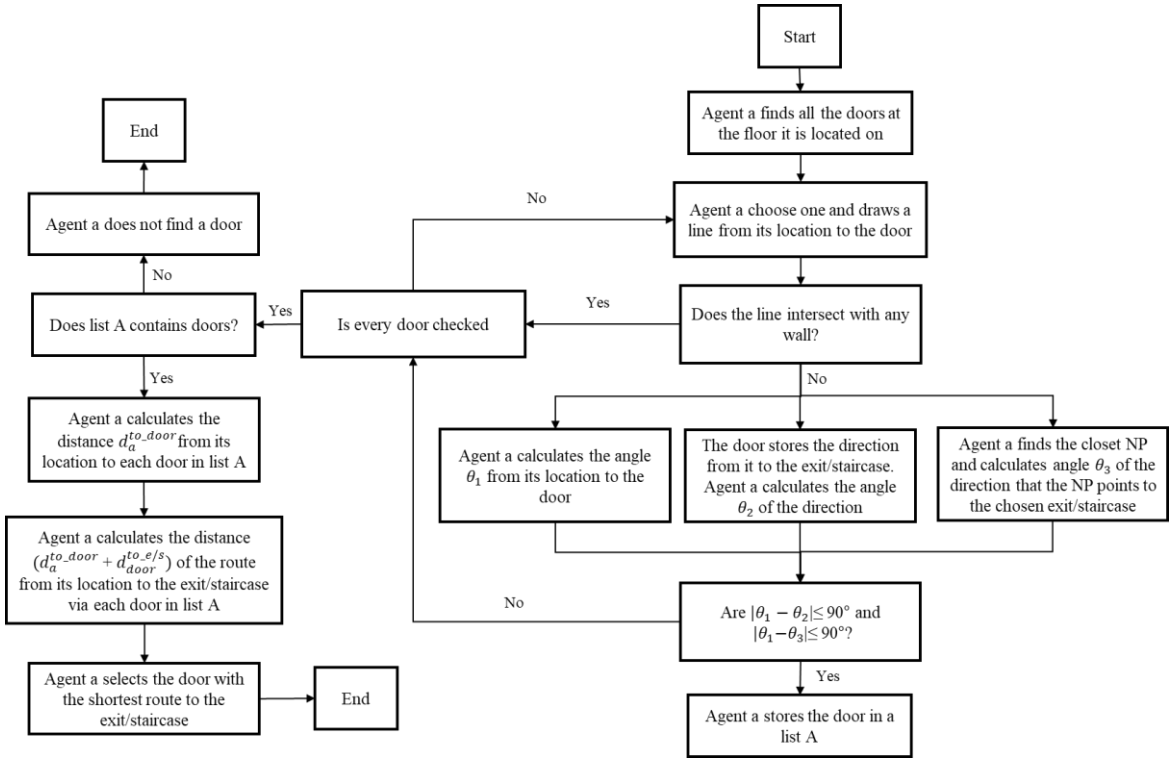

Figure 5. Select an Internal Door to Move to

CASE STUDY AND SIMULATION EXPERIMENTS

Layout of a Two-floor Building

For a case study, the agent-based evacuations modeled and simulated occur in a two-floor building. Figure 6 presents the layout of the virtual spatial environment used; specifically the ground floor and mezzanine floor of the Stephenson Building at Newcastle University, UK. In Figure 6, exits, internal doors, walls and staircases are colored blue, green, grey, and red respectively. It can be seen that there are nine exits (E1 to E9) and eight staircases (S1 to S8) on the ground floor. On the lower connecting floor, we show the staircases and on the upper floor we indicate the first steps of each staircase. The staircase on the mezzanine floor, leading to the first floor, are not shown as they are not included in the simulations.

Figure 6. Layout of a Two-floor Building

Simulation Experiments

Preliminary simulations experiments have been defined and performed to investigate the effect on evacuation time of (i) exit configurations and (ii) familiarity of agents with the building layout. On the two floors of the Stephenson Building at Newcastle University shown in Figure 6, four exit configurations have been considered, referred to as EC1, EC2, EC3 and EC4. In relation to Figure 6, for EC1 four exits are considered, namely E1, E3, E5, and E9 (e.g. those in the 'corners' of the building). In EC2, the five exits E5 to E9 are considered (e.g. those on one 'side' of the building). EC3 consists of seven exits, E1 to E4 and E7 to E9 (e.g. lacking exits on one 'corner' of the building), and finally EC4 includes all nine exits E1 to E9. For exit configurations EC1 to EC4, the main entrances/exits are set as E5, E9, E3 and E2 respectively. In terms of levels of familiarity with the building layout, combinations of the number of agents with F = 1 and F = 2 have been varied from zero to 400. Based on combinations of exit configurations and the number of agents with different levels of familiarity, twenty simulation experiments have been defined as presented in Table 2. For all simulation experiments, Figure 6 indicates the initial position of the 400 agents (each represented as three circles and colored black) distributed over the two floors. Each experiment was conducted once without repetition since the model does not currently include uncertainty in agent behavior.

Table 2. Simulation Experiments

Simulation experiment	Number of agents with familiarity level F		Exit configuration	Evacuation time (seconds)
	F = 1	F = 2		
SE1	400	0	EC1	133.3
SE2			EC2	127.3
SE3			EC3	114.1
SE4			EC4	99.7
SE5	300	100	EC1	133.3
SE6			EC2	127.9
SE7			EC3	114.1
SE8			EC4	99.7
SE9	200	200	EC1	101.5
SE10			EC2	128.5
SE11			EC3	114.1
SE12			EC4	97.9
SE13	100	300	EC1	99.1
SE14			EC2	99.1
SE15			EC3	95.5
SE16			EC4	66.7
SE17	0	400	EC1	95.6
SE18			EC2	87.1
SE19			EC3	95.6
SE20			EC4	62.5

SIMULATION RESULTS

For each simulation experiment in the two-floor building layout in Figure 6, the evacuation time of agents is indicated in Table 2.

Effect of Exit Configurations on Evacuation Time

Figures 7(a) and 7(b) present the relationship between the number of evacuated agents against time for experiments 1 to 4 (all 400 agents with F = 1) and 17 to 20 (all 400 agents with F = 2) respectively.

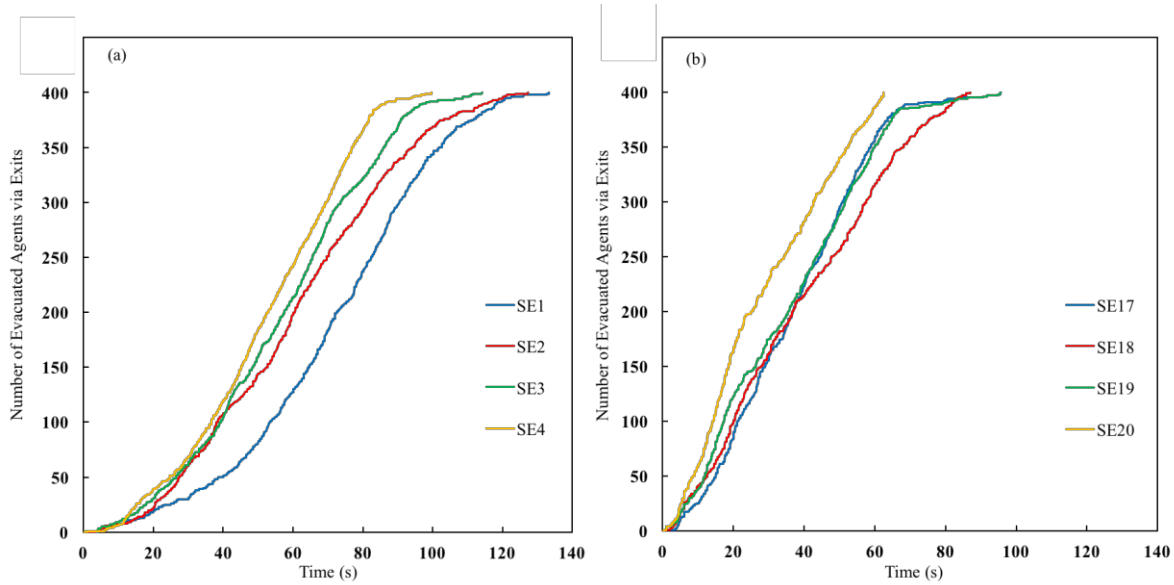

Figure 7. Number of Evacuated Agents versus time for (a) SE1 to SE4 and (b) SE17 to SE20

For simulation experiments SE1 to SE4, all agents have knowledge of one exit (i.e. the main entrance/exit), namely E5, E9, E3, and E2 respectively. Further, in Table 2 it can be seen that SE4 has the shortest evacuation time of 99.7 secs, which is 33.6 secs, 27.6 secs and 14.4 secs less than that of SE2, SE3 and SE4 respectively. This shortest evacuation time is likely due to the total moving distance of all agents to exit E2 being the shortest. Also, in Figure 7(a), it can be observed that from 0 to 42 secs, the evacuation rate in SE2, SE3 and SE4 are similar at approximately 3 agents/second. In contrast, for SE1 the evacuation rate is approximately 1.3 agents/second. Beyond 42 seconds, SE4 has the greatest evacuation rate of 6.2 agents/second until 82.7 seconds at which point it reduces to 1.2 agents/second until all agents have evacuated after 99.7 seconds.

For simulation experiments SE17 to SE20, all agents have knowledge of all building exits. In Table 2, it can be seen that the evacuation time of SE20, which uses exit configuration EC4, is the shortest at 62.5 secs, which is 33.1 secs, 24.6 secs and 33.1 secs less than that of SE17, SE18 and SE19 respectively. From Figure 7(b), it can be seen that the evacuate rate of SE20 is greatest than that of other three experiments throughout the evacuation, which is on average 6.4 agents/second. This result is as expected given there are nine exits from which agents may evacuate in exit configuration EC4, whereas there are four, five and seven exits in EC1, EC2 and EC3 respectively. However, as seen in Table 2, the evacuation time of 95.6 secs for SE17, using EC1 with four exits, is the same as for SE19, using EC3 with seven exits. Yielding the same evacuation time in these two experiments could be attributed to the location of the exits in EC1 to EC3.

Effect of Familiarity of Agents on Evacuation Time

From Table 2, it can be seen that for experiments using exit configurations EC1 to EC4, a non-linear relationship exists between evacuation time and the number of agents with familiarity $F = 2$. In the experiments for each respective exit configuration, there is a *turning point* in evacuation time as the number of agents with familiarity $F = 2$ increases.

For EC1, the evacuation time of both experiments SE1 and SE5 is 133.3 secs, in which the number of agents with familiarity $F = 2$ is 0 and 100 respectively. Also, the evacuation time has a relatively dramatic reduction from 133.3 secs to 101.5 secs when the number of agents with familiarity $F = 2$ increases from 100 in SE5 to 200 in SE9. The evacuation time of experiments having 300 and 400 agents with familiarity $F = 2$, i.e. SE13 and SE17, are 99.1 secs and 95.6 secs respectively, which is marginally less than that of experiment SE9. For experiments using exit configurations EC2 to EC4, the *turning point* referred to earlier occurs in the experiments that have 300 agents with familiarity $F = 2$, i.e. SE14, SE15 and SE16. Thus, it is suggested that having more agents with greater familiarity with building exits does not necessarily reduce evacuation time. This could be attributable to the agents with lower familiarity having a significant influence on total evacuation time.

Figure 8 presents the relationship between the number of evacuated agents against time for experiments using EC1 (Figure 8(a)), EC2 (Figure 8(b)), EC3 (Figure 8(c)) and EC4 (Figure 8(d)). In Figure 8, for each exit configuration, it can be observed that for experiments with similar evacuation times, the evacuation rate is not always greater for those experiments in which more agents have greater familiarity with building exits. For

example, the evacuation time of both experiments SE1 and SE5 is 133.3 secs, which have zero and 100 agents with familiarity F = 2 respectively. Further, for the first 26 secs, the evacuation rate of both experiments is 1.3 agents/second. Subsequently, for SE1, the evacuation rate increases slightly to 1.5 agents/second until 44 secs have elapsed, at which time it increases dramatically to 5 agents/second until 102.5 secs, when the rate reduces to 1.6 agents/second. For SE5, after 26 secs the evacuation rate increases to 5 agents/second until 90 secs have elapsed, after which it reduces to 1.1 agents/second. Thus, the evacuation rate of experiment SE5, with 100 agents having familiarity F = 2, is greater than that of SE1, with no agents having familiarity F = 2, from 26 to 44 secs. However, the evacuation rate is lower from 90 to 133.3 secs.

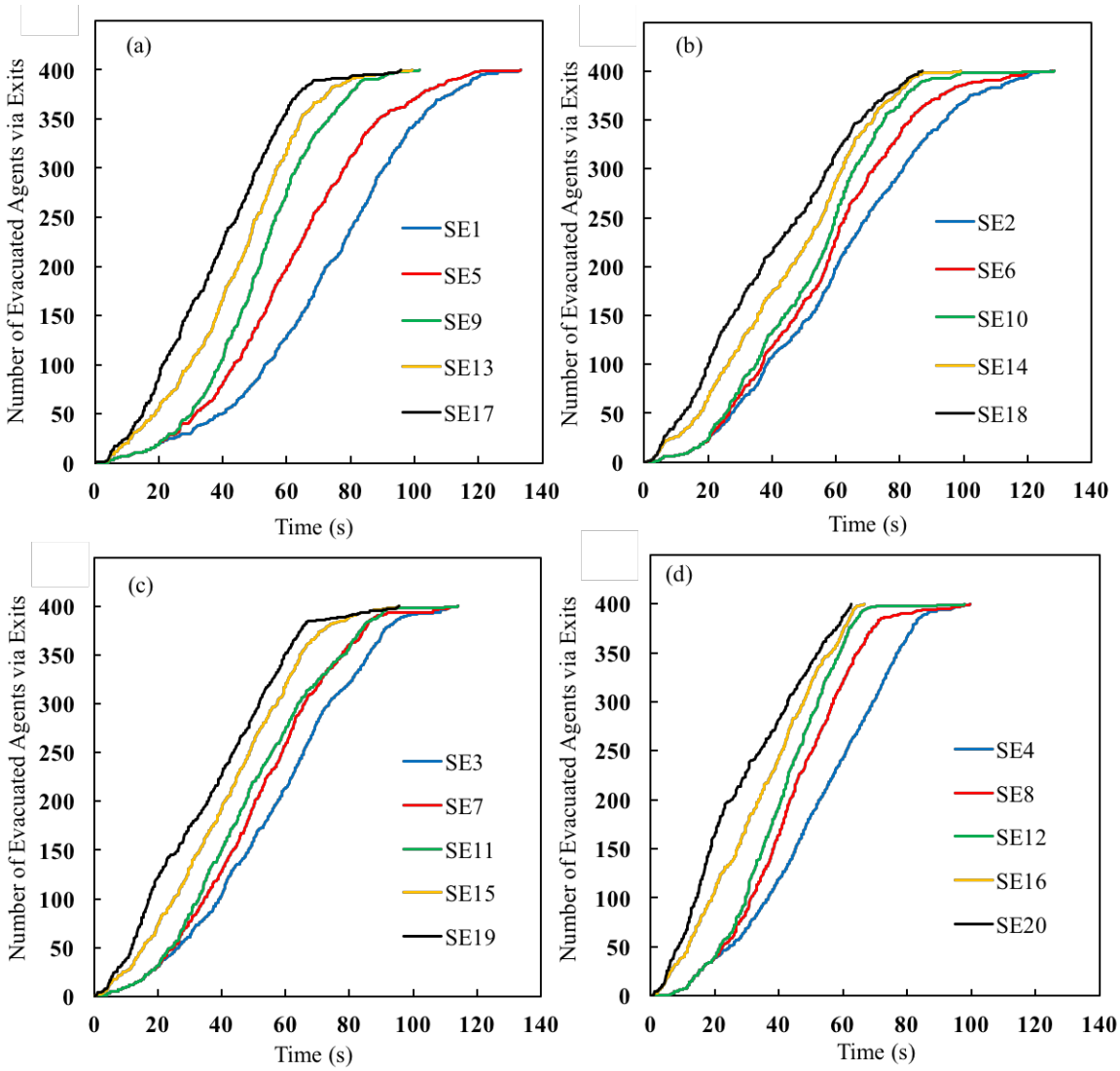

Figure 8. Number of Evacuated Agents versus time for (a) SE1, SE5, SE9, SE13 and SE17, (b) SE2, SE6, SE10, SE14 and SE18, (c) SE3, SE7, SE11, SE15 and SE19, and (d) SE4, SE8, SE12, SE16, and SE20

CONCLUSION AND FUTURE WORK

The focus of the ongoing research reported in this paper is agent-based modeling and simulation of emergency evacuation of a multi-floor building including stairs. In the agent-based model described, the virtual spatial environment is constructed and represented as a three-dimensional space. In this space, agents are represented as a projection of three circles and have three attributes, namely body size, speed, and familiarity level. Familiarity level, ranging from 1 to 2, is used to represent an agent's knowledge of the exits and staircases in a building. Each agent selects the exit it will use to evacuate the building from those it has knowledge of and is closest to its location. The novel contribution of this research is the navigation method for agents to identify the shortest route to an exit in a building within a complex layout.

Preliminary simulation experiments using a two floor building have been defined and performed to investigate

the effect on evacuation time of (i) exit configurations, and (ii) familiarity of agents with the building layout. In assessing the effect of exit configurations for the two-floor building considered, results show that the location of the main entrance/exit has a significant influence on evacuation time. In addition, having more exits does not necessarily lead to a shorter evacuation time as the relative locations of the exits also exits has an influence. In terms of the effect of the number of agents with familiarity of building exits on evacuation time, having more agents with high familiarity does not significantly reduce evacuation time in most cases for the two-floor building considered as the agents with less familiarity have a dominant influence on the evacuation time.

The research reported in this paper provides a foundation for a more sophisticated agent-based model to be developed and more complex scenarios to be considered. In terms of future work, a rich set of social theories exist regarding individual and social behaviors in emergency situations, from which key elements can be extracted and organized to be incorporated into the further development of the preliminary agent-based model presented in this paper. At an individual level, evacuees can make independent decisions based on emotion, past experience and knowledge. For example, if feeling highly stressed, evacuees are more likely to move quickly or exhibit aggressive behaviors such as pushing past people and in a hurry (Challenger et al., 2009). Also, based on past experience and knowledge, people are often reluctant to evacuate via an emergency exit instead preferring to use the exit with which they are most familiar, typically their entrance and exit route. Social behaviors involve interactions among evacuees. First of all, in a social group with pre-existing relationship (e.g. families and friends), group members will prefer to move together as a unit at the same speed and follow the same goals (Cornwell, 2003; Mawson, 2005; Sime, 1983, 1985). Secondly, interaction among evacuees who are unknown to each other in the crowd exists. That is, evacuees in a crowd may (1) exhibit coordination, cooperation and helping behaviors due to a shared identity in an emergency (Drury and Cocking, 2007; Drury et al., 2009), (2) act rationally and take into account the density around an exit and the distance to an exit simultaneously to achieve a quicker evacuation (Mintz, 1951; Simon, 1957), (3) show a tendency towards mass behavior, that is to mimic one another's actions (e.g. go with the flow), particularly in uncertain and unfamiliar situations (Helbing et al., 2002) and (4) prefer not to move in the opposing direction to the main crowd flow, even if the direct route they subsequently choose is crowded (Challenger et al., 2009). Further, a herding phenomenon may lead to serious congestion and uneven usage of available exits. In a congested area, evacuees may invert their stances to increase throughput, and thus their shape and size will have an influence. Body-to-body contact regularly occurs between individuals in a densely-packed crowd, resulting in not just pushing, but also shoving and falling down, and potentially in trampling and crushing. Finally, evacuees do not exist in isolation but engage in dynamic interplay with security authorities, such as the police or stewards (Challenger et al., 2009). The occurrence of security authorities will help normal evacuees respond more effectively (Donald and Canter, 1992). Also in terms of future work, empirical findings will continue to be explored for calibrating the parameters and validating the results of the further developed agent-based model. Further, more simulation experiments will be considered in which the individual and social behaviors vary.

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