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MULTI-AGENT BASED SIMULATION OF ELDERLY EGRESS PROCESS AND FALL ACCIDENT IN SENIOR APARTMENT BUILDINGS

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ABSTRACT

A means of egress from buildings is a critical aspect of building design and an important part of building fire regulations. However, elderly evacuees are often overlooked, being regarded as part of the average population, thereby ignoring the limitations elderly people may have. The computational egress model is a useful tool to evaluate postulated “what-if” scenarios, aiming to predict building egress performance under these designated scenarios. This paper first applies Multi-agent Based Simulation (MABS) supported by NetLogo to simulate the evacuation scenarios where evacuees are all elderly people, then statistical analysis is utilized to interpret results, and comparative analysis is conducted to offer some suggestions for egress design and crowd management.

1 INTRODUCTION

The development of egress regulations has generally been motivated by tragic losses in human history—often significant fire events in which large numbers of lives were lost (Tubbs and Meacham 2007). The primary aim of an egress design is to allow people to move from a hazardous location to a location of relative safety during a hazardous event (ICC 2016). An egress system, which encompasses evacuation plans together with crowd management, forms the basis of suitable life safety design for emergency events. In order to protect the life and property of citizens, effective egress systems and hazard precautions are necessary. However, although many studies are devoted to egress of multi-family buildings, most of these studies assume that evacuees are drawn from a population having an average physical capacity. Although these investigations highlight many egress attributes, they fail to provide specific conclusions that can be applied to selected segments of the population such as the elderly. In fact, statistics indicate that the proportion of seniors worldwide has been steadily growing since 1960. By 2050, it is estimated that the global increase of individuals over the age of 60 will rise to 2 billion. In Canada, one in four Canadians will be 65 or over by 2061 (Puts et al. 2017). Furthermore, due to changes in lifestyle, older adults tend to live in seniors’ homes where social interactions are easier to establish. As a result of this aggregation of older adults in this type of facility, i.e., apartment buildings, it is vital to conduct elderly-specific egress studies since this segment of the population is vulnerable during evacuation (Prot and Clements 2017). In other words, there is a need to re-evaluate egress design and crowd management methods for elderly people according to their vulnerability as they tend to move at a slower speed (Lord et al. 2005), and have a greater potential of falling (Sharifi et al. 2015).

To evaluate a performance-based life-safety egress design, a comparison between the required safe escape time (RSET), or the time required for evacuation, and the available safe escape time (ASET), or the time to loss of tenability, is required (Purser 2003). In order to guarantee the life safety of evacuees, RSET should be less than ASET (NFPA 2003). ASET is often restricted by the structural design of a building and the construction material used, and RSET is usually pre-calculated by different methods. Generally, the total evacuation time required includes three components: the detection time, the pre-movement time (delay time), and the travel time. In this paper, the detection time is assumed to be negligible, representing an ideal situation that the alarm system takes no time to detect the emergency. As for the remaining two components (delay time and travel time), different scenarios should be set to meet various evacuation conditions.

Several techniques to simulate RSET have emerged in the last 50 years. Depending on the methods by which the individuals are simulated, Equation-Based Models and Multi-Agent Based Simulation (MABS) Models are common simulation applications (Wilensky and Rand 2015). The equation-based models typically must make assumptions of homogeneity, and always require a knowledge of the aggregate behavior. By contrast, the MABS models are designed to model a heterogeneous population and only require the understanding of common sense behaviors of the individual agent (Weiss 1999). NetLogo, a well-known agent-based simulation software which provides a powerful visualization toolkit, is selected as the simulation environment. In NetLogo, the abstract building model is represented by patches, and evacuees are represented by turtles.

The structure of the remainder of this paper is as follows. We first review and comment on the literature on egress behavior involving elderly people. Then, the methodology, including the comparative analysis method and NetLogo, is introduced. The methods mentioned are showcased using NetLogo in the case study to optimize total evacuation time and injury potential in apartment buildings where elderly people live and some alternatives are compared to offer suggestions for building design and crowd management.

2 LITERATURE REVIEW

In recent decades, research on evacuation plan performance has been carried out by analyzing previously recorded evacuation drills. Through these recordings, engineers, building owners, and managers can develop an understanding of what occurs inside the building during an evacuation. Recently more research is focused on simulation approaches to achieve a better evacuation plan. However, few studies focus on the influence of specific occupant groups with shared challenges, e.g., the elderly. The emergence of senior housing where elderly people live together with assisted living facilities and elderly-friendly design is becoming increasingly popular in Canada and around the world.

However, elderly populations have suffered disproportionate morbidity and mortality in the event of major disasters (Prot and Clements 2017). This is often due to elderly evacuees being overlooked and regarded as average population, ignoring their possible limitations. Therefore, a look into the specific characteristics of elderly people that will influence their behavior during the evacuation process is necessary. This literature review focuses on two major attributes that characterize older adults and have a significant impact on egress performance: (1) slow speed of the evacuees, and (2) the increased risk of falling.

2.1 Lower Speed

In general, there is a trend showing a decline in a person's mobility speed after the age of 50 years. Lord et al. (2005) reported that the average horizontal walking speed for people aged 18 to 50 is 1.12 m/s, but this number decreases to 0.85 m/s for those 50 years of age or more. Given that currently the data used for standard design is based on mixed groups, it is necessary to re-evaluate the average evacuation speed in senior housing, and for this reason, the RSET in egress where elderly people dominate the population should be re-calculated. Kuligowski et al. (2013) conducted a study in an assisted-living facility examining the speed of elderly people when travelling in a staircase as presented in Table 1.

Table 1: Elderly speed on stairs in assisted-living facility.

Speed (m/s)	Notes
0.23 ± 0.08	Cane
0.21 ± 0.03	Stair descent device
0.41 ± 0.17	Older adults (no assistance)

2.2 Fall Accident

Clogging is the principal phenomenon during many evacuation processes of pedestrians in an emergency situation. As people push to escape from danger, compression forces may increase to harmful levels. Individuals may fall, while others may try to dodge those who have fallen, or simply pass through them (Cassol et al. 2017). On the other hand, falls are common for elderly people, and the risk of falling increases dramatically with age. Falling is the leading cause of injury-related visits to emergency departments in the United States and the primary etiology of accidental deaths in persons over the age of 65 (Fuller 2000). A survey dating back to 1990 reveals a positive correlation between the percentage of respondents reporting a fall and the age of these individuals, as presented in Table 2 (Askham et al. 1990). In light of this, it is worth investigating the impact of older adult fall accidents on the duration and the dynamics of the evacuation process.

Table 2: Percentage of respondents reporting a fall as increasing with age.

Age	Percentage reporting a fall
65–69 years	22.4%
70–74 years	27.9%
80–84 years	39.6%
85+ years	35.2%

Based on the factors highlighted above, namely, the combination of a lower walking speed with a higher probability of falling, it is clear that these risk potentials must be taken into account in terms of egress in multi-story senior housing facilities in order to build accurate models that will reflect the limitations associated with the evacuation of older individuals.

3 METHODOLOGY

In this section, we first introduce some basic knowledge of egress, including escape time, total evacuation time, egress safety evaluation index, and then construct the modeling environment using a general platform of egress simulation in apartment buildings, which allows flexible modification of parameters. Then the steps for building an MABS model are explained.

3.1 Basic Knowledge of Egress

Generally, the required escape time per person includes three components: the detection time, the pre-movement time (delay time), and the movement time. Figure 1 provides an overview of the evacuation process. Total evacuation time refers to the escape time of the last evacuee reaching the exit.

3.1.1 Delay Time

For the purpose of evaluating the escape time, the delay time must be calculated. Proulx and Pineau (1996) suggest that it normally takes 0.5 min to 5.0 min for individuals to begin the evacuation process after hearing the fire alarm, for an average of 3.0 min; delays are also reported to be as long as 25 min due to occupants ignoring the alarm. In general, delay time varies from person to person and is influenced by a number of factors (ICC 2016) such as the effectiveness of training and time of day.

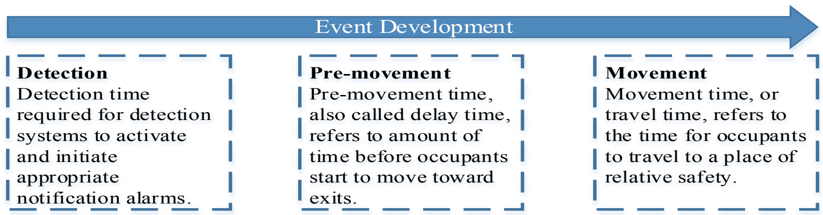

Figure 1: Escape time (Tubbs and Meacham 2007).

3.1.2 Movement Time

Movement time includes the time required for movement in rooms and corridors, through doors, and on stairs/safe elevators. People move according to their desired speed and abilities when space is sufficient; however, as occupant density increases, walking speed may decrease. In crowded spaces, movement can be restricted to a shuffle or even recurring stoppages (Nelson and MacLennan 1995). Table 3 presents the average walking speed of elderly people without assistance on flat walkways as well as travelling down stairs, and the respective adjusted walking speed in crowed spaces.

Table 3: Elderly pedestrian average walking speed (Bukowski 2008).

	Horizontally	Descending stairs
Average walking speed	0.85 m/s	0.35m/s
Average walking speed in crowded space (≥ 4 p/m^2)	0.72 m/s	0.25 m/s

3.1.3 Total Evacuation Time and Egress Safety Evaluation

RSET can be calculated using the following equation: $RSET = T_{escape} \times e$, where T_{escape} represents the escape time of each evacuee; and e represents the apparent evacuation efficiency. Since the calculated evacuation time is based on a model, thus approximate discrepancies between the modeled evacuation time and the actual evacuation time may occur. The difference between modeled evacuation time and actual evacuation time can be expressed in terms of evacuation efficiency (Nelson and MacLennan 1995). In this paper, e is set to 1.5 (conservative). To guarantee the life safety of evacuees, RSET should be less than ASET. since the fire-resistance rating for residential building corridors (occupant load > 30 persons) is required to be greater than 30 min (ICC 2016), thus ASET is set to be 30 min in this research. So the performance criteria require RSET to be less than 30 min and the escape time less than 20 min.

3.2 Develop the Model Environment

In reality, the graphical model of the building can be as complex as engineering drawings, and as simple as a brief sketch. Naturally, the level of detail of the environment needs to be described in concert with the objective of the simulation. If the simulation is aiming to observe a detailed behavior of agents when facing obstacle elements, a high level of detail about rooms, walls, corridors, obstacles, etc. is required. However, in situations where details of wayfinding behavior are simply represented by average travel speed, a lower level of detail is more realistic since this will largely reduce the complexity of the model and thus reduce the computational power needed for simulation.

For practical purposes, the abstraction of the building used to conduct the simulation in NetLogo is represented by patches, which are set as 0.5 m × 0.5 m each, and evacuees are represented by turtles whose attributes such as speed, risk of falling, etc. are assumed to be variable. Turtles move one step per clock tick thus allowing the total evacuation time to be estimated from the number of ticks (Wilensky and Rand 2015).

The detailed steps to build the simplified egress components in NetLogo are as follows:

1. Select the number of staircases and number of floors.
2. Calculate the length of the corridor between staircases. The width of the corridor is set to 2 m (4 patches), similar to the international building code (ICC 2016).
3. Locate the apartment doors per floor. This egress model represents the apartments by doors that are connected to the corridor as grids and regards the door as the starting point of the egress process. Interval length between each door grid can be either set as default or read from the provided external data sheet.
4. Locate branch corridors. Branch corridors are simplified in the same way as apartment doors.
5. Calculate the average travel distance in the staircase between two floors. The width of the staircase is set to 1 m, rounded from that which is stated in the international building code (ICC 2016). When occupants travel in the staircase, two types of movement are considered: vertical travel along stairs and horizontal travel along landings. Based on user judgment, the travel distance between two floors is calculated as expressed in Eq. (1), where L represents travel distance between two floors, H refers to the height of one floor, and b represents stair width.

$$L = [2H + \pi \times b] / 2 \tag{1}$$

Since grid cell (0.5 m × 0.5 m) is used to draw the stairs, the length is then rounded to ensure the number of grids used to represent stairs is an integer.

3.3 Develop the MABS Model

3.3.1 Purpose

The model is designed to simulate the evacuation process of occupants (seniors) from a multi-story residential building in response to an emergency alarm and evacuating the building under various scenarios, including different delay time groups and different populations of occupants.

3.3.2 State Variables and Scales

The agents represented in the model of interest are essentially an abstraction of elderly individuals. These individuals are characterized by their state variables: age, location, staircase option, delay time, moving speed on stairs, and moving speed in corridors. Simulation time proceeds in discrete steps (0.5 s per step). The model is spatially explicit by converting the building plan into simplified grids representing essential egress components.

3.3.3 Process Overview and Scheduling

Each individual, i.e., turtle, in the model is traced from appearing in the start points to disappearing when reaching the exit. Within each run of the evacuation simulation, the following processes occur in the following order for each entity: location (where agents are situated before they start to move); delay; move to corridor; move to staircase; fall down or encounter fallen individual; and reach the exit. Individuals are processed in a randomized sequence for every simulation run. The patterns describing the above processes are introduced in Section 3.3.7 below.

3.3.4 Design Concepts

1. *Emergence.* Pedestrian dynamics and queuing behavior emerge from the behavior of individuals, but individual behavior is entirely imposed by the wayfinding pattern. A certain level of agent vibration (i.e., agents change direction like a vibrating ball) is imposed onto the model. The performance of the dynamic model is evaluated by the trajectory test results: the lower the result, the better the performance. A certain level of "vibration" of the trajectory is suggested to resemble the reality. The behavior of vibration in reality does occur in some cases. For example, in a queuing situation, the person at the end of the queue may continue moving from the current group to the next group in the case where the other queue becomes shorter. The acceptable result is determined by the user. However, this can be controlled and defined by changing the parameters of the wayfinding pattern.
2. *Interaction*. Two types of interactions are modeled: (i) individuals changing their direction when their original target patch is occupied by another individual; and (ii) individuals slowing down when they are in congestion situation (surrounded by more than four neighbors).

3.3.5 Initialization

Every simulation begins with a specified number of individuals, i.e., turtles. The staircase in the given environment model that is closest to each individual is selected as the dominant egress route. Locations and delay time of each individual are randomly initialized; the delay time is generated using triangular distribution and location is uniformly distributed for the given start points.

3.3.6 Input

The environmental variation of the model is simplified and calibrated from the existing building plans. The process of generating environmental variation is described in Section 3.2.

3.3.7 Sub-Models

1. *Locating*. The individuals are populated randomly into the designed start points (i.e., apartment unit doors).
2. *Delay Time*. In the evacuation simulation, the second step is to collect data on the delay time, analyze it, and conform to the specific distribution. Through analyzing the delay time data from several drills provided by Proulx et al. (1994), the delay time in the proposed model is generated stochastically using Monte Carlo method with triangular distribution. A random variate, U, is drawn from the uniform distribution in the interval (0, 1), and then the speed variate is calculated using Eq. (2).

$$\begin{cases} X = a + \sqrt{U(b-a)(c-a)} & for\ 0 \le U \le F_{(c)} \\ X = b - \sqrt{(1-U)(b-a)(c-a)} & for\ F_{(c)} \le U \le 1 \end{cases} \tag{2}$$

   where X represents the actual delay time before travel; $F_{(c)} = (c-a)/(b-a)$, U represents random variate drawn from the uniform distribution in the interval (0, 1); and a, b *and* c refer to low-delay value, high-delay value, and mode (most likely) delay time value, respectively.
3. *Movement.* To simulate individual travel behavior, an individual decision-making algorithm is applied to account for the wayfinding actions performed during the egress. In this model, Markov Chain is chosen to describe the stochastic wayfinding process. Each individual has four

independent choices with probabilities, namely, go straight forward, go parallel, go diagonal, and stop (depicted as A, B, and C in Figure 4). Suppose that a given occupant follows the sequence of steps defined as $X_1, X_2, X_3 \ldots$ with the Markov property, namely that the probability of moving to the next state (step count) depends only on the present state and not on the previous states as expressed in Eq. (3).

$$P(X_{n+1} = x \mid X_1 = x_1, X_2 = x_2, \ldots, X_n = x_n) = P(x_{n+1} = x \mid X_n = x_n) \tag{3}$$

4. *Fall Accident*. When an individual falls, the other individuals would walk around to avoid them until the fallen individual eventually stands up and continues walking. However, when the crowd is very dense, some individuals may not be able to walk around a fallen individual. The simulation enters into a state of congestion characterized by a speed equal to zero. This is simulated using a sub-model approach that is activated by a fall-down flag. If the fall-down flag is deployed, the variable "block" starts to countdown. "Block" here refers to simulation time "ticks". During the block time, the speed of this individual becomes 0. Other pedestrian individuals cannot walk around the fallen pedestrian and thus are forced to change direction. At the end of the countdown (the variable "block" reaches 0), the speed returns to normal.
5. *Reach Exit*. When an individual reaches the exit, all relevant information regarding their evacuation process is generated and documented before the individual is discarded. The collected data from the collective agents can then be processed to obtain a statistical overview of the egress simulation.

4 CASE STUDY

To understand the influence of different scenario parameters on simulation results, a series of experiments are designed based on a drill and the simulation outcomes are compared. The drill is selected from a joint research project that was undertaken by the National Research Council of Canada (NRC) and Canada Mortgage and Housing Corporation (CMHC) to study evacuation drills in midrise apartment buildings in which the occupants have mixed physical abilities (Proulx and Pineau 1996).

4.1 Drill Model

The building structural information is generated from building 3 presented in the report by Proulx et al. (1994) and remains constant as the base environment where "what-if" experiments can be carried out (see Figure 2). The apartment building comprises 7 stories and 3 staircases with the middle staircase assumed to be out of service (as staged during the drill experiment). In total, there are 118 units, including activity rooms on floor 1; and the lengths of the two corridors are rounded to 27 m and 18 m, respectively. The travel distance between two floors is 5 m.

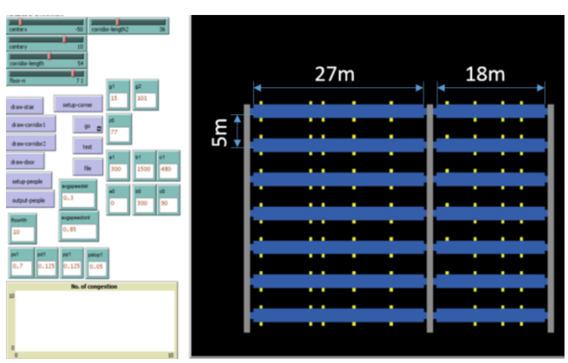

Figure 2: Visualized model of drill building.

The attributes associated with each agent are summarized in Figure 3 and it is further assumed that these agents follow the same dynamic rules to "travel" within the building model. A detailed example of agents traveling in the staircase is explained in Figure 4. When agents travel across the patches, they are designed to possess their individual perspective, which allows them to choose their own paths based on information available at their specific location and the people around them. To be specific, one evacuee agent at one patch makes their decision by noticing the neighbor patches (see A, B, and C in Figure 4) around them and whether or not the patches are occupied. The decision-making process while the agent is traveling down stairs is explained in Figure 5.

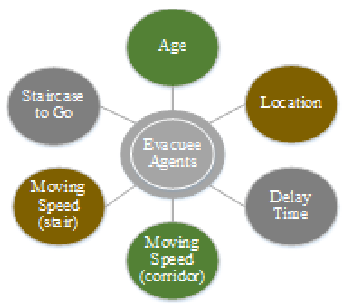

Figure 3: Agent variables.

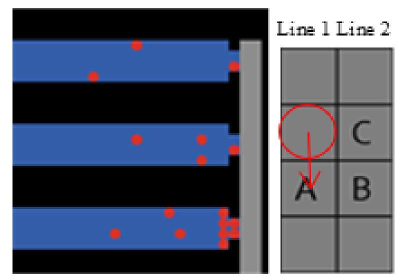

Figure 4: Visualized model of agents.

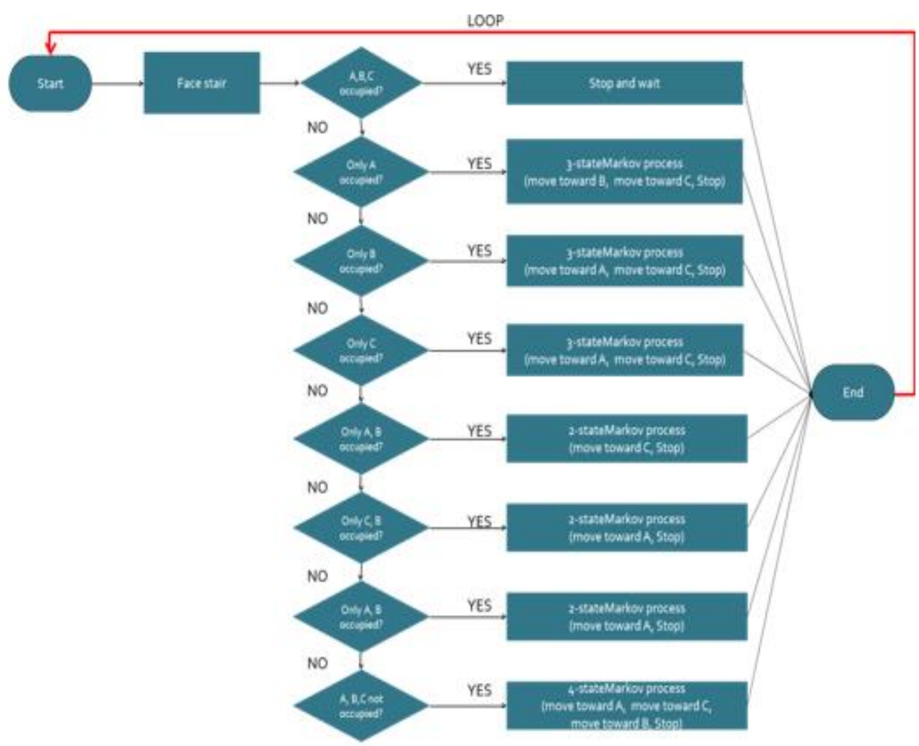

Figure 5: Decision-making process of descending staircase.

After running the drill model 30 times, the evacuation timing results are collected. The data are analyzed in two aspects, that is, movement time, and escape time,) and will be compared with the real data reported in the drill. Based on statistical analysis, we are 95% confident that the mean of the simulated movement time of each agent is between 71.6 s and 77.4 s, and the mean of escape time of each agent is between 578.5

s and 725.5 s. The mean of movement time and escape time reported in the drill is 75 s and 657 s, respectively. These results are comforting it may be indicative that the assumptions of the proposed model are able to capture the most important factors affecting the escape time and movement time of the sample used in the drill. The next step is to apply the same approach to the case of an elderly population, which is the primary purpose of this work.

4.2 Experiment Model Simulation

After the drill model is checked, the model is modified to the scenario where all occupants of the building are older adults (> 50 years) with a lower mobility speed compared to those that are younger. The speed and occupant data are collected from another drill from the same experiment. For the elderly model, there is an average of more than 7 people out of 77 with escape time greater than 1,200 s (20 min) and REST more than 30 min, which means that more than 7 occupants are at a high potential of hazard. To optimize this problem, a series of "what-if" scenarios are then designed to test the possible parameters that may influence the total evacuation time thus leading to a hazard potential. The parameters that have been identified and tested are summarized in Table 4. Details about the parameters are provided in the following section.

Table 4: Evacuation parameters in case study.

Parameter	Value	Definition
Pedestrian age	> 50	Senior housing
Early delay group	Accumulated	N/A
Early delay time (s)	[0, 300, 90]	Triangular distribution
Late delay time(s)	[300, 1500, 480]	Triangular distribution
Number of evacuees	Accumulated	N/A
Average Travel Speed	0.85 m/s in corridor; 0.3 m/s on stairs	Non-assisted
Fall accident	Accumulated	Evacuee falls and blocks the way
Fall duration	0.5 – 1.0 hr	Duration an accident blocks the way

4.2.1 Early Delay Group (EDG) vs Late Delay Group (LDG)

A sensitivity analysis for the number of people who react early is applied to identify the influence of delay time on the total evacuation time. In the original scenario of the drill, a set of 33 people were assumed to be in the EDG and 44 in LDG with a total number of evacuees equaling 77. The modified scenarios are designed decreasing the number of people in the LDG by 7 each time.

4.2.2 Congestion and Fall Accident

Pedestrian density is closely related to the occurrence of congestion, which may lead to longer evacuation times. Alternative scenarios are obtained by increasing the number of evacuees 20 at a time, beginning with 77 in the first scenario and ending with 217 in the final scenario, with delay times chosen from the set {0s, 300s, 90s} and a fall down duration of 30 min. The fall accident simulation is designed in three scenarios: not considering fall accident, considering 1 fall, and considering 2 falls.

4.3 Modified Scenarios

Figure 6 presents an example of modified scenarios. As the example scenario (137 occupants, 1 fall) indicates, 90 s after the start of evacuation, nearly half of the occupants have started moving and the others still remain inside their apartments (Figure 6a). At approximately 200 s (Figure 6b), agent 7 falls down and blocks the way. Figure 6c depicts the consequential congestion (represented by agents turning yellow in the simulation) after a fall occurs. During the visualized egress process, data of delay time, movement time, escape time of each agent, and number of agents in congestion are recorded in a separate text file which can then be used for further analysis.

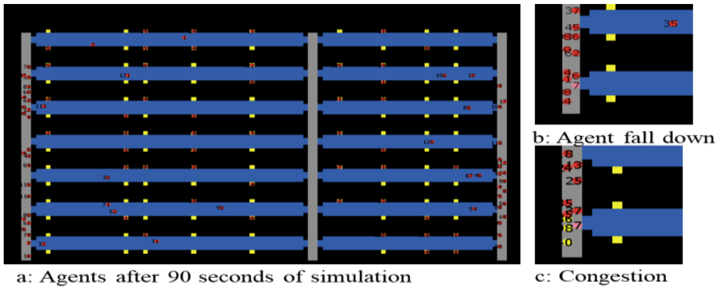

Figure 6: Fall accident simulation scenarios.

5 DISCUSSION

5.1 Delay Time Factor to Evacuation Safe

The escape time of each agent is wide spread during the whole evacuation process, some occupants reach the exit during the first minute while others require more than 20 min; this is clearly highlighted as a hazard situation by the egress safety evaluation method. This long delay for some occupants to reach safety is tested as the leading correlation to total evacuation time. Based on this experiment, the number of LDG residing in a building is suggested to be less than 28 out of 77 to guarantee the life safety of each evacuee. The detailed results could be seen in Figure 7.

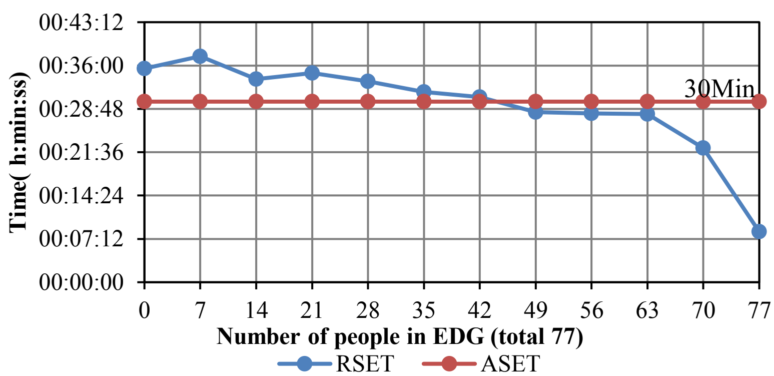

Figure 7: Total evacuation time of scenarios with different delay groups.

5.2 Pedestrian Density and Fall Accident

One of the main limitations of evacuation drills is that participants do not include all the occupants; for example, in the initial drill scenario, only 77 of 255 occupants participated in the drill. According to Figure 8, there is a trend showing an increase in RSET of the last evacuee when the number of occupants who attend the evacuation experiment grows. When the number of evacuees reaches 217, the RSET of the last evacuee increases from 9 min 3 sec to 10 min 33 sec. Fall accidents also contribute to longer RSET, and the influence of fall accidents becomes more significant as the number of evacuees increases. When the number of evacuees reaches 217, the RSET of the last evacuee considering 1 fall and 2 falls become 11 min 28 sec and 12 min 28 sec respectively.

The situation of congestion also worsens corresponding to an increase in evacuee number. According to Figure 9, 70 of 217 people are in a crowded situation (surrounded by more than 4 neighbors), which may lead to potential hazards. The number of evacuees in congestion significantly increases when fall accidents occur. When the number of evacuees is 77, the number of evacuees in congestion is 2 considering no fall accidents, but the number increases to 14 considering 1 fall, and 18 considering 2 falls. More than 43% of evacuees are in a crowded situation when 2 fall accidents occur.

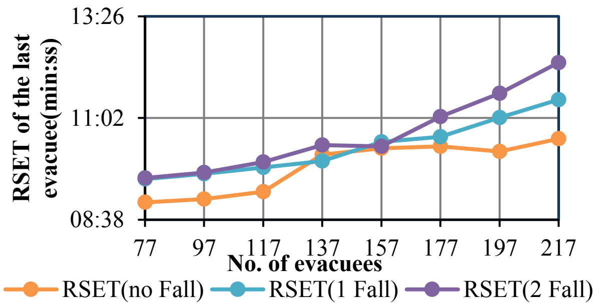

Figure 8: Average movement time.

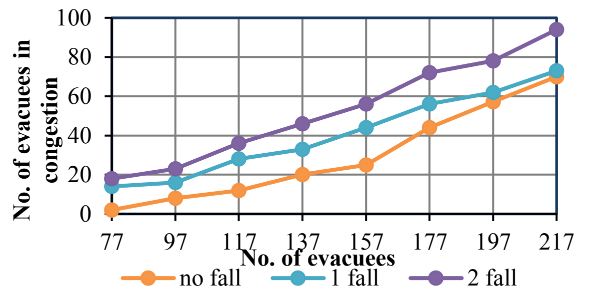

Figure 9: Maximum number of evacuees in congestion.

6 CONCLUSIONS

By using this MABS model, the effects of delay time, evacuee number, and fall accident are evaluated. The key advantage of the model is the flexible manufacturer interface that allows people to change multiple parameters of the scenarios, including elderly attributes, which therefore can be easily modified to simulate different senior apartment buildings without the need of coding. According to the case studies, long delay time and fall accidents are suggested to have a significant influence on egress safety evaluation. The high simulation speed allows numerous runs for the purpose of efficient quantitative analysis. The MABS model now under development can possibly be applied to work as a supplement to evacuation drills, and also to evaluate egress safety for a multi-floor building. Further research can be undertaken in the following areas: (1) identifying evaluation of factors that increase the potential of fall accidents; (2) developing assisted methods such as evacuation chairs.

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