Multi-agent Based Simulation of Elderly Egress Process and Fall Accident in Senior Apartment Buildings

by

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ABSTRACT

A means of egress from buildings is a critical aspect of building design and an important part of building and fire regulations. Poor egress evacuation performance poses a threat to both personal and property safety; thus, it is necessary to maintain an effective egress system for buildings. However, elderly evacuees are often overlooked, being regarded as part of the average population, thereby ignoring the limitations elderly people may have. A computational egress model is a useful tool to evaluate postulated "what-if" scenarios, aiming to predict building egress performance under these designated scenarios. This thesis first applies an MABS (Multi-Agent-Based Simulation) method (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.

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CHAPTER 1: INTRODUCTION

1.1 Research Motivation

The word “egress” refers to the action of going out of or leaving a place. The development of egress regulations has generally been motivated by tragic losses in human history—often particularly significant fire events in which large numbers of lives were lost (Tubbs 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 real or perceived hazard event (International Code Council (ICC) 2016). An egress system, namely evacuation plans combined with crowd management, forms the basis of sufficient life safety design within a building in the event of an emergency situation (Tubbs 2007). In order to protect the life and property of citizens, an effective egress system and hazard precautions are necessary.

The proportion of seniors within the global population has been steadily growing since 1960. By 2050 it is estimated that, internationally, the increase of people over the age of 60 will rise to 2 billion; by 2061, one in four Canadians will be 65 years of age or over (Puts et al. 2017). Since elderly people are vulnerable during building evacuation (Prot and Clements 2017), 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 more slowly (Lord et al. 2005) and have a greater potential of falling (Sharifi et al. 2015).

1.2 Research Objectives

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 (Society of Fire Protection Engineers (SFPE) 2003). ASET is often restricted by the structural design and materials used, and RSET is usually precalculated by various methods (Tavares and Galea 2009). Generally, total required evacuation time comrprises three components: the detection time, the pre-movement time (delay time), and the travel time. In the present research, the assumption is made that the detection time (the amount of time required for the system to detect the fire and sound the alarm) is ignored as an ideal situation that the system recognize the fire immediately. Thus, for the two main components, the premovement time (delay time), and the 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 method by which the individuals are simulated, Equation-Based Models and Multi-Agent-Based (MAB) 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 behaviour. By contrast, the MAB models are designed to model a heterogeneous population and only require the understanding of common sense behaviours of individual agents (Weiss 1999). NetLogo, which is a visualized agent-based simulation software, is selected as the simulation platform.

1.3 Thesis Organization

The structure of the remainder of this thesis is as follows. In Chapter 2, a thorough review of the existing literature is conducted on the egress behaviour involving elderly people. Then, in Chapter 3, the methodology, including the comparative analysis method and NetLogo, is introduced. In Chapter 4, these methods are applied in a case study to optimize total evacuation time and injury potential in midrise apartment buildings and some alternatives are compared to provide some suggestions for building design and crowd management. Chapter 5 presents the conclusions of this research, its contributions, and the directions of future work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The application of Multi-Agent Based Simulation (MABS) in emergency evacuation (egress) simulation for various crowds and scenarios is a relatively recent research field, and this thesis would be incomplete without a thorough introduction of related fields. Chapter 2. presents an introduction to current regulatory requirements for means of egress in residential buildings in emergency evacuations. A common argument in the field for the need to re-evaluate egress design to reflect the specific characteristics of elderly people and senior housing is explored in Section 2.2. Section 2.3 touches on the background of egress research approaches and explores the application of the MABS approach in pedestrian crowd simulation and the relevant research.

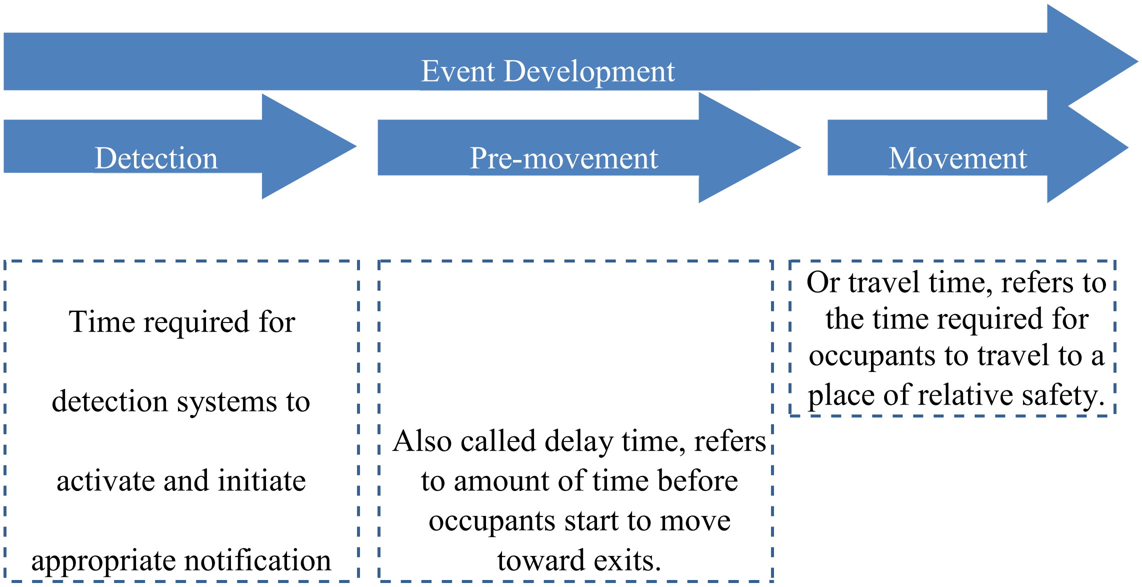
2.2 Review of Residential Egress Design Requirements

Egress from a building is a critical aspect of building design and an important feature of building and fire regulations. The prescriptive egress codes and standards are primarily embodied in the International Building Code (IBC) of the International Code Council (ICC) (IBC 2016; National Fire Protection Association (NFPA) 2017) and Life Safety Code of the National Fire Protection Association (NFBA 2017). In this section, the components of egress design and how they are evaluated are introduced, and the related regulations and management approaches are reviewed.

2.2.1 Life Safety and Means of Egress

According to (ICC 2016), the phrase “means of egress” refers to the ability to exit the structure, primarily in the event of an emergency such as a fire. Specifically, a means of egress is broken down into three parts: the path of travel to an exit, the exit itself, and the exit discharge (the path to a safe area outside) (ICC 2016). An egress system, or evacuation plans combined with crowd management, forms the basis of suitable life safety design for emergency events (Tubbs 2007).

To evaluate a performance-based life-safety egress design, a comparison between the RSET and the ASET is required (Purser 2003). When RSET is less than ASET, evacuees are enabled to exit the building within a safe time period (SFPE 2003). ASET is often restricted by the structural design and material used, and RSET is usually pre-calculated by different methods (Tavares and Galea 2009). Generally, the required total evacuation time includes three components: the detection time, the pre-movement time, and the travel time. Figure 2-1 provides an overview of the evacuation process:



Time required for detection systems to activate and initiate appropriate notification

Also called delay time, refers to amount of time before occupants start to move toward exits.

Or travel time, refers to the time required for occupants to travel to a place of relative safety.

Figure 2-1: Evacuation Time

(Tubbs 2007)

2.2.1.1 Detection and Pre-Movement Time

Events requiring evacuation can be detected through manual means or automatic systems. Currently, automatic systems are commonly designed and installed to address fire events and the release of hazardous material (Tubbs 2007; Zeng et al. 2017). After occupants receive the notifications, there is a delay before they initiate the evacuation process. The delay time includes the time to notify, reaction time, and pre-evacuation time in most cases. Literature (Proulx and Pineau 1996) suggests that delay time varies from less than a few seconds to more than 5 minutes, and may vary significantly in different buildings. In general, the delay time is influenced by several factors (IBC 2016):

- the effectiveness of emergency alarms;
- the effectiveness of training; and
- the time of day, weather, etc.

Proulx (2001) provides a set of conditions that may help estimate occupant delay times. These conditions and time estimates are listed in Table 2-1. From the table, it can be observed that live directives using a voice communication system have a significant advantage of short recognition time compared to the other two methods. Warning systems, using alarm bells or similar, has the worst performance out of three. Proulx suggested that this may be explained as people are used to the alarm bells.

Table2-1:
Recognition time of different occupancy type and characteristics
(Adapted from: SFPE Handbook Table 3-1)

Occupancy Type and Characteristics	**Recognition Time (minutes)**		
	W1	**W2**	**W3**
Offices and schools (occupants are awake and familiar with the building alarm systems and evacuation procedures)	<1	3	>4
Shops, exhibitions, museums, leisure centres, and other assembly buildings	<2	3	>6
Dormitories, boarding schools, and apartment buildings	<2	4	>5
Hotels and boarding houses	<2	4	>6
Hospitals, nursing homes, and other institutional establishments	<3	5	>8

W1: Live directives using a voice communication system
W2: Nondirective voice messages (pre-recorded) and/or informative visual display W3: Warning system using alarm bell, siren, or similar

2.2.1.2 Occupant Travel Time

Travel time, which refers to the time required for evacuees to travel to a place of safety, includes the time required for movement in rooms and corridors, through doors, and on stairs or safe elevators. According to IBC (2016), the total travel time is largely dependent on three factors: (1) crowd density; (2) occupant abilities; and (3) available clear width (regardless of obstacles).

Movement occurs according to a person's 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 1995). Egress doors, aisles, hallways, stairs, etc. are components of a building that restrict occupant movement, thus architectural design influences travel time more than pre-movement time. Egress width, as mentioned above, affects occupant capacity and can create queuing during evacuation. The flow rate at an exit door is constrained by both specific flow rate and width as expressed in Equation 2.1 (IBC 2016):

$$\mathrm{F}_c = F_s \times W_e \tag{2.1}$$

where F_c represents the flow rate at an exit door (persons/second); F_s represents the specific flow (persons/meter/second); and W_e represents the effective width. A range of exit-specific flow is presented in several studies, from 1.330 p/m/s (IBC 2016) to 1.488 p/m/s (NFPA 2017).

2.2.2 Residential Design Code for Egress

The National Board of Fire Underwriters (NBFU) developed the National Building Code, the first model building regulation in the US in 1905. Later in 1914, the Life Safety Code was originated by a NFPA committee (NFPA 2O17).

Regulations related to egress include the *International Building Code* (IBC 2016), and the *Life Safety Code* (NFPA 2017) In the IBC (2016), the means of egress is defined by three components: the exit, the exit access, and the exit discharge. These components are illustrated in Figure 2-2.

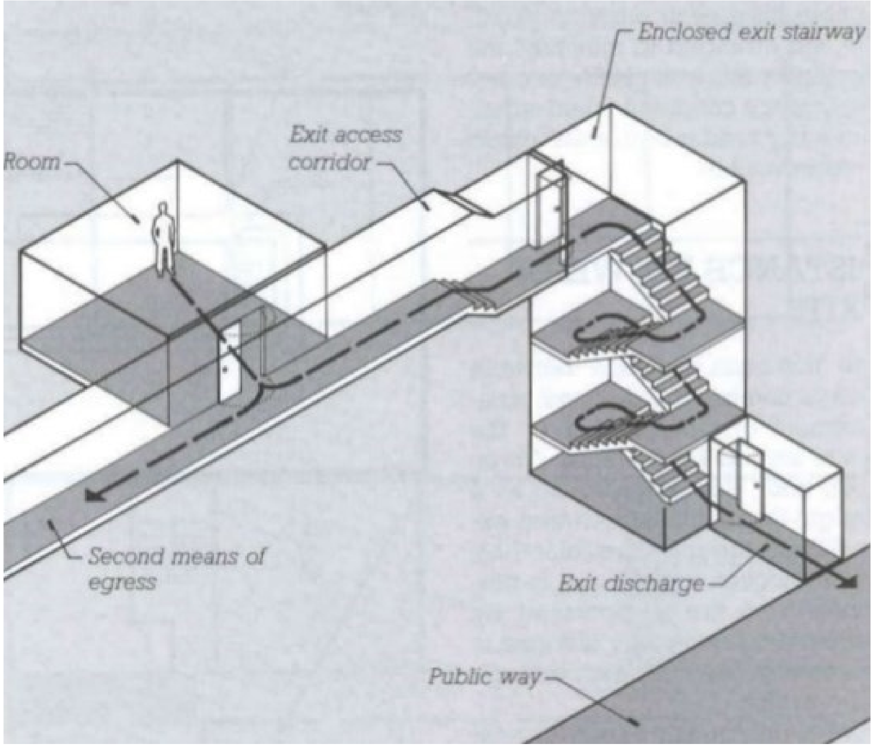


Figure 2-2: Typical exit components within a building

(Adapted from Ochshorn 2017)

However, due to the scope of the present research, only regulations related to this thesis are presented here. For a more detailed summary of the design regulations, please refer to the study by Tubbs (2007).

Occupant Load: The occupant load factor is used to specify the minimum amount of space needed per person for normal anticipated use of a space. Typically, the occupant load factor is known as the floor area per building occupant. According to the Life Safety Code (National Fire Protection Association 2011), the Occupant Load factor is 200 gross ft^2 per occupant for residential buildings.

Egress Width and Capacity: Within prescriptive codes, egress capacity is expressed in terms of required width per occupant. Egress width requirements are dependent on the designed purpose of occupancy of a building. Table 2-2 provides egress width per occupant (measured in in/occupant) for residential buildings in both sprinkler and non-sprinkler protected buildings as per IBC (2016). Furthermore, a minimum 44-in width for exit stairs and passageways is required by IBC (2016) if the width calculated from the table is less than 44 in. For example, if a residential apartment without sprinkler system has a total of 200 occupants, the required stairway width is calculated as 60 in (200 × 0.3), and the width of other egress components is calculated as 44 in ($0.2 \times 200 < 44$).

Table 2-2:
IBC Egress width per occupant served
(Adapted from IBC 2016)

	Without Sprinkler Systems		**With Sprinkler Systems**[1]	
Occupancy	**Stairways (in/occ.)**	**Other Egress Components (in/occ.)**	**Stairways (in/occ.)**	**Other Egress Components (in/occ.)**
Residential	0.30	0.20	0.20	0.15

[1] *Reduced egress widths are not allowed within the life safety code.*

Number and Location of Exits: According to the IBC (2016), the number of exits required on a given floor or the number of egress components required in a given space is directly related to the number of occupants within the space. The maximum occupant load for residential buildings is 10 persons per exit.

Travel Distance Limitation: The concept of maximum travel distance has historically been a prominent egress requirement in prescriptive codes since it is directly related to the travel time (Tavares 2010). The IBC (2016) requirement for residential buildings is 200 ft. without a sprinkler system and 250 ft. with sprinkler system. However, the NFPA (2011) requires 175 ft. and 325 ft., respectively.

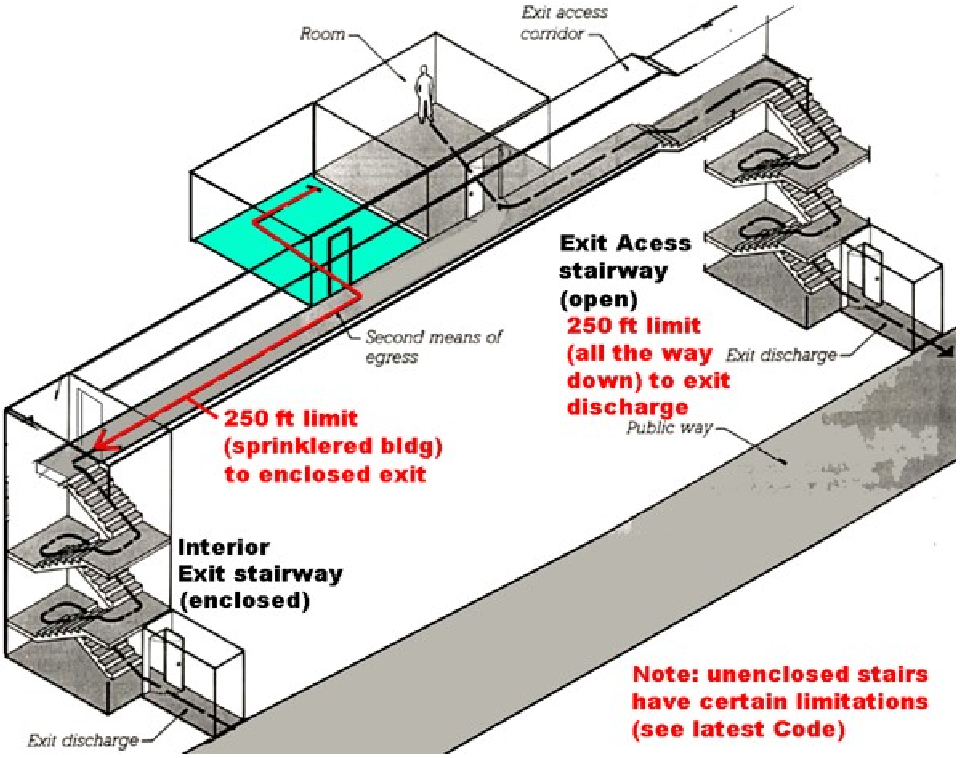


Figure 2-3: Maximum Travel Distance
(Adapted from IBC 2016)

Corridor: The corridors are generally designed with fire-resistant construction, and the fire-resistance rating for residential building corridors with an occupant load greater than 30 is required to be greater than 0.5 hr (IBC 2016). If evacuees stay in the corridor longer than the designed rating hr, the corridor structure may fail thereby putting evacuees in danger. The codes also include requirements for the interior finishing, lighting, signage, headroom, handrails, stair tread geometry, etc.

2.2.3 Evacuation Plan and Crowd Management

After means of egress and support systems are designed, emergency evacuation plans are developed. Evacuation plans offer benefits for both the occupants and the building managers/owners. By providing training (in some cases in the form of evacuation drills), occupants can become familiar with egress plans and what to do in case of emergency; and, managers/owners receive valuable information regarding evacuation time and procedures based on the results (Abbott and Geddie 2000). Evacuation is especially important for high-occupancy buildings that apply egress strategies such as phased evacuation or defend-in-place (where people remain in a designed place and wait to be evacuated), and also for buildings with complicated evacuation routes or procedures (Tubbs 2007).

In recent decades, considerable research on the performance of evacuation plans has been carried out by analyzing drill videos. By carrying out and recording these drills, engineers, building owners, and managers improve their understanding of what occurs inside the building during an evacuation. Proulx (1995) compared the evacuation drills of 4 mid-rise residential buildings and found that in cases where the occupants did not hear the alarm bell, lengthy delays occur.

Recently, research is focusing on simulation approaches in order to improve evacuation plans. Several studies have been conducted to reduce pre-evacuation (delay) time. Li et al. (2014) applied an agent-based model (ABM) algorithm to quickly locate occupants and accurately position them to carry out the most suitable egress route in buildings. By using thermal imaging cameras as sensors to determine the location of occupants and uploading the location information to the BIM model of the building, the control centre of the building is able to gain an understanding of the entire building. A sequence-based localization algorithm, which uses ABM methodology to calculate the nearest location sequence, is then formed to help the command center arrange occupants and routes. Cassol et al. (2017) found that by optimizing the ratios of each person selecting a particular route at a specific spatial location, they can achieve a better evacuation plan based on a quantitatively validated metric for evacuation performance; and Han et al. (2006) developed a onedestination evacuation approach to provide flexibility in the optimization process compared to fixed-route plans.

Few studies have been conducted on the influence of different occupant arrangements in terms of where they start the evacuation process and the influence of different building plans on the evacuation performance.

2.3 Re-evaluation of Egress Design for Senior Housing

As mentioned above, the proportion of seniors within the global population has been steadily growing since 1960. By 2050 it is estimated that, internationally, the increase in people over the age of 60 will rise to 2 billion. Furthermore, by 2061, one in four

Canadians will be 65 or over (Puts et al. 2017). For the purpose of this thesis, older persons, seniors, and elderly people are considered to be 55 years of age or older (Manicaros and Stimson 1999). Senior housing, which includes a community for elderly people to live together as well as assisted living facilities and elderly-friendly design, is becoming increasingly popular in Canada and all around the world. Currently, several studies (Day et al. 2002; Parker et al. 2004; Lok, Lok, Canbaz 2017; Jennings, Sycara, Wooldridge 1998) demonstrate the need to improve the quality of life of older adults and provide the elements that older people require to remain socially connected. Furthermore researchers are calling for the reevaluation of building code standards, which are primarily conducted in a general scope and focus on the average change of human factors and new techniques in industry; yet little effort has been made to address the egress design specializations for senior housing.

Although plenty of research has been carried out to improve the life quality of elderly people, elderly populations suffer 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 behaviour during the evacuation process is necessary for an egress design to reflect the specific behaviours of seniors. The general characteristics of elderly occupants that may influence the egress design are summarized below.

2.3.1 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) provide the distribution for walking speeds by age and ability using Monte Carlo method. According to their research, the average horizontal walking speed for people aged 18 to 50 is 1.12 m/s; this number decreases to 0.85 m/s for people 50 years of age or more. It is also found that when required to change from the preferred normal walking speed to walking quickly, the elderly fail to achieve the same increase in speed and stride length as compared to young adults (Shkuratova, Morris, Huxham 2004). Given that currently the data used for standard design is based on mixed groups, considering both young and old, 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 recalculated and then tested in a critical scenario for elderly safety.

Speed Data: a significant amount of data about elderly speed has been published in recent years, in several categories as age, gender, mobile ability, scenario, and so on. (Kuligowski et al. 2013) reviewed relevant data and summarized them in table 2-3.

Table 2-3:
Movement speeds from studies of seniors and people with mobility impairments
(Adapted from: Kuligowski et al. 2013)

Year	**Speed (m/s)**	**Notes**	**Source**
1987	0.67	Men (over 50 years)	(Fruin 1987)
	0.56	Women (over 50 years)	
	0.67	Men (over 50 years)	

	0.63	Women (over 50 years)	
1999	0.36 ± 0.14	Disability (without movement aid)	(Boyce et al. 2017)
	0.32 ± 0.12	Disability (with cane)	
	0.11 to 0.23	Over 75 years (with assistance)	
2004	0.88 ± 0.17	0.15 m (6.0 in) by 0.33 m (13.1 in) stair	(Fujiyama and Tyler 2004)
	0.35 ± 0.17	Population (all evacuees)	
2010	0.23 ± 0.08	Cane	(Adams and Galea 2011)
	0.25 ± 0.13	Assisting/assisted occupant	
	0.18 ± 0.04	Assisted by firefighter	
	0.21 ± 0.03	Stair descent device	
2012	0.41 ± 0.17	Older adults (no assistance)	(Hedman and Glenn)

Some studies also consider the distribution of speed in aged groups. Sliwinski et al. (1994) demonstrated that proportional slowing is “uniform in the old adults, such that the fastest and slowest old individuals were slowed by the same factor”. They argue that since “the regression of old–young mean reaction times (RTs) can be insensitive to differential age effects”, comparisons of old and young distributions are recommended to support claims regarding proportional slowing and uniformity of age effects across individuals.

2.3.2 Fall Potential

Congestion 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 (Cornes, Frank, Dorso 2017). On the other hand, falls are common for elderly people, and the risk of falling increases dramatically with age. For example, one study shows that the cumulative incidences of any fall among individuals ≥ 65 years of age are 29.3% and 37.2% among men and women, respectively (Sharifi et al. 2015); and falls are 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 years (Fuller 2000). These studies lead us to question the fall potential of elderly people during the evacuation process.

Notably, the risk of falling increases with age. A survey conducted in 1981 in Newcastle, England reveals the percentage of respondents reporting a fall as increasing with age as presented in Table 2-4 (Askham et al. 1990).

Table 2-4:
Data on the percentage of respondents reporting a fall as increasing with age (Adapted from Askham et al. 1990)

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

Fuller (2000) also investigated the risk factors that may lead to a fall. He listed the factors and classified them into either intrinsic or extrinsic. In most cases, a single fall may result from multiple causes, both intrinsic and extrinsic. These factors can be found in Table 2-5. According to his research, the more factors one occupant possesses, the higher potential of falling. Furthermore, fall potential during emergencies tends to be higher than in normal scenarios.

Table 2-5:
Risk factors for fall
Adapted from: Fuller et al. 2000

Demographic factors	Older age (especially ≥ 75 years) Older age (especially ≥ 75 years) White race Household status Living alone
Historical factors	Use of cane or walker Previous falls Acute illness
Physical deficits	Chronic conditions, especially neuromuscular disorders Medications, especially the use of four or more prescription drugs Cognitive impairment Reduced vision Foot problems Neurologic changes Decreased hearing
Others	Environmental hazards Risky behaviours

For these reasons, it is necessary to conduct a study focusing on the consequences of a fall during egress (which may lead to the high potential of injury and evacuation delay time); it should also test the egress plan in a critical scenario to ensure the safety of the elderly.

2.4 Support Systems and Assisted Egress Method

Life safety relies on various systems within buildings to prevent fire and other disasters resulting in injury or loss of property or life. These support systems include the basic building construction, fire detection systems, and means of egress methods. Most systems are required by building regulations. Often, additional systems, such as assisted egress methods, are provided to meet the needs of the design team, building owner, or occupants. One example of assisted egress methods is the stair descent device, which helps the building designer improve the level of accessibility of the building, and enables mobility-impaired occupants to travel up and down stairs more easily. Another example is the evacuation elevator, an assisted egress method that is significant in tall buildings.

2.4.1 Evacuation using Elevators

It is common for multi-story buildings to display signs that read, “Use stairs in case of emergency”; but, not everyone is capable of using stairs. For example, in a seniors’ apartment building, there may be elderly people in wheelchairs, with injuries, or with certain medical or mobility issues. Usually, these people are classified as “mobility

impaired occupants” and are not considered as occupants who participate in the evacuation drills. They are often informed to remain in their home and wait to be rescued by firefighters, which is very time-consuming and it becomes more dangerous as time passes. In such cases, elevators can be more
efficient than stairs.

Elevator use in emergencies has been a topic of research for more than two decades (Klote 1993). If elevators are included in a building’s evacuation plan, those plans must also be responsible for the safety of both the occupants and emergency workers (e.g., fire fighters reaching the upper levels in time). There are several benefits to applying elevators as assisted egress methods, as follows (Kuligowski 2003):

- In very tall buildings, the amount of time required to use stairs to evacuate can be significant, even if a sufficient number of staircases are provided. Elevators can decrease the total evacuation time.
- Elevators are the most familiar transit method for most occupants, so they may be more willing to evacuate using elevators.
- Elevators can help occupants who may be not able to use stairs effectively.

A protected elevator that is safe to use in the event of an emergency evacuation should meet the following features (Klote 1993):

- smoke and heat protection;
- emergency power;
- water protection;
- overheating protection;

- earthquake protection;
- emergency communication;
- controls (manual or automatic).

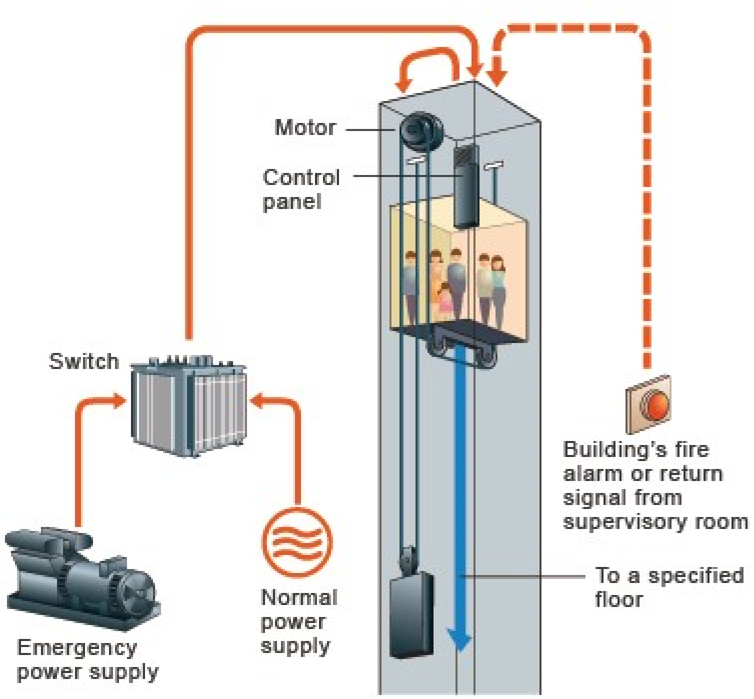


Figure 2-4: Example of fire safe elevator
(Mitsubishi Electrical Corporation 2016)

2.4.1.1 Design Considerations for Elevator Egress Methods

If an elevator evacuation system is identified as a viable option for providing egress for a given building, the design of the system is required to carry out a Life Safety Evaluation, as described below (NFPA 2017):

1) A timed egress analysis should be carried out to review expected evacuation time. It is suggested to reach the goal that the total evacuation time of all

occupants with the use of elevators should be no greater than evacuation without elevators.

2) Specialized signage to instruct occupants on the use of the elevator egress system.
3) Essential training and communications should be provided.

2.5 Egress Research Using Crowd Simulation Models

The use of computational egress models to predict building egress during fire and other emergency situations is increasing throughout the building design industry. A crowd, by definition, is any group of people gathered together in one location. But there are different types of crowds, like the pedestrians in a subway station, customers in a shopping mall, and occupants in an apartment building, and their makeup, reason for being, and the environment wherein they form can influence their behaviour under both normal and emergency situations (Berlonghi 1993). Therefore, egress simulation can be regarded as a sub-field of crowd simulation in general. Usually, each individual in a crowd is called a “pedestrian”. In this section, a basic review of this research approach is provided, addressing the advantage and limitation, followed by a general introduction to and explanation of crowd simulation; finally, several models from previous studies are explored.

2.5.1 Introduction

Crowd models can be categorized as follows: (1) according to the method of representing individuals, multi-agent based models and equation-based models (Wilensky and Rand 2015); (2) according to different terms of motion dynamics, rule-based models (e.g., route choice models), force systems, and cellular automata models (Pelechano, Allbeck, Badler 2008); and (3) according to the method of representing time and space, discrete-event models (e.g., queuing models, cellular automata), continuous models (e.g., force models), and mixed discrete-continuous models (e.g., route choice models).

2.5.1.1 Advantage

Computer simulation for egress research is necessary for multiple reasons. Gaines (1979) stated a number of good reasons for using computer simulation as a problemsolving tool. Ali (Ali 2006) generalized the reasons as five main aspects: (1) The physical system is not accessible; (2) The experiment may be hazardous; (3) The cost of experimentation is too expensive; (4) The time constants of the system are not compatible with those of the experimenter; (5) Control variables, and/or system parameters may be inaccessible. Sulistio, Yeo, and Buyya (2004) add that “simulation tools support the creation of repeatable and controllable environments for a feasibility study and performance evaluation. These simulation environments facilitate researchers, educators, and students to conduct effective research, teaching and learning with ease.”

2.5.1.2 Limitations

Although the field of crowd simulation has shown tremendous advances in the industry, limitations still exist. One of the clear shortcomings of computational simulation is that any time or money invested in the simulation is not invested in the real scenario (Larochelle 2009). However, this situation may be acceptable because the simulation results may bring significant savings and may reduce the possibility of problems in reality.

Another difficulty involves the complexity of the models. The input data (transition probabilities and temporal distributions) are generally difficult to construct reliably. Also, considering the large quantity of data in one model, a relatively large amount of time and computing power is required. The complexity of a model increases proportionately with the need to represent reality. The aim of such models is to simulate scenarios as near to reality as possible. However, not all researchers are expert to create simulation models successfully as the way they expected.

Finally, Beard (1992) pointed out that the term "validation" is misleading, since "it is logically impossible for a scientific theory in general and a model, in particular, to be 'proven correct'". The most common method is to compare theoretical prediction with experimental results and highlight the differences.

It is important to keep in mind that models are abstractions of reality, which leave out certain details for various reasons. Rather than focusing on whether a model is good or bad in absolute terms, one should focus on whether or not a model has the potential to assist in terms of gaining a better understanding in a given case. If a given model offers this potential then its applicability depends upon the case to which it is applied and the method by which the results are used and interpreted (Beard 1992).

2.5.2 Crowd Simulation

A major goal of crowd simulation is to steer crowds realistically and recreate human dynamic behaviours. There exist several overarching approaches to crowd simulation and artificial intelligence (AI), each providing advantages and disadvantages based on crowd size and timescale. Using these characteristics, there are three main approaches to crowd simulation: flow-based, entity-based, and agentbased (Zhou et al. 2010). For the purposes of the present research, only the agentbased approach is presented in this thesis. For a more detailed summary of the various approaches, please see studies by Ali (2006) and Zhou et al. (2010).

2.5.2.1 Multi-Agent-Based Simulation

Multi-Agent Based Simulation (MABS) is a computer simulation technique that was introduced in Section 2.3.1. MABS uses agents as a programming framework. It is necessary to mention agents and multi-agent systems.

Agent

The word "Agent" is a concept first introduced in the AI field, where it is believed that "an 'Agent' is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators" (Russell, Norvig, Intelligence 1995). Soon after, multi-agent systems (MAS) attracted the interest of researchers beyond traditional computer science. Wooldridge and Jennings (1995) defined the sharing properties of agents as follows:

- Autonomy: agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal states.
- Social ability: agents interact with other agents (and possibly humans) via agent communication language (ACL).
- Reactivity: agents perceive their environment (which may be the physical world, a user via a graphical user interface, a collection of other agents, the

Internet, or perhaps all of these combined), and respond in a timely fashion to changes that occur.

- Pro-activeness: agents do not simply act in response to their environment, and they are able to exhibit goal-directed behaviour by taking initiative.

Multi-agent System

Based on the definition of agent, a multi-agent system (MAS) can, therefore, be defined as a collection of possibly heterogeneous, computational entities, having their own problem-solving capabilities and which are able to interact together in order to reach an overall goal (Ferber 1999). In MAS, agents usually operate in a dynamic, decentralized complex environment, in which a single input action can often produce unexpected results.

Multi-agent systems share a number of key features (Jennings, Sycara, Wooldridge 1998):

- each agent has incomplete information or capabilities for solving the problem and, thus, has a limited viewpoint;
- there is no global system control;
- data are decentralized;
- computation is asynchronous (tasks should run in parallel to other tasks).

The widespread use of MAS in computer simulation produced a new computer simulation field called Multi-Agent-Based Simulation (MABS). MABS is defined by

Weiss (1999) as “an approach used to simulate the interactions of multiple autonomous agents in an environment.”

MABS has clearly become a primary methodology and set of tools for understanding complex systems in the areas of natural science, social science, and engineering (Wilensky and Rand 2015). Compared to other modelling methods, MABS is more competitive in situations where (1) the population is heterogeneous; (2) the aggregate behaviour rule is unknown; and (3) a detailed result for each individual is needed.

The following sections present the existing egress models and elderly models, and discuss whether they provide sufficient support for the physical and psychological characteristics of elderly persons, including movements, decisionmaking behaviours, and associated interactions, to be plausible in situations of egress model for senior housing.

2.5.2.2 Previous Studies

For the sake of brevity, only the models that are pertinent for the egress simulation and the elderly characteristics simulation, and more specifically the arguments discussed in Section 2.2, will be presented. Other models, such as macro-simulation and fluid dynamics can be found in research conducted by Duives, Daamen, and Hoogendoorn (2013).

2.5.2.2.1 Hendrich’s Predictive Fall Risk Factor Model

As discussed in previous sections, it is necessary and of value to consider the potential of falling for elderly persons when they evacuate in an emergency scenario. Several recent retrospective case-control studies have been performed to identify fall risk factors. These studies generally commence by presenting a long list of possible risk factors and use logistic regression analyses to determine which of these factors have a significant association with falls.

Hendrich, Bender, and Nyhuis (2003) present a large concurrent case (344)/control(780) study to validate the Hendrich II Fall Risk Model. The authors of the study focus on a predictive fall risk factor model that could be used in a diverse acute care population to identify individuals at risk of falls. Table 2-6 from the article depicts the model briefly.

Hendrich suggests that "an evaluation of a limited number of clinical factors can be highly predictive of fall risk", and is more relevant to practice and less timeconsuming compared to some studies with as many as 21 risk factors (Conley, Schultz, Selvin 1999).

Table 2-6:
Hendrich II Fall Risk Model

Risk Factor (≥ 5 = High Risk)	**Risk Points**
Confusion/disorientation	4
Depression	2
Altered urinary elimination	1
Dizziness/vertigo	1
Gender (male)	1
Any prescribed antiepileptics	2
Any prescribed benzodiazepines	1

The Hendrich II model uses summed points for various risks factors, and the higher the score, the greater the risk of falling. If the summed points is no less than 5, the individual is considered to be at a high risk of falling. According to the authors of the study, this model performs well under experimental testing: 74.9% and 73.9% of patients were correctly identified to be of high-risk or not at high risk, respectively (Hendrich, Bender, and Nyhuis 2003).

Their study also notes that this model only considers intrinsic factors; thus, extrinsic factors such as lighting, footwear, and the use of restraints, which are also important aspects of fall risk analysis, are not included in this model. It is also worth noting that their research was conducted using a general hospital population rather than being restricted to an elderly population.

2.5.3 ABM Simulation Tools

The first agent-based simulation tool is StarLogo, developed by a group of scientists at MIT Media Lab in 1990. Later, in the mid-1990s, the Santa Fe Institute developed Swarm and Wilensky developed NetLogo. Since then a significant amount of ABM software has been developed, both academic and commercial. The ABM approach became widely available and was able to be used in various domains. In the present reserach, Netlogo is used since it provides a simplified programing language and graphical interface (Railsback and Grimm 2011). NetLogo encompasses four types of agents:

1. Mobile agents, namely turtles.

2. Patches: the fixed square cells (grids) that represent space.
3. Links: the relationships among turtles such as networks to represent that they are connected.
4. The observer: the overall controller of the modelling system to observe and make orders; this is different from the agents' point of view.

2.6 Pedestrian Dynamic Models in ABM

Several simulation techniques have emerged in the past half-century as more advanced techniques are required to simulate increasingly complex domains. Based on the diverse observation and representation scales, there are essentially three types of pedestrian models: microscopic, mesoscopic, and macroscopic.

2.6.1 Pedestrian Dynamic Model

Macroscopic scale, as the name implies, regards the individual behaviours in a broader view of group behaviours as flows by assuming that the particles are homogeneous and the crowd size is large enough to apply an assumption of continuity to each flow. Many pedestrian dynamic models have been developed over the years. Traditionally, the first step to begin a pedestrian simulation model design is the selection of the most appropriate scale to describe the scenario at hand. Agent-based modelling is an example of a microscopic model.

2.6.1.1 Macroscopic Model

Macroscopic pedestrian models, such as Gas kinetics model, regards the pedestrian group as fluid flows and applies the classical Maxwell-Boltzmann statistics to describe the motion of a crowd (Henderson 1971). The regression model treats the pedestrian crowds as different lane flows and uses statistically-established relations between different flows to predict pedestrian flow behaviours (Milazzo et al. 1998; Wilensky and Rand 2015).

2.6.1.2 Mesoscopic Model

Mesoscopic model, mainly referred to as the Lattice Gas Automaton (LGA), is a bridge between the macroscopic fluid system model and the microscopic Cellular Automata model. Though it uses the Cellular Automata approach to model the microscopic behaviour, it still regards the pedestrian behaviour as the macroscopic behaviour of a fluid (Buick 1997). That is to say, though the mesoscopic model focuses on single particles (pedestrians), it generalizes the behaviours of all individuals as statistic distribution rather than tracking and describing each individual behaviour like in the microscopic model.

2.6.1.3 Microscopic Model

The description of the pedestrian dynamics at the microscopic level is based on the assumption that every person can be tracked individually, and their trajectory can be forecasted (Cristiani, Piccoli, Tosin 2014).

An integrated microscopic model may involve several of these categories. For instance, to simulate a stadium evacuation process, the user may choose to (a) regard the pedestrians as a multi-agent system, (b) simplify the stadium environment in cellular automata model, and (c) apply queuing model together with route choice model to describe the evacuation process.

2.6.2 Pedestrian Models in ABM

2.6.2.1 Cellular Automata (CA) Model

Cellular automata (CA) are discrete dynamic systems, compared to continuous dynamic systems defined by partial equations (Toffoli and Margolus 1988). The CA system can be regarded as the counterpart concept of "field" in physics. In a CA model, space is idealized as a regular grid of cells, and time advances in discrete steps. Each cell has its own state, and the number of states is finite. The state of each cell changes at each time step according to the status of the neighbour cells following some specific behavioural rules. For example, in a pedestrian model, the state of each cell can be either empty or occupied by a single pedestrian. When pedestrians move to various locations, the cell states change between empty and occupied (Cristiani, Piccoli, Tosin 2014).

The behaviour rules deployed in order to define a CA model are given in words (e.g., "go","move"), and thus are easy to understand. The following are some common rules shared by pedestrian CA models.

1. Each pedestrian is allowed to move one cell away per step.
2. To avoid collisions, no more than one pedestrian can occupy any given cell at any given time. If the target cell is occupied, the pedestrian cannot move. If the cell is targeted by more than one pedestrian, only the winner (based on a certain completion rule, usually is randomly chosen by the system) can move to the target cell.
3. Each pedestrian has a matrix of preferences, and the matrix can be either cell-dependent or time-dependent, or both.

According to the listed assumptions of behaviour rules, the limitations of CA models are clear. Since pedestrians are only allowed to move to an adjacent free cell, this model will become unrealistic when pedestrians are crowded in high-density situations. In a high-density situation, each pedestrian has the option to move to a limited number of adjacent free cells, and in some cases has no adjacent free cells within which to move. Thus, some pedestrians with the sole option of one free cell within which to move may continuously travel back and forth, like a vibrating ball.

2.6.2.2 Pedestrian Behaviour Rules

When designing models to simulate pedestrian behaviour, rules are built to describe the process. Some important behaviour rules for pedestrians are introduced below.

1. Target

   In most situations, the environment where pedestrians move is bounded, and pedestrians have a desired destination (sometimes more than one) to be reached, e.g., the exits of a building (Cristiani, Piccoli, Tosin 2014).

2. Repulsion

   Pedestrians try to avoid collisions, and they tend to stop or change direction when they feel that they are too close to other people (Cristiani, Piccoli, Tosin 2014).

3. Attraction

   In some cases, pedestrians have a tendency to travel in a group, by following others or by remaining close to one another (Cristiani, Piccoli, Tosin 2014).

4. Maintaining direction

   Pedestrians tend to prefer to continue in the same direction if they are not forced to change directions (Cristiani, Piccoli, Tosin 2014).

5. Visual field

Pedestrians can only visualize their surrounding environment rather than the entire situation. The visual field can be limited by head orientation, nearby obstacles, as well as light conditions (Cristiani, Piccoli, Tosin 2014).

6. Sensory Regions

A sensory region is the surrounding space one pedestrian takes into account through which they recognize the local environment and make decisions (Cristiani, Piccoli, Tosin 2014).

7. Fatigue

It is known that when a movement is performed repetitively, muscle fatigue may lead to changes in local parameters of movement. Such changes may include decreased range of motion at the main joint, decreased movement velocity and muscle force, and changes in the spectrum of muscle electromyogram (Cote, Mathieu, Levin 2002).

CHAPTER 3 METHODOLOGY

3.1 Introduction

In order to create an MABS model for egress system evaluation in mid-rise housing, aiming to find the most appropriate solution to reduce the total evacuation time and ensure the safety of the elderly, the present research process is divided into 3 stages.

Stage 1 constructs a general platform for crowd simulation based on approaches and models introduced in Chapter 2. The basic elements which form this platform are as follows:

(1) An abstract building model, which is derived from a complex building plan using a simplification strategy.
(2) A multi-agent based pedestrian dynamics model including parameters of speed and ability to avoid a collision.
(3) An algorithm to generate the total evacuation time of each evacuee, the average evacuation time, and the evacuation time interval between two evacuees.
(4) A visualized interface.
(5) The ability to add new characteristics (parameters) to each evacuee.

NetLogo, which is a visualized agent-based simulation software, is selected as the simulation environment. In NetLogo, the abstract building model is represented by patches, which are set to be 0.5 m × 0.5 m each, and evacuees are represented by turtles, with speed and other characteristics of each turtle given as variables. The turtles move one step per clock-tick, therefore the total travel time can be estimated from the number of ticks (Wilensky and Rand 2015). To calculate each evacuee's total evacuation time, the turtles (evacuees) are designed to have a delay time variable, which constrains them to wait for the designed delay time before they start to move. As introduced in Section 2.1.1.1, total evacuation time is equal to the sum of detection time, delay time, and travel time. In this model, the assumption is made that the detection time is ignored as an ideal situation.

Stage 2 is designed to simulate the scenario of a recorded evacuation drill using the platform built in stage 1 in order to check the validity of the model. The drill was selected from a joint research project that was undertaken by the National Research Council of Canada (NRCan) and the Canada Mortgage and Housing Corporation (CMHC) to study evacuation drills in mid-rise apartment buildings that house occupants of varying physical abilities (Proulx, Latour, MacLaurin 1994). Comparisons are made between the recorded data and the observed data from the model.

Based on the scenario tested in stage 2, stage 3 initializes the scenario of evacuation in senior housing. Parameters such as long delay, number of evacuees, mobility-impairment, and egress components are also considered in addition to speed distribution is this scenario. A series of experiments are designed and carried out to determine the relationships among delay time, the number of evacuees, average evacuation time, congestion time, and total evacuation time using statistical analyses in order to find the solution to optimize the egress performance, aiming to minimize total evacuation time as well as ensure life safety.

3.2 Construction of Multi-agent Based Simulation Model

To study the process of evacuating a building, a Multi-Agent Based Simulation

Model, which allows heterogeneous particles with different characteristics (e.g., velocity) to explore virtual environments with doors, corridors, and stairwells, is needed. In reality, a graphical model of a 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 the behaviour details of agents when they encounter graphical elements, a high level of detail about rooms, walls, corridors, obstacles, etc., is required. However, in situations where details of wayfinding behaviour 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.

3.2.1 Construction of a MABSM

The objective of this model is to create a general platform for crowd simulation that can be used to model the majority of mid-rise residential buildings—5 to 8 floors, as defined by City of Edmonton (2009)—with few variable changes. To achieve this, the graphical model of the building is simplified to fundamental egress components. The egress process is also simplified as follows: (1) occupants appear at apartment door (ready to evacuate); (2) occupants decide which stairwell to take; (3) occupants travel along corridor; (4) occupants travel on the stairs; and (5) occupants reach the exit.

The model can be constructed by observing the following rules:

1. The modelling method is a partial behavioural model (Kuligowski, Peacock, Hoskins 2005). The model simulates and calculates occupant movement, and contains certain features that simulate human behaviour, including:
    - Distribution of delay time
    - The randomness of start location where occupants begin to move
    - Choice of egress route
    - Walking speeds and the distribution of velocity
    - Simulated wayfinding procedure
    - Group
    - Fall event
2. The building environment is simulated by way of fine network structure. This means that occupants are allowed to populate a discretized space with a lattice connecting discrete positions (small grid-cells). The default size of one grid-cell is 0.5 m × 0.5 m in this case.
3. The model is designed with an individual perspective, and the simulated occupants are tracked individually throughout the simulation.
4. The simulated occupants of this model each have their own individual perspective in order to choose their paths based on information available at their specific location and the people around them. For example, one occupant at one cell may make a decision by noticing the eight surrounding neighbour-cells and whether or not the cells are occupied.
5. The model is considered to have low occupant density, thus push behaviour is not simulated. Several occupant movement rules are used in this model:

- Empty cell: Occupants will not move into an adjacent grid-cell unless it is empty.
- Occupant density: Considering the shoulder width of the 97.5th percentile for adult males is 20 in (510 mm) (NFPA, 2017), each occupant in this model is represented as a circle with a 250-mm radius.
- Probabilistic algorithm: To simulate individual travel behaviour, an individual decision-making algorithm is applied to account for the wayfinding actions performed during egress. In this model, Markov Chain is chosen to describe the stochastic wayfinding process. Each occupant has four independent choices with probabilities, namely, go straight forward, go parallel, go diagonally, and stop. Suppose that each occupant has their step count variables X_1, X_2, X_3, ...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.

$$P(X_{n+1} = x \mid X_1 = x_1, X_2 = x_2, \dots, X_n = x_n) = P(X_{n+1} = x \mid , X_n = x_n) \quad (3.1)$$

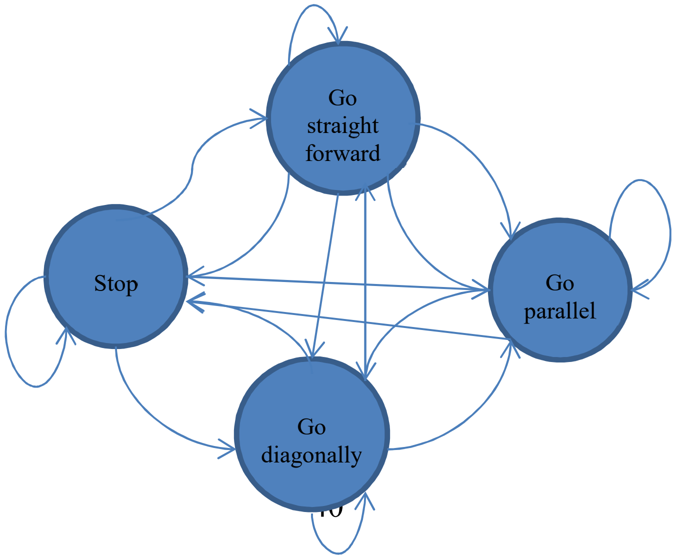


Figure 3-1: Markov Chain

- Acquiring knowledge: Simulated occupants can acquire knowledge based on individual fields of vision from their own perspective.

6. NetLogo is chosen as the simulation software which has a built-in visualization interface. The primary features and consequences of the model are:

1. Build egress components: By cutting off the "branch corridors", the egress scenarios in mid-rise residential buildings can be simplified as two main types: the one-stair case and the two-stair case. In both cases, the corridor is simplified as straight lines connected with stairs. For buildings with three staircases, the scenario can be viewed as a combination of the one-stair case and two-stair case by assuming that occupants make rational choices; in other words, occupants will not choose the most remote staircase if they have one or two closer staircases to choose from.


(a) one-stair case (b) two-stair case

Figure 3-2: 2 types of simplified models

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

1) Select the type of egress scenario (one staircase, two staircases, or combination of two) for simulation.
2) Select the number of floors.
3) Input the length of the corridor. The width of the corridor is set as 2 m as per the ICC Code (ICC, 2016).
4) Input the number of apartment units per floor. This egress model only displays the apartment door connected to the corridor as one grid and regards it as the start point of the egress. A default interval length (6 m) between each door is provided. Data of door intervals can also be read from external files.
5) Add branch corridors. Branch corridors are calibrated in a similar manner to apartment doors; occupants living in the branch corridors are collected at the point where the branch corridor meets the main corridor.
6) Input the average travel distance in the staircase between two floors. The width of the staircase is set to 1 m (44 in) as per the ICC (2016) code requirement. When occupants travel in the staircase, two types of movement are considered: vertical travel on stairs and horizontal travel on landings. Based on user judgment, the following equation is applied to calculate the travel distance between two floors. Since grid cells (0.5 m × 0.5 m) are used to draw the stairs, the length is then rounded to ensure the number of grids used to represent the stairs is an integer.

$$L = H + \pi * b / 2 \qquad (3.2)$$

where

L = travel distance (vertical and horizontal between two floors)

H = height of one floor b = stair width

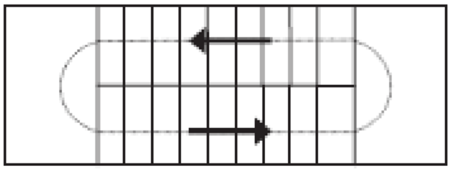


Figure 3-3: Staircase plan view

7) Construct the egress component model in NetLogo with a flexible operation interface and 2D visual interface.

2. Initialization of evacuees (radius of circle = 0.25 m) with their own characteristics (average travel speed in the corridor, average travel speed on stairs, and delay time). The actual speed variates during travel are generated stochastically using Monte Carlo method with triangular distribution. Using a random number generator built within NetLogo, a random variate (*U*) is drawn from the uniform distribution in the interval (0, 1), then the speed variate is calculated as expressed in Equation 3.3.

$$\begin{cases} X = a + \sqrt{U(b-a)(c-a)} & for\ 0 \leq U < F_{(c)} \\ X = b - \sqrt{(1-U)(b-a)(c-a)} & for\ F_{(c)} \leq U < 1 \end{cases} \qquad (3.3)$$

where

X = actual speed variates during travel

U = random variate drawn from uniform distribution in interval (0, 1)

a =low-speed value *b = high-speed value*

c = mode (most likely) speed value

The parameters *a*, *b*, and *c* can be found in many publications regarding travel speed. Also, as discussed in Section 2.1, the delay time is a significant factor that influences the egress process. In this MABS model, for the sake of simplicity, the delay time of each evacuee is defined as below:

$$T_{delay} = T_{door} - T_{alarm} \tag{3.4}$$

where

T_{delay} =*delay time of evacuee*

T_{door} = *time at which evacuee reaches the apartment door/branch corridor intersection* T_{alarm} = *time at which alarm sounds*

3. To simulate the delay time, two triangular distribution models are applied to represent the early reaction group and the late reaction group. Monte Carlo method is used.
4. Initialization of the start-evacuation location. Evacuees created in step 2 are then distributed randomly to the apartment doors. Since the start-evacuation location of each evacuee differs with every test, a minimum number of tests (30) is suggested.
5. Construct the travel and wayfinding process in the egress route. The first step is to choose the egress route, namely, which corridor and staircase to travel on. For scenarios with only one staircase, evacuees go directly toward the direction of the stairs. For scenarios with more than one staircase, the choice is made based on the definition of staircase distance parameter (d)

$$\mathrm{d} = \frac{D_a}{D_b} \tag{3.5}$$

where D_a and D_b represent the distance from the nearest staircase and the second nearest, respectively. When evacuees stand in the corridor, they choose the target staircase according to the following rules:

a) the evacuee chooses the nearest staircase if $d \leq 0.5$;

b) the evacuee chooses either the nearest or the second nearest staircase by a 50/50 chance if $0.67 < d <= 1$.

Note that this rule of choosing a staircase only applies to the situation when evacuees step out of the apartment door and are ready to evacuate. In this research scope it is guaranteed that every individual will own their own target staircase, and once the target staircase is chosen, it will not be changed during the rest of the evacuation process.

The second step is to build the pedestrian dynamics using Markov chain. Given the following probabilities: P_1 (evacuees go straight forward), P_2 (evacuees go forward and diagonal), P_3 (evacuees go parallel), and P_4 (evacuees stop), the rule of travel in the corridor is then determined according to the availability of the target cell (Cell A, B, and C as illustrated in Figure 3-4) and the chosen probabilities. To include the accidental conditions when evacuees stop during their movement, the possibility ratio of P_4 when they are able to move forward remains 0.05.

By assuming that evacuees during evacuation never turn back, one evacuee (or turtle in NetLogo) at one cell (or patch in NetLogo) can move to either patch A, B, or C, or stop and wait. If the patch is occupied, the turtle cannot move into that patch. The grid graphs of turtles travelling in a corridor and in a staircase are presented in Figure 3-4 and Figure 3-5, respectively. The decision-making process in one step loop is illustrated in Figure 3-6. The pedestrian dynamics rules are applied when travel in the staircase is equal to when traveling in the corridor. Codes of the Markov chain process can be found in the code appendix.

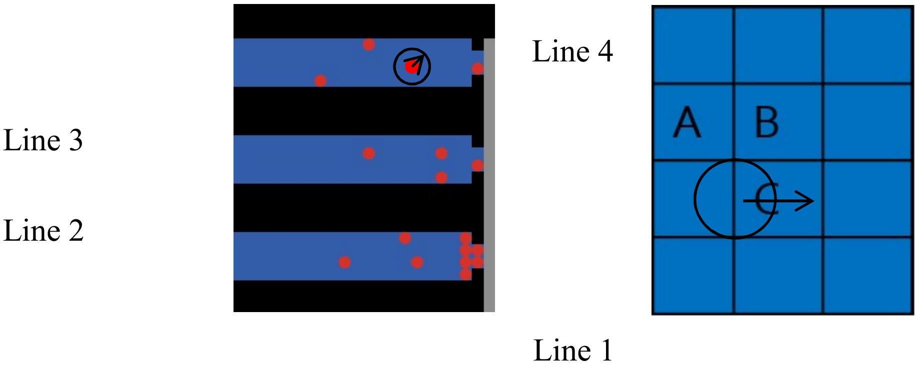


Figure 3-4: Visual interface view of corridor

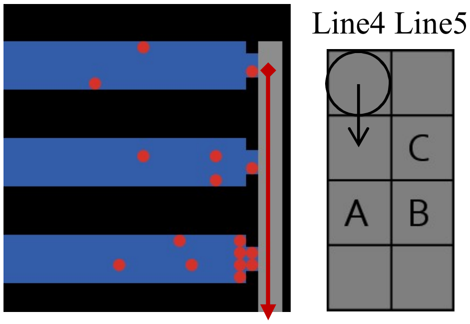


Figure 3-5: Visual interface view of staircase

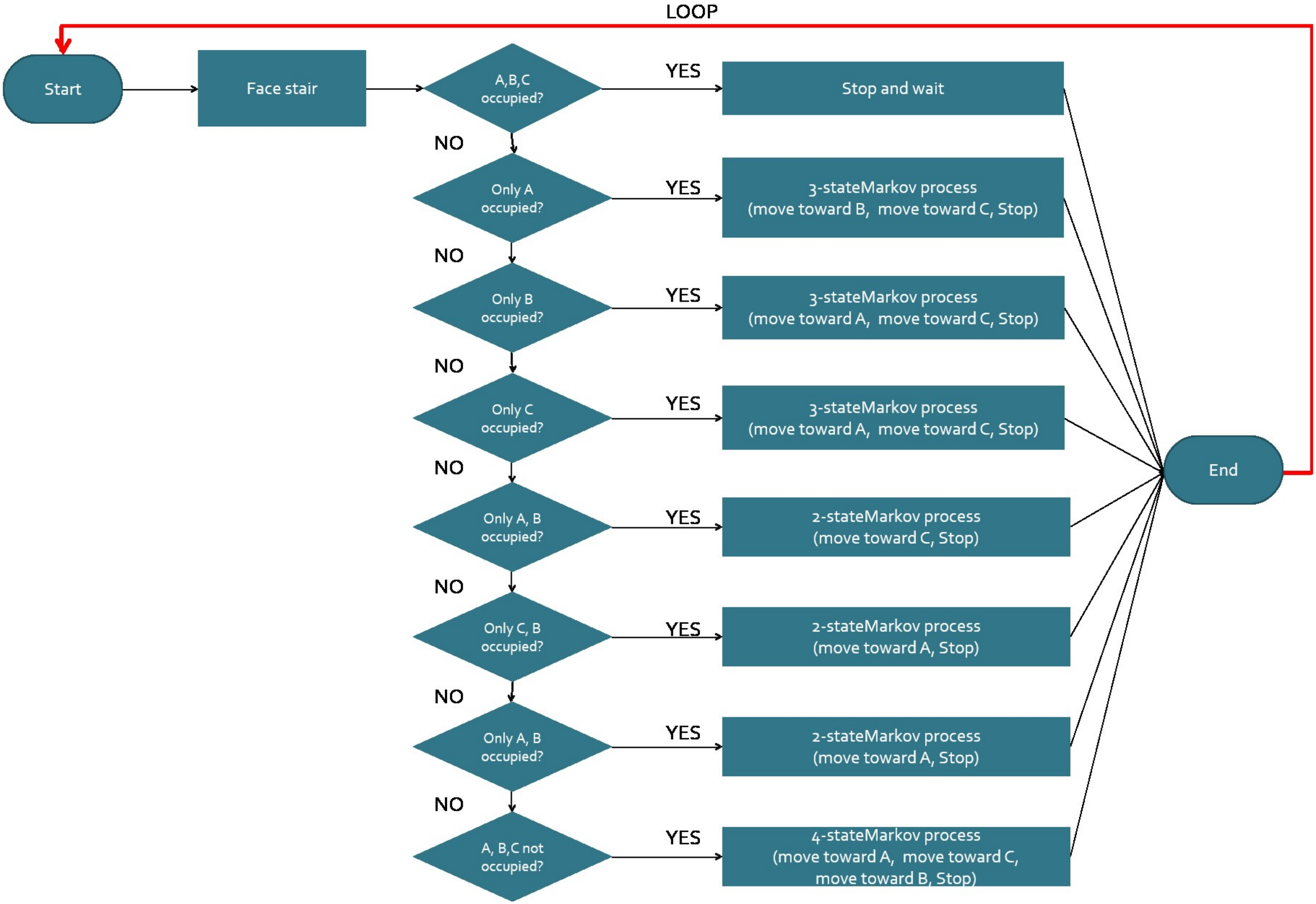


Figure 3-6: Decision-making process

6. After evacuees reach the exit, data regarding the egress process are generated. The exported data are in .txt form and contain delay time, time required to reach the exit, and travel time of each evacuee. The platform also offers monitors that can track the data along with simulation time.

3.2.2 Reality and Reliability Test for Pedestrian Dynamic Model

One of the key issues that may occur when a probability model is used to simulate pedestrian behaviour is vibration (agents vibrate back and forth between two available cells). So a vibration test is applied to justify the reality and reliability of this model. The level of reality and reliability is determined by the user’s choice.

The steps for this vibration test are introduced below.

3.2.2.1 Pre-assumptions

In this model, the four state probabilities, p_1 (go straight forward), p_2 (go parallel), p_3 (go diagonal), p_4 (stop), are first given by assumption. The pre-assumptions include:

a) The priority level of four choices is:$p_1 \gg p_2 = p_3 \gg p_4$.

b) In this test, $p_4 = 0.05$, considering that people seldom stop during the evacuation process. The accidental cases where people stop during evacuation may include: reading signs, listening to broadcasts, planning for next steps, etc.

c) The choice preferences among the four options may vary from person to person, the data used in this model only represents the average.

d) 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 behaviour of vibration in reality does occur in some cases. For example, in a queuing situation, the person at the tail end may continue moving from the current group to the next group in the event of a shorter queue. The acceptable result is determined by the user.

3.2.2.2 Trajectory Index Definition

A test turtle is built with the same start point in each run. During its travel, the heading data of each step is recorded. The vibration index, *v*, is defined in Equation 3.6.

$$\mathrm{v} = \frac{n_1}{n_2} \tag{3.6}$$

where

n_1= *times of heading change count during egress progress*

n_2 = *total steps*

The sensitivity test for p_1 (the probability of going straight) is designed with a 0.05 increment per run. The results are presented in Figure 3-9.

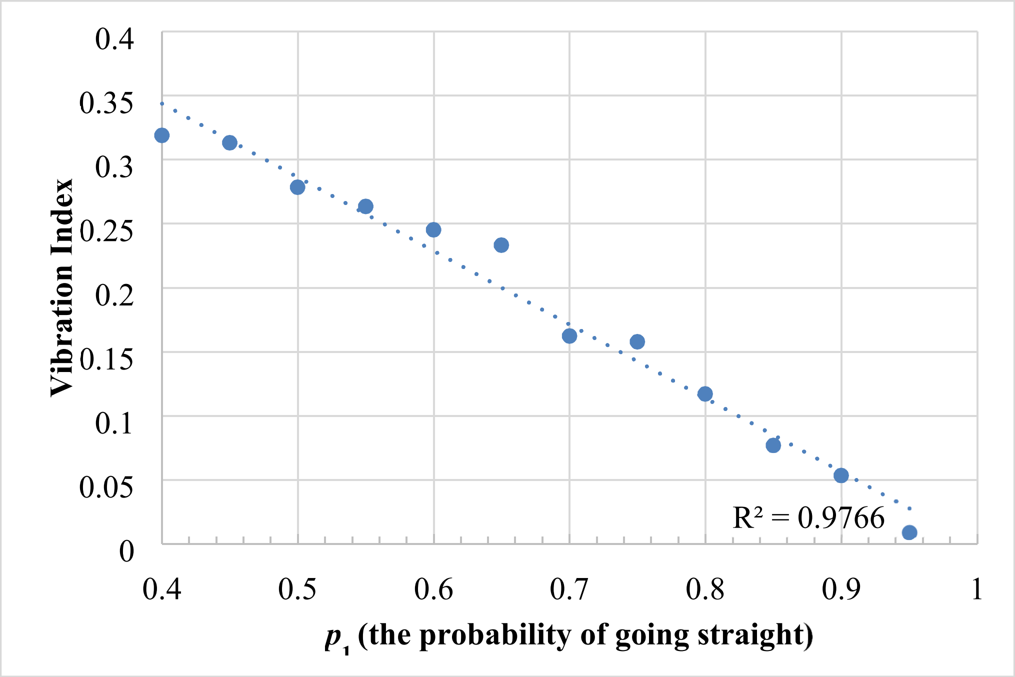


Figure 3-9: Vibration Index

3.2.3 Summary and Conclusions

In summary, a multi-agent based simulation model is constructed, which allows for a Monte Carlo simulation for both the delay factor and the travel speed. The advantages of the model over previous models include:

1) capturing egress performance;
2) integrating the whole egress process;
3) no building plan constraint;
4) no homogeneous pre-assumption needed such that the number of pedestrian groups can be determined by the user; and
5) quick simulation speed that allows numerous runs for the purpose of statistical analysis.

The disadvantage of this model is the limited intelligence level of the simulated evacuees. High-intelligence-level behaviours, such as communication, learning, and group organization, are not considered in this model. However, in scenarios where pedestrian density is low, these behaviours can be ignored as they appear to be the secondary factors that affect total evacuation duration.

Occasional behaviors such as going the wrong way are not included as well, but can be simulated as a case study to test the influence of individuals making mistakes on the total evacuation process.

3.3 Multi-agent Based Simulation of Drill Model and Calibrated Model for Research

In Section 3.2, a Multi-Agent Based Egress Model is constructed. Here, the model is used to simulate the evacuation drill process that was recorded and presented by Proulx, Latour, and MacLaurin (1994). The simulated model here is referred to as the drill model. The overall objective of the drill model is to check the validity of the model to whether it is able to effectively represent the process of what occured during the recorded drill and if the results generated from the drill model (e.g., the evacuation time) fit with reality. The drill model is then calibrated to meet the needs of the research. Pre-assumptions and simplifications are made to build the calibrated model. The details about the drill model and the calibrated model are introduced in the following subsections.

3.3.1 Introduction of Drill Model

Evacuation drills are necessary nowadays. The frequency of the fire drills may be dictated by local codes, rules, by property managers or building policies, or by insurance requirements. The purpose of practise drills is to keep employees prepared, to educate occupants about the evacuation procedures, and to familiarize them with the building and its surroundings. Occupants usually enter and leave a building through the same entrance and exit and take the same elevator to their desired floor, but rarely stop to consider where stairs are located and where they lead. Increasing their familiarity with evacuation procedures and the building itself maximizes the potential of a successful evacuation. Usually, the evacuation drills are recorded on video cameras located throughout the buildings. The cameras record such events as the time to respond to the alarm, the location, time and frequency of movements and the interaction between occupants. From these recordings, various statistical calculations can be performed to gain a better understanding of the drill process. However, though drills have many benefits, they are limited in many aspects compared with computation simulation models, as is discussed in section 2.4.1.1. An egress model resembling the real drill process is then simulated for the purpose of the research.

The real drill to be simulated is selected from a joint research project by the NRCC and CMHC (Proulx, Latour, MacLaurin 1994) in order to study evacuation drills in mid-rise apartment buildings that house occupants of varying physical abilities. The building where this drill took place was in Toronto, Ontario, and the drill took place on a weekday between 6:45 P.M. and 7:30 P.M., aiming to capture the largest possible number of occupants in their homes, yet before bedtime for most people. As illustrated in the building plan in Figure 3-10, the apartment building comprises 7 storeys and 3 staircases, but the central staircase (Stair B) is out of service. There are a total of 118 units, including activity rooms on floor 1 where occupants meet for activities; and the lengths of the two corridors between each staircase are rounded to 27 m and 18 m, respectively. The travel distance on the stairs between two floors is 5 m.

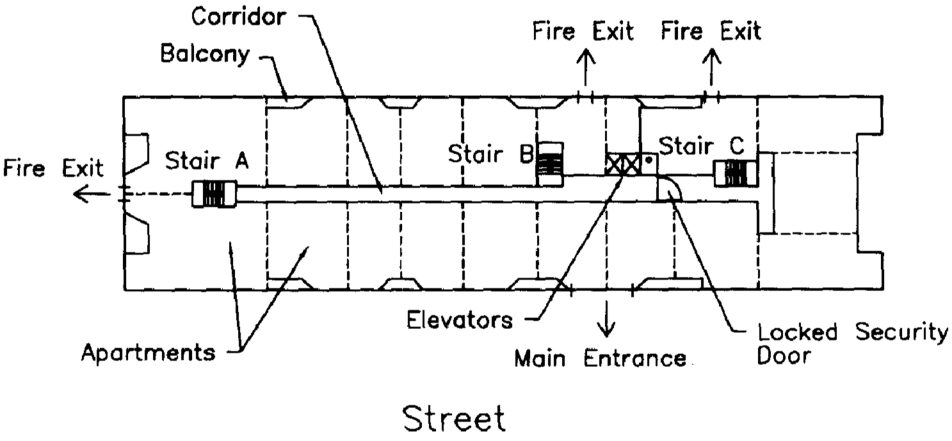


Figure 3-10: Building plan

During the drill, the following data were gathered: the age, average speed, and gender of each evacuee; the time required to respond to the alarm; the direction of movement; the time required for all occupants to reach a safe area; and the time required to completely evacuate the building. There are three categories of time information recorded for each occupant: the delay time, the movement time, and the total evacuation time. Details about these types of time information are provided in Section 2.2.1.

To build the drill model, the following steps are carried out:

1) The initial step is to build the building model. Based on the building plan and elevation provided, a simplified building model is then constructed following the steps presented in Section 3.2.1. In the building where the drill took place, the staircase B near the entrance is blocked during the evacuation. For this reason, only staircases A and C were used (Figure 3-10).
2) The second step is to build the turtles. The variables for each agent are summarized in Figure 3-11. Most of the data for the variables are gathered from the drill report and are given to the turtles, only the location information is unavailable. To solve this, the turtles are randomly distributed to the apartment doors at the start of the simulation. After turtles with all variable information are located and represented in the model, they wait at the start point until the delay time is over. All turtles will follow the same dynamic rule to "travel" within the abstract building model after they begin to move.

   It should be noted that in this drill scenario, several occupants are too young to travel independently. During the evacuation process, they are carried by adults. Theses occupants are ignored in the drill model.

Figure 3-11: Agent variables travelling in the corridor

3) The third step is to build the dynamic model. According to the drill, there is a 25/75 distribution of occupants in the left and right staircases, respectively. The central staircase (staircase B) is locked during the drill process. A random number generator is built for each occupant, resulting in a good match for the assumption made in Section 3.2.1. The Markov chain variables, p_1, p_2, p_3, and p_4, chosen for this drill are 0.7, 0.125, 0.125, and 0.05, respectively.

3.3.2 Introduction of Calibrated Model

To apply this Multi-Agent Based Model of an evacuation process to the study of elderly people and perform statistical analysis to explore the effects of various parameters and scenarios, a calibrated model is developed from the original drill model and will be applied as the base model in the case study, which is presented in Chapter 4. The details that are calibrated are outlined below:

1) The turtles all represent elderly people. The average speeds of elderly people both on the stairs and in the corridor are given based on their varying levels of mobility impairment. Speed data and distribution models for different age groups on the stairs as well as in the corridor are largely derived from publications. The data used in this model are listed in Table 2-3 of the literature review (Chapter 2). To simulate the individual difference of each occupant's travel speed, triangular distribution is applied.

2) The delay time is set to be randomly generated from triangular distribution. As discussed in Section 2.2, delay time can be regarded as early delay and late delay. Thus, two triangular distributions are applied to describe the early delay group (short delay time) and late delay group (long delay time), and Monte Carlo is applied to simulate the delay time of an individual.

With the exception of these calibrated details, the rest of the model remains the same as the drill model; that is to say, the building environment, the total number of evacuees, the number of evacuees that belong to early delay group and late delay group, and the dynamic model.

3.3.3 Modifying Modelling Scenarios

To understand the influence of different scenario parameters on simulation results, a series of experiments are designed and the simulation outcomes are compared with the calibrated model in Chapter 4. Once the drill model in Section 3.3.1 is developed and tested, the calibrated model can be created as the base model where modified "what-if" scenarios take place. In each "what-if" scenario, only one or two parameters will be changed and tested. A sensitivity report is conducted to identify how simulation results are influenced by varying the parameters (Chapter4). Table 3-1 displays the parameters that are tested in the experiment.

Table 3-1:
All parameters designed to modify scenarios

Parameter	**Value**	**Definition**	**Reference**
Distribution of pedestrian agents in early reaction group and late reaction group	The accumulated value of evacuees in early reaction group	7 per increment	N/A
Number of evacuees	The accumulated value of evacuees	20 per increment	N/A
A fall accident	The accumulated value of fall accident	Whether or not evacuee falls down and blocks the way	(Fuller 2000)
Fall duration	0-1 hr	How long will the accident block the way	(Hendrich,2009)
Egress width	1.0 m, 1.5 m	The width of staircases	N/A
Number of staircases	2, 3	The number of staircases in use	N/A

3.3.2.1 Pedestrian Age

As discussed in Chapter2.2.1, pedestrians of different age groups have different walking speeds according to observation-based statistics. Table 3-5 presents average walking speed on flat walkways as well as going down stairs for elderly people and the time that each pedestrian agent spends on one 0.5 m × 0.5 m grid in real time.

Table 3-2:
Elderly pedestrian average walking speed

	Horizontally	**Going down stairs**
Average walking speed in real time	0.8 m/s	0.35 m/s
Average walking speed on (0.5 m × 0.5 m) patch in real time	1.6 patch/s	0.7 patch/s
Average walking speed on (0.5 m × 0.5 m) patch in ticks	0.8 patch/tick	0.35 patch/tick

A comparison of the elderly scenario with the mixed age scenario is made by comparing the total evacuation time in Chapter 4.

3.3.2.2 Early Delay vs. Late Delay

In an investigation conducted by Wood (1980), when people encountered a fire, 15% chose to extinguish the fire first, 13% raised the fire alarm, while only 9.5% immediately attempted to evacuate. Studies inducate that trained occupants have a faster response to fire alarms compared to less trained occupants. In a case study in Japan (Nakano and Hagiwara 2000), 90% of the subjects left their rooms within 90 seconds, with only a few delayed 5 minutes. However, Proulx, Latour, and MacLaurin (1994) also argue that in buildings where the number of false alarms is high, occupants are reluctant to respond to an alarm, which will lead to a longer delay time.

A sensitivity analysis on the number of people in the early reaction group is applied to identify the influence of delay time on the evacuation performance, including total evacuation time and clogging situation. As introduced in Section 3.2.2, the scenario of the calibrated base model is set to 44 people in the early delay group and 33 in the late delay group, totalling 77 evacuees (Proulx, Latour, MacLaurin 1994). The modified scenario is designed as presented in Table 3-3. The simulation results of the scenario will be showed and discussed in the case study in

Chapter 4.

Table 3-3:
Tested distribution of pedestrians in early delay group and late delay group

	1	2	3	4	5	6	7	8	9	10	11	12
Evacuees in early delay group	0	7	14	21	28	35	42	49	56	63	70	77
Evacuees in late delay group	77	70	63	56	49	42	35	28	21	14	7	0

3.3.2.3 Number of Evacuees

Pedestrian density is closely related to the occurrence of conflicts, i.e., situations where several people try to occupy the same space (Kirchner, Nishinari, Schadschneider 2003). High pedestrian density may lead to clogging and queuing, thereby influencing the total evacuation time. A sensitivity analysis on the number of evacuees is applied to compare average total evacuation time with various pedestrian density. The maximum number of evacuees is calculated from the total number of apartment units (109). By assuming that all apartments are occupied and each is occupied by a two elderly people, the maximum number of evacuees is 218 in this building scenario.

3.2.3.4 Fall Accident and Time Duration on the Floor

As discussed in Section 2.2.2, elderly people have a high potential to fall during evacuation due to both physical and mental conditions. The fact is that they could fall at any time during the evacuation process, while walking in a corridor or going down stairs, and thus become new obstacles for the other evacuees. When an evacuee falls, the other individuals will walk around to avoid the fallen person until the individual would eventually stand up and continue walking.

The time duration for a fallen individual to stand up varies from case to case. For severe situations, such as a hip fracture, the fallen individual may be unable to stand up without assistance. When the crowd is very dense, some individuals may not be able to walk around such an obstacle and could also trip or fall. This model approach can also simulate this effect with a given fall duration. An example of coding to simulate a fall is presented in Figure 3-12. If the variable of falling occurs, the fallen pedestrian agent turns green, and the variable "block" begins to countdown. "Block" here refers to the number of simulation time "ticks". During the block time, the speed of this pedestrian agent becomes 0. After the countdown ends, the colour of this agent returns to yellow, and the speed returns to normal.

```
ask turtles with [ falldown? = true]
 [ ifelse block > 0   [ set
color  green             set
avgspeedstr  0          set
avgspeedcrd  0          set
blocks (block - 1)      set
block blocks] [  set color
red       set  avgspeedcrd
0.85

  set avgspeedstr 0.3 ]]
```

Figure 3-12: Code example of fall simulation

CHAPTER 4 CASE STUDY

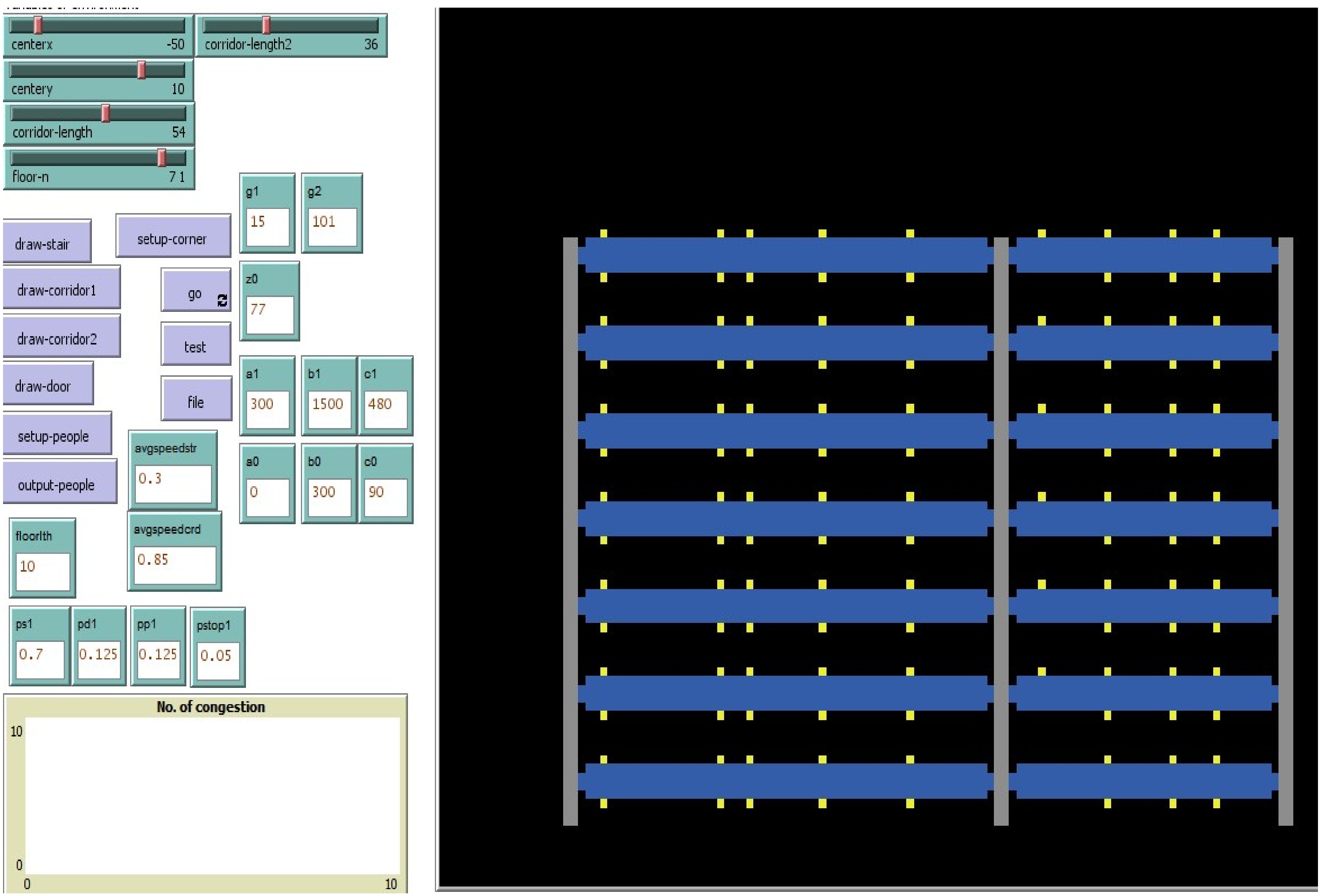
The pattern of human behaviour is one of the most complex areas of modern research. Variability in movement and delay times, as well as the variability of inputs relating to the built egress model and inputs relating to the modelled building, will affect the output of the model. The variable inputs address uncertainty in the results. Few studies in the areas of computer egress model uncertainty and predictive capability has been carried out to date thereby leaving the user the task of determining the uncertainty levels of most models. In the presented case study, this problem is addressed by evaluating the experiment model against a scenario with parameters calibrated from the drill model to resemble the elderly group, the calibrated model.. The drill is selected from a joint research project that was undertaken by the National Research Council of Canada and Canada Mortgage and Housing Corporation to study evacuation drills in midrise apartment buildings with mixed abilities occupants (Proulx and Pineau 1996). Additionally, sensitivity analysis is also conducted to determine the uncertainty associated with the output. To identify the variables that may cause potential hazards during the evacuation process in senior apartment buildings, the case study is designed to follow two steps: (1) to check the validity of the model prior to conducting experiments; and (2) to test the variables using sensitivity analysis.

4.1 Validity Check Results of the Drill Model

Before experiments are designed and carried out, it is necessary to check the validitiy of the model wherein the experiments take place. To check the vilidity, an evacuation drill process is simulated, and the results of the drill model are collected, analyzed, and compared with the real data. The building information of the drill is generated from building 3 presented in the report by Proulx, Latour, and MacLaurin (1994), and will remain constant as the base environment where the "what-if" experiments take place.

The building environment where the drill took place is developed based on the general platform explained in Section 3.2.2 (Figure 4-1). The apartment building has 7 storeys and 3 staircases with the mid staircase out of usage. There are a total of 118 units, including activity rooms in floor 1; and the lengths of the two corridors are rounded as 27m and 18m, respectively. The travel distance between two floors is 5 m.

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 between578.5 s and725.5 s. The mean of movement time and escape time reported in the drill is 75 seconds and 657 seconds, 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.



centerx -50
corridor-length2 36
centery 10
corridor-length 54
floor-n 7 1
g1 15
g2 101
z0 77
a1 300
b1 1500
c1 480
avgspeedstr 0.3
a0 0
b0 300
c0 90
floorlth 10
avgspeedcrd 0.85
ps1 0.7
pd1 0.125
pp1 0.125
pstop1 0.05

Figure 4-1: A visualized model of the drill building

4.2 Calibrated Model and Experimental Model Simulation

To understand the influence of different scenario parameters on simulation results, a series of experiments are designed based on the drill model and the simulation outcomes are compared.

Figure 4-2 illustrates the egress safety evaluation process. Within the NetLogo modelling environment, the MABS modelling representing elderly behaviour is built and tested in Chapter 3 To run the model, the scenario, which aims to test the sensitivity report of one variable, is first set, and 30 is set as the total run count. After the series of models are run, the process of the simulation is compared with the actual (recorded) drill scenario to determine if the model represents reality. Then, the results of the experimental scenario are compared with the calibrated base model scenario to obtain the egress safety performance. Furthermore, after evaluating the results, sensitivity analysis regarding different delay time groups and occupant population is carried out. The potential hazards, such as long evacuation time and substantial congestion, which may occur in several situations are then identified.

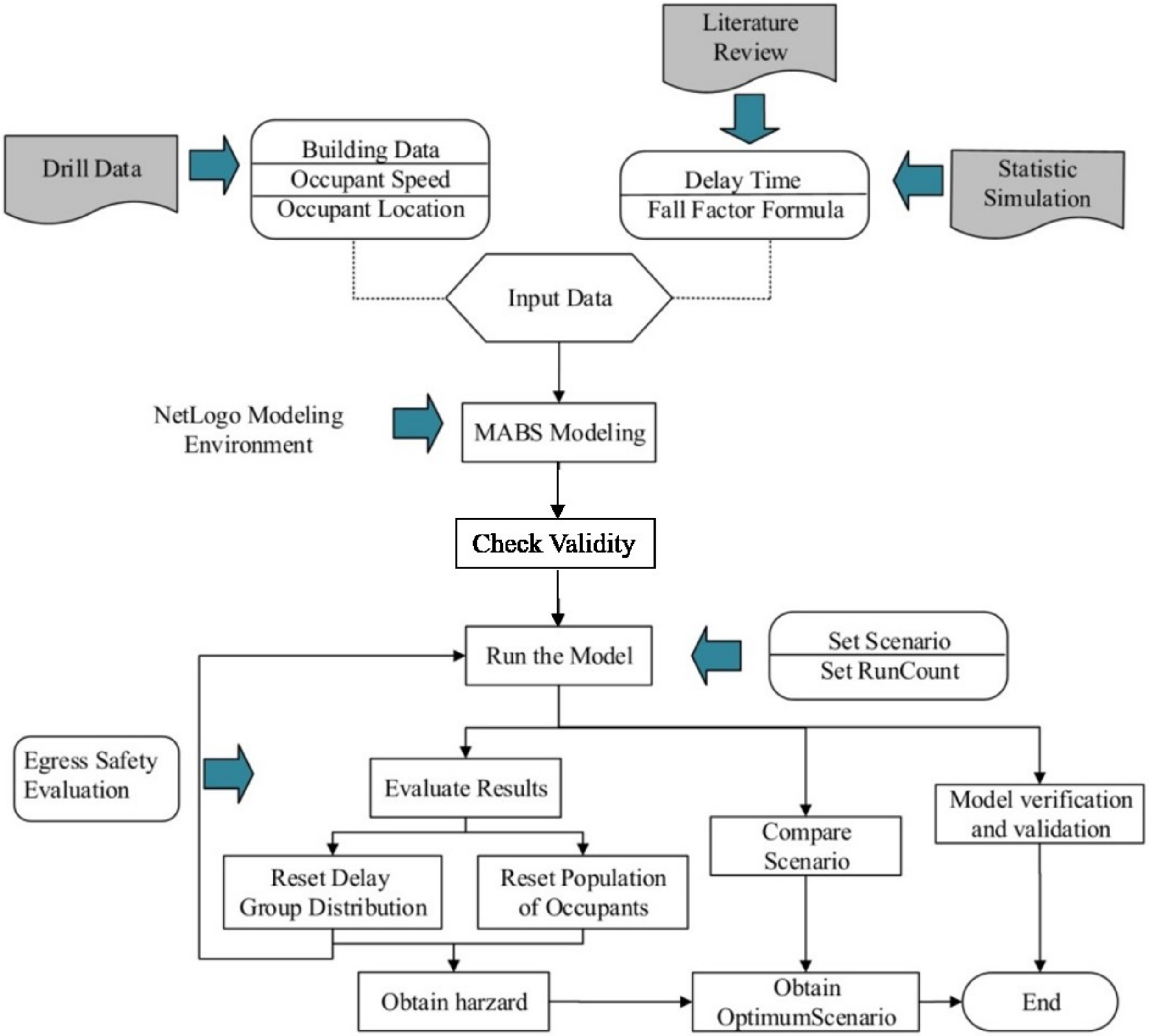


Figure 4-2: Simulation process for egress safety evaluation

Several indexes are used to indicate the results of the tested model, including the delay time, the movement time, the total evacuation time (escape time) of each evacuee, the average delay time, the average movement time, the average total evacuation time, and the total evacuation time of the evacuation process. For each individual, the delay time indicates the speed required to respond to the emergency; the movement time indicates how long the occupant spends traveling in the egress route and the total evacuation time indicates how long the occupant spends moving to a safe place. The average results of each individual index provide the building manager a complete picture of the occupant behaviour pattern. The total evacuation time of the evacuation process is defined as the time that elapses until the final person exits the building successfully, thus terminating the evacuation process. In this research, these indexes are compared with the ASET (Available Safe Escape Time) to evaluate the egress performance, as introduced in Section 2.2.1. Also, the number of people in a congestion situation is collected during the simulated scenario as an indicator of the environmental situation. A large number of people in a congestion situation results in a crowded evacuation process. In this research, the congestion situation occurs when an agent (turtle) is fully surrounded by others, that is to say, the neighbouring patches (before, after, left, and right) of the turtle are all occupied.

4.2.1 Introduction of the Calibrated Model

After the validity of the drill model is checked, the model is then modified to meet the pre-assumptions of the research framework as the calibrated model. To study the behaviour of elderly people during the evacuation process, the occupant agents simulated in the model are set to represent “elderly people” with a lower speed compared to younger age groups. The speed and occupant data are collected from another drill from the same experiment. The basic parameters of the elderly model are listed in Table 4-1.

Table 4-1:
Evacuation parameters in case study

Parameter	**Value**	**Definition**
Pedestrian age	≥ 50	Senior apartments
Early delay group	33	N/A
Late delay group	44	N/A
Early delay time (s)	[0, 300, 90]	Triangular distribution
Late delay time (s)	[300, 1500, 480]	Triangular distribution
Number of evacuees	77	N/A
Travel Speed (Nonassisted)	0.85 ± 0.15 m/s in corridor; 0.3 ± 0.1 m/s on stairs	The moving speed of elderly people (normal distribution)
A fall accident	0	Whether evacuee falls down and blocks the way
Fall duration	[0.5h, 1h]	The length of time the accident will block the way when a fall occurs

After running the model 30 times, several results that indicate a high potential for hazard are identified. For the elderly model, an average of more than 7 people out of 77 with a total travel time of more than 20 minutes and REST more than 30 minutes, 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 designed to test the possible variables that may influence the total evacuation time thus leading to a hazard potential. The parameters that have been defined and tested are summarized in Table 4-2. Details about the variables are provided in the following section.

Table 4-2:
Variables being tested in case study

Parameter	Value	Definition
Delay time	N/A	Test the influence of delay time
Number of evacuees	77 to 217	Test the influence of population
A fall accident	0, 1, 2	Test the consequence after evacuees fall down and block the way
Staircase width	1 m, 1.5 m	Test the influence of stair width
Number of staircases	2, 3	Test the influence of stair number

4.2.2 Early Delay Group (EDG) vs. Late Delay Group (LDG)

Since delay time varies from person to person as well as case to case, it is reasonable to consider the situation statistically from the points of view of each group. This is carried out by changing the different model inputs for the same scenario and then analyzing the output to determine the effect of changing the variables.

A sensitivity analysis on the number of people of early reaction was applied to identify the influence of delay time on the total evacuation time. The original scenario of the calibrated model is set to have 33 people in Early Delay Group (EDG) and 44 in the Late Delay group (LDG) with a total number of evacuees equal to 77. These data are obtained from the drill scenario and remain constant in the calibrated model. The modified experimental scenarios considering different delay behaviours are designed as the number of people in LDG changed 7 per scenario.

To simulate human behaviour, two possible delay reactions prior to the start of evacuation are applied: the EDG (evacuees begin to move within 5 minutes) and the LDG (evacuees begin to move after more than 5 minutes have elapsed). Each occupant is given a label at the beginning of the simulation. Integer “Z0” is set to be the number of occupants that belong to the EDG. The code that is applied in order to set the delay time is presented in Figure 4-3a. If the label of the occupant is less than Z0, the delay time of the occupant is randomly generated from the triangular distribution of the EDG, which is [a0, b0, c0]; otherwise, the delay time of the occupant will be generated from the triangular distribution of the LDG. The code that is applied to represent how agents stop and wait for the given delay time prior to travel is presented in Figure 4-3b.

```
ask turtles
  [
  ask turtles with
 [ ([ycor] of self + 1 - centery ) mod floorlth   = 0 ]
  [ifelse ticks >= delay-time
    [ set heading 0
      ifelse count turtles-on patch-ahead 1 = 0
      [fd 1]
      [stop]]
[stop]]
   ask turtles with
 [ ([ycor] of self - 4 - centery ) mod floorlth   = 0 ]
  [ifelse ticks >= delay-time
    [ set heading 180
      ifelse count turtles-on patch-ahead 1 = 0
      [fd 1]
      [stop]]
    [stop]]
```

Figure 4-3a: Code example of delay time set to agents.

```
ask seniors
  [  let seniors1 []
    set seniors1 lput  label seniors1
set seniors1 lput xcor seniors1     set
seniors1 lput ycor seniors1     set
seniors1 lput group seniors1     if
label <= z0
   [ let y0 random-float 1.000
if y0 <= (c0 - a0)/(b0 - a0)
    [set delay-time 2 * round (a0 + sqrt(y0 * (b0 - a0)*(c0 - a0)))]
if y0 > (c0 - a0)/(b0 - a0)
      [ set delay-time 2 * round (b0 - sqrt((1 - y0) * (b0 - a0)*(b0 - a0)))]] end
    if label > z0
     [ let y1 random-float 1.000
if y1 <= (c1 - a1)/(b1 - a1)
        [set delay-time max list (0)( 2 * round (a1 + sqrt(y1 * (b1 - a1)*(c1 - a1))) ) ]
if y1 > (c1 - a1)/(b1 - a1)
      [ set delay-time 2 * round (b1 - sqrt((1 - y1) * (b1 - a1)*(b1 - a1)))] ]] end
```

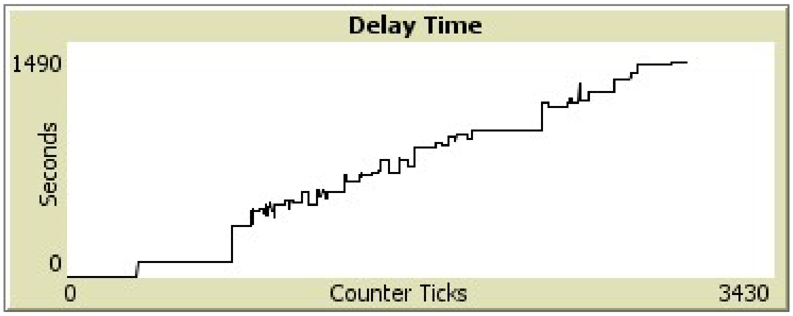
Figure 4-3b: Code example of agents delay before travel.

The results of each scenario test are listed in Table 4-3 and Table 4-4. The average delay time per person indicates the average time that elapses before each evacuee begin to evacuate. It is clear that the more people in the LDG, the longer the average delay time per person. According to Table 4-3, it can be observed that the average travel time per person and average total evacuation time decrease significantly along with the decrease of average delay time per person. At the same time, the average movement time per person increases slightly. Figure 4-4 provides an example of results when the number of people in the EDG is 0 (Row 1). Figure 44a and Figure 4-4b suggest that there is a significant correlation between average delay time per person and average total travel time per person. According to Figure 4-4a, the total evacuation time is well spread during the whole evacuation process, some evacuees having reached the exit during the first minute; however, others reached the exit after over 20 minutes, which is highlighted as a hazard situation by the egress safety evaluation method.

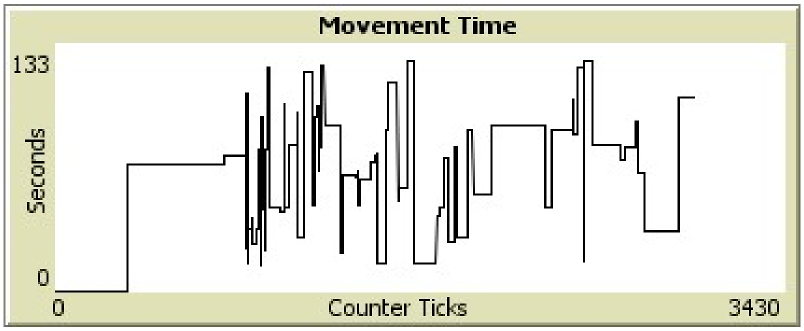
Table 4-3:
Experiment results of evacuation time regarding different delay groups.

	Early delay group	Late delay group	Average delay time per person (min:sec)	Average movement time per person (min:sec)	Average total per person (min:sec)	Total evacuation time per run (min:sec)
1	0	77	14:21	1:07	14:39	23:40
2	7	70	13:15	1:02	15:35	25:01
3	14	63	0:20	1:08	16:34	22:30
4	21	56	12:06	1:07	14:43	23:09
5	28	49	9:11	1:14	13:14	22:14
6	35	42	8:16	1:08	10:35	21:05
7	42	35	7:29	1:08	9:48	20:31
8	49	28	6:32	1:05	9:06	18:49
9	56	21	4:48	1:09	7:14	18:43
10	63	14	3:47	1:11	6:10	18:37
11	70	7	3:33	1:12	5:02	14:52
12	77	0	3:08	1:15	4:26	5:35

(a): Escape time (seconds) per person throughout the evacuation process.



(b): Delay time (seconds) per person throughout the evacuation process.



(c): Movement time (seconds) per person throughout the evacuation process.

Figure 4-4: Simulation results per person throughout the evacuation process.

The potential hazards of congestion and late arrival are also examined. The number of people experiencing congestion, the number of people that require more than 20 minutes to evacuate the building, as well as the number of people that require more than 25 minutes to evacuate the building are listed in Table 4-4.

Table 4-4:
Experiment results of potential hazards regarding different delay groups.

	Early delay group	Late delay group	No. of occupants in congestion	No. of occupants > 25 minutes	No. of occupants > 20 minutes
1	0	77	4	2	28
2	7	70	2	2	22
3	14	63	3	3	29

4	21	56	2	2	21
5	28	49	3	3	24
6	35	42	1	1	12
7	42	35	0	0	12
8	49	28	0	1	12
9	56	21	0	0	6
10	63	14	0	0	1
11	70	7	0	0	2
12	77	0	0	0	0

The results for the number of occupants that require more than 20 minutes to exit the building are presented in Figure 4-5. Since a total evacuation time of over 20 minutes is highlighted as a hazard situation by the egress safety evaluation method, it is suggested that the number of occupants which belong to the LDG will influence the egress performance. In this case, if all occupants begin to travel after 5 minutes, 28 of the 77 may suffer injury during evacuation. The number of people at high risk of injury decreases significantly with the decrease of people in the LDG. In order go ensure life safety of all evacuees, a maximum of 14 of the 77 evacuees can be in the LDG, and the ideal situation will be all people begin evacuation in the first 5 minutes.

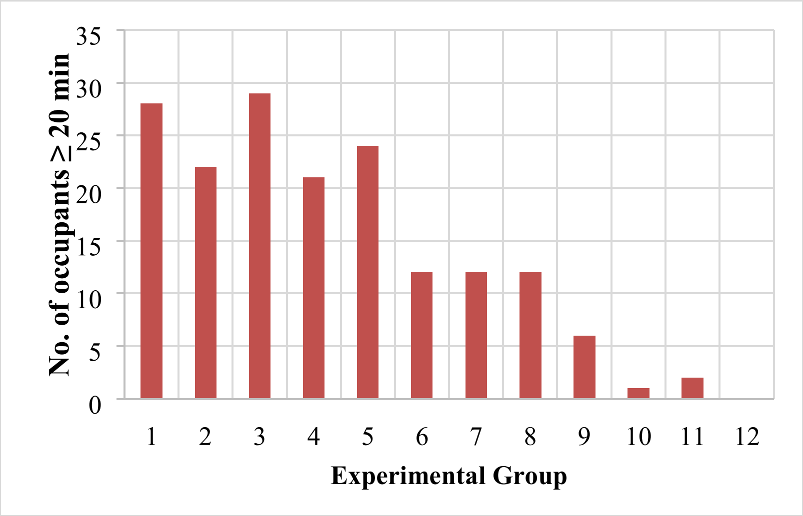


Figure 4-5: Number of occupants in congestion situation during evacuation.

4.2.3 Number of Evacuees

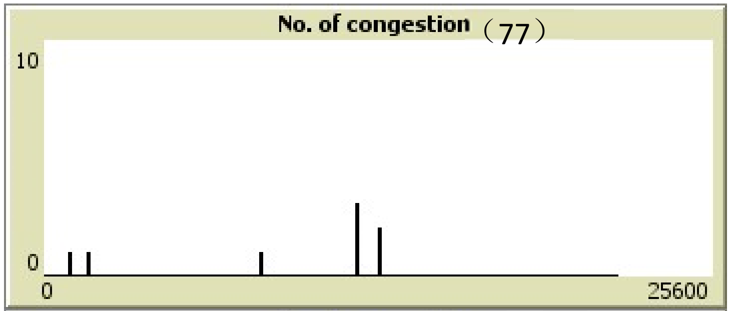
One of the principal limitations of evacuation drills is that participants do not include all the occupants; for example, in the initial drill scenario, only 77 of 250 participated in the drill. Pedestrian density is closely related to the occurrence of clogging, which may lead to longer evacuation time. It is also reported that in crowded situations, the walking speed of pedestrians will decrease since people tend to keep a distance from others in an effort to remain safe. The modified scenarios are designed by increasing the number of people by 20 each time, from 77 to 217. The delay time of each occupant is set in the EDG in order to avoid the influence of a long delay time on the results. When the number of people in a congestion situation reaches the threshold (in this model, 10 people is selected as the threshold), the travel speed of these occupants in congestion will decrease. In this model, this is achieved by decreasing the travel speed of these occupants to 75% of the original speed.

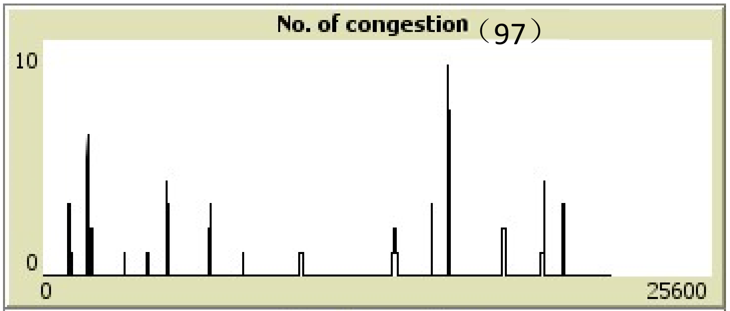
Table 4-5 presents the results of the various scenarios based on the number of occupants. An increase in average movement time per person is observed as the number of occupants who participate in the evacuation grows. When the number of evacuees reaches 217, the average movement time per person increases from 1:14 minutes to 1:36 minutes. The average total evacuation time per person increases by almost 20% when the number of occupants increases from 77 to 217, from 3:05 minutes to 3:40 minutes, and the average total evacuation time per experiment increases from 5:02 minutes to 7:02 minutes. Figure 4-6 illustrates the situation of congestion based on the number of occupants. From Figure 4-6, it can be observed that when the number of occupants is low (less than 120, nealy half of the total population), the number of people in congested situations remains at a low level (less than 10). Congestion also worsens as the number of evacuees increases. In some scenarios, as many as 63 of the 217 (more than 1/4) evacuees are in a congested situation (surrounded by more than 4 people), which may lead to potential hazards.

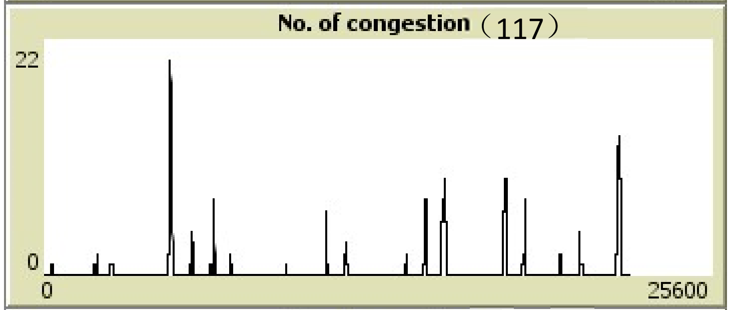
Table 4-5:
Experiment results based on number of occupants.

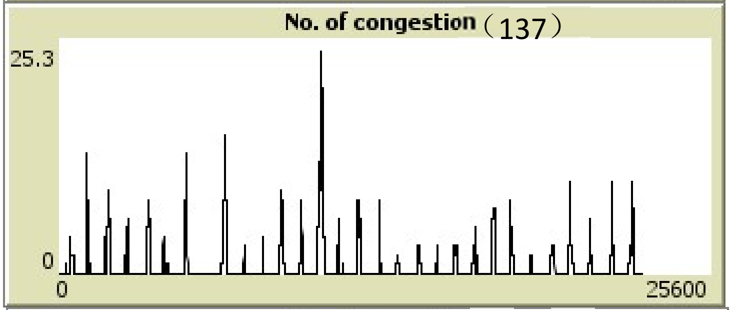
No. of occupants	Average movement time per person (min:sec)	Average total evacuation time per person (min:sec)	Average total evacuation time per experiment (min:sec)	No. of occupants in congestion
77	1:14	3:05	6:02	4
97	1:14	3:03	6:05	4
117	1:16	3:07	6:12	7
137	1:22	3:14	6:47	10
157	1:28	3:25	6:53	21
177	1:24	3:24	6:55	33
197	1:26	3:25	6:50	38
217	1:36	3:40	7:02	63

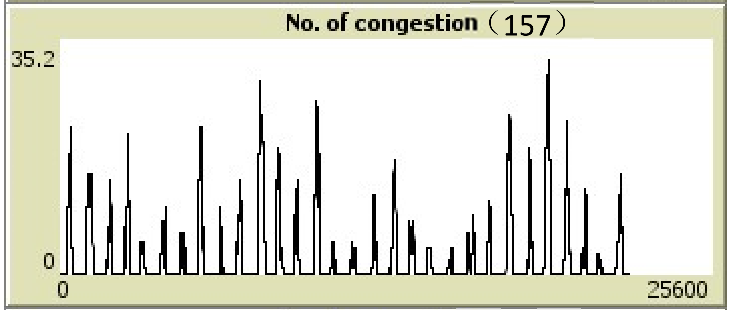
Figure 4-7 provides an example of results when the number of occupants that need to evacuate from the building reaches 217. When compared with the example results shown in Figure 4-5, it can be observed that due to congestion, the movement time of each occupant increases significantly.

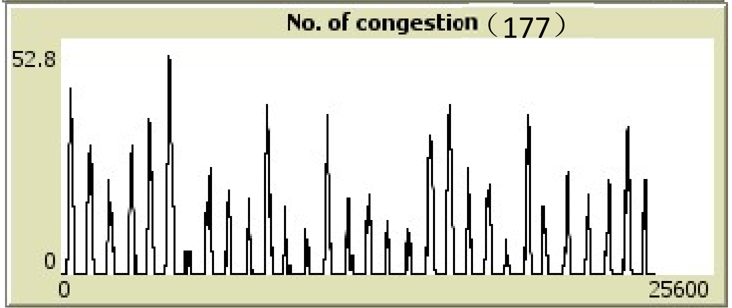

No. of congestion（77）
10
0
0
25600

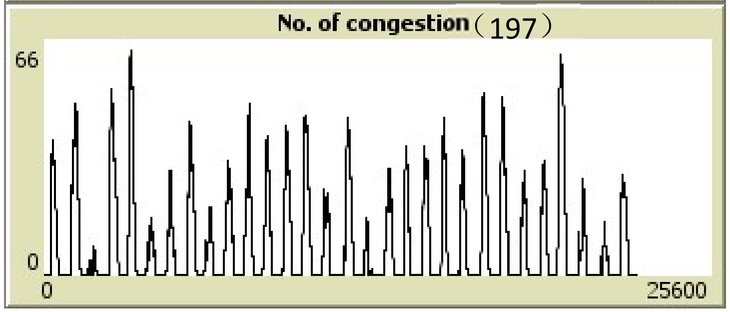

No. of congestion（97）
10
0
0
25600


No. of congestion（117）
22
0
0
25600


No. of congestion（137）
25.3
0
0
25600


No. of congestion（157）
35.2
0
0
25600


No. of congestion（177）
52.8
0
0
25600


No. of congestion（197）
66
0
0
25600

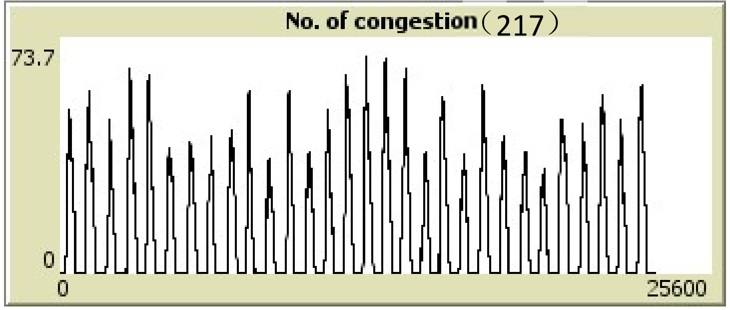
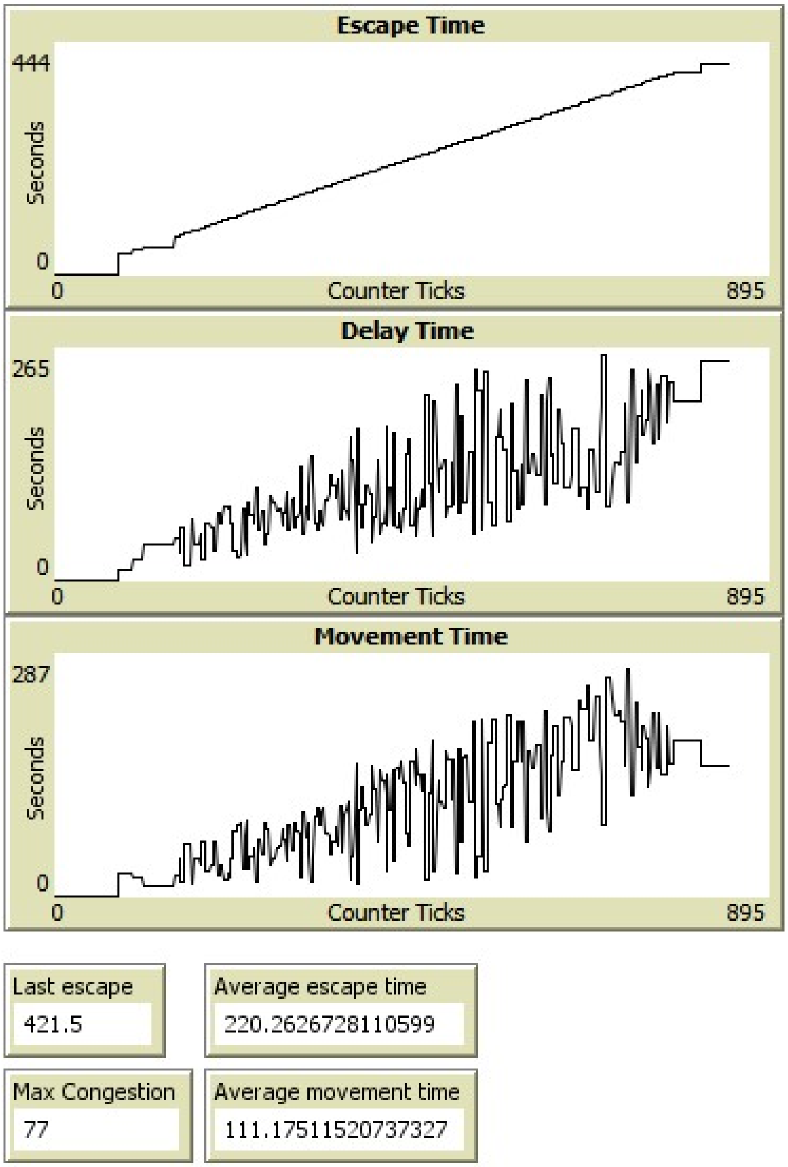

No. of congestion（217）
73.7
0
0
25600

Figure 4-6: Simulation results based on number of occupants in congestion situation during evacuation



Last escape 421.5

Average escape time 220.2626728110599

Max Congestion 77

Average movement time 111.17511520737327

Figure 4-7: Results of one run of simulation during evacuation

4.2.4 Fall accidents

As discussed in previous chapters, elderly people are a demographic with at a high risk of falling. Situations of crowding increase this risk. Notably, fall accidents may occur during the evacuation process in senior apartments. The experiments in this study are thus designed to test the influence of falls on the total evacuation process of the building. The fall duration is set randomly between 30 minutes and 60 minutes.

The simulation of a fall accident is designed in two scenarios: considering 1 fall, and considering 2 falls, and the results are compared with the experiment result in Section 4.2.2. In this experiment, the fall accident is assumed to occur in the staircase and at a lower floor, aiming to determine the most serious impact after the fall accident occurs. When considering 2 falls, the 2-fall accident scenarios are designed to occur in a random location of a lower floor (below the 3rd floor) in the two staircases.

Figure 4-8 provides an example of the modified scenarios. As presented in the example scenario (217 occupants, 1 fall), it can be observed that 90 seconds into the evacuation, nearly half of the occupants have started moving and the others still remain at home (4-8a). At approximately the 200-second mark (4-8b), agent 7 (pink) experiences a fall and blocks the evacuation path. Figure 4-8c presents the consequential congestion (agents turn yellow) after a fall. Before agent 6 passes agent 7, agent 6 remains red since it is only surrounded by 2 agents (agent 4 and agent 1); however, when agent 6 passes agent 7, it becomes surrounded by 4 agents (agents 15, 37, 7, and 8), thereby entering a congested situation, and agent 6 turns yellow. The same situation occurs when other agents pass the fallen agent. During the visualized egress process, data of delay time, movement time, total evacuation time of each agent, and number of agents in congestion are recorded in the excel document separately. The results of the average total evacuation time per run, the average total evacuation time per person, the average movement time per person, as well as the maximum number of people in congestion situation are monitored at the interface, which can be easily read from. Figure 4-9 and Figure 4-10 provide example outcomes of this simulation.

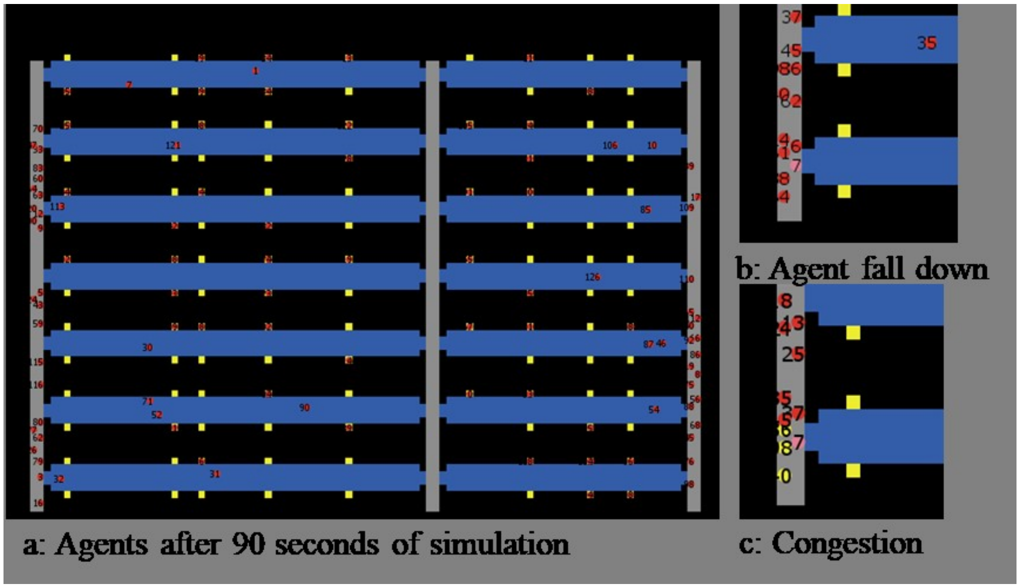


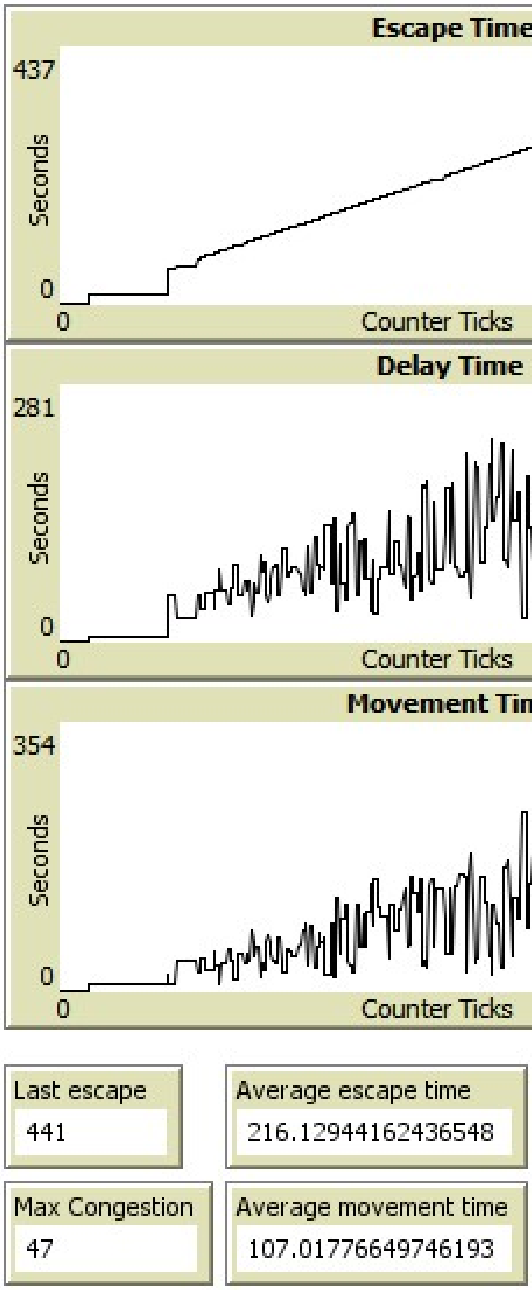
Figure 4-8: Simulation scenario example of fall accident.

The simulation results for various evacuation populations are presented in Table 4-6 for one fall and Table 4-7 for two falls. Comparisons between the two scenarios as well as the base scenario are made.

Table 4-6:
Simulation results considering 1 fall

No. of occupants	Average movement time per person (min:sec)	Average total evacuation time per person (min:sec)	Average total evacuation time per run (min:sec)	No. of occupants in congestion
77	1:13	3:04	6:24	14
97	1:17	3:06	6:29	17
117	1:25	3:16	6:35	28
137	1:27	3:18	6:41	34
157	1:29	3:29	6:59	42
177	1:39	3:38	7:04	47
197	1:48	3:41	7:22	53

217	1:55	3:46	7:39	63



Last escape: 441

Average escape time: 216.12944162436548

Max Congestion: 47

Average movement time: 107.01776649746193

Figure 4-9: Simulation results from single run for evacuation considering 1 fall.

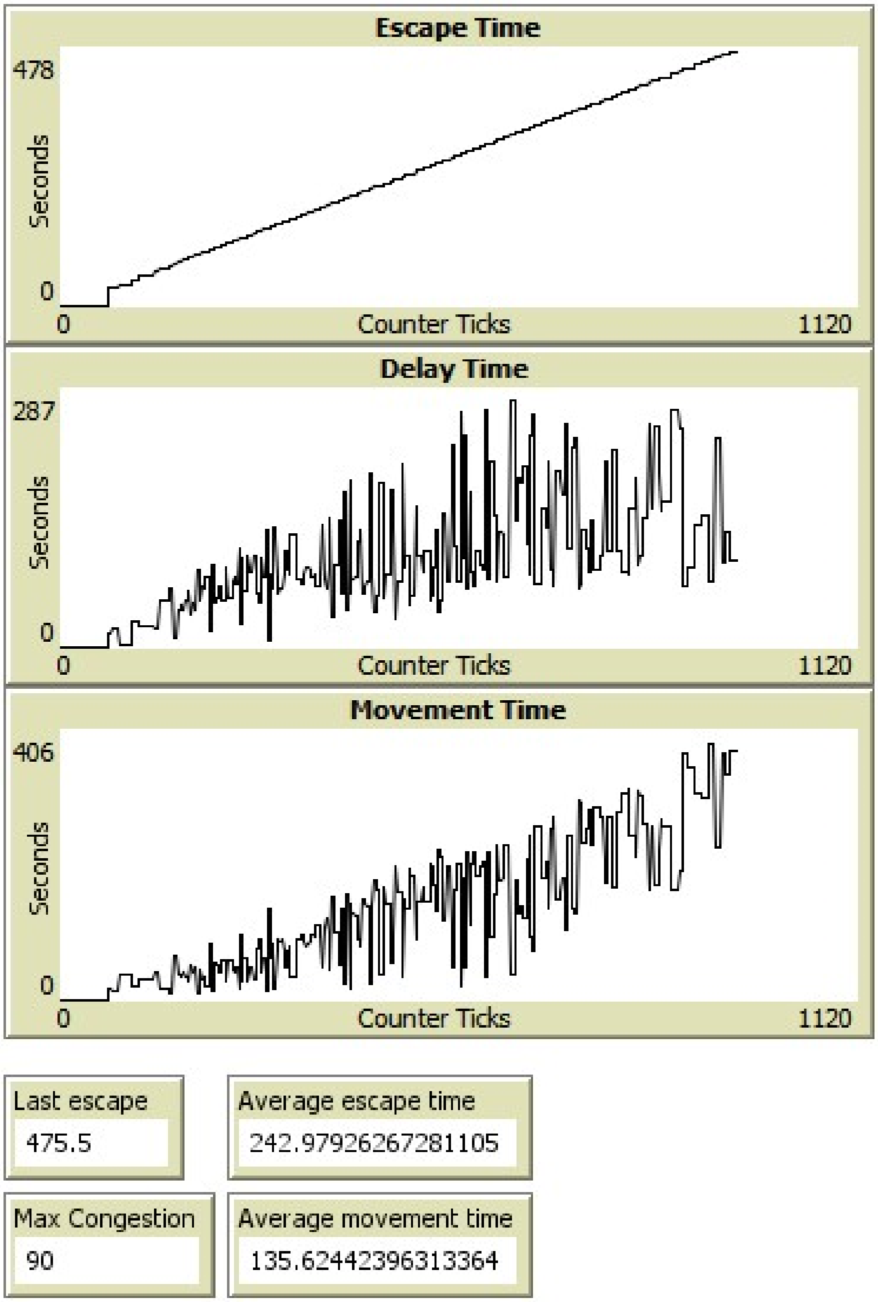
Table 4-7:
Simulation results considering 2 falls

No. of occupants	Average movement time per person (min:sec)	Average total evacuation time per person (min:sec)	Average total evacuation time per run (min:sec)	No. of occupants in congestion
77	1:13	3:07	6:25	18
97	1:17	3:17	6:30	23
117	1:30	3:29	6:40	39
137	1:29	3:30	6:56	45
157	1:27	3:35	6:55	57
177	1:47	3:47	7:23	80
197	2:11	4:03	7:45	87
217	2:22	4:12	8:14	99

As can be seen from Tables 4-5 and 4-6, the number of evacuees in congestion increases significantly in the case of fall accidents. When the number of evacuees is 77, the number of evacuees in congestion is 4 considering no fall accidents, but the number increases to 14 considering 1 fall, and 18 considering 2 falls. Nearly 50% of evacuees are in a crowded situation when 2 fall accidents occur and the number of evacuees reaches 217.

Fall accidents also contribute to longer total evacuation time, and the influence of fall accidents becomes more significant as the number of evacuees increases. As shown in the simulation results, when the number of evacuees reaches

217, the average total evacuation time considering 1 fall reaches 206 seconds, and the average total evacuation time considering 2 falls reaches 216 seconds. Figure 411 presents the comparison among the three scenarios: no fall, 1 fall, and 2 falls.



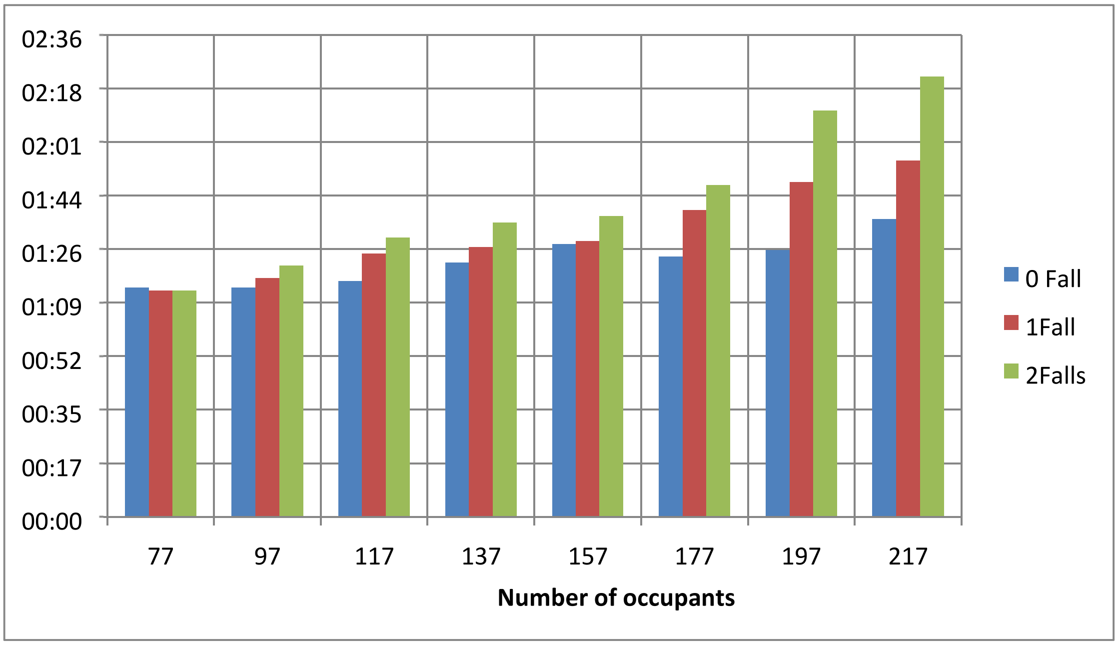
Last escape
475.5

Average escape time
242.97926267281105

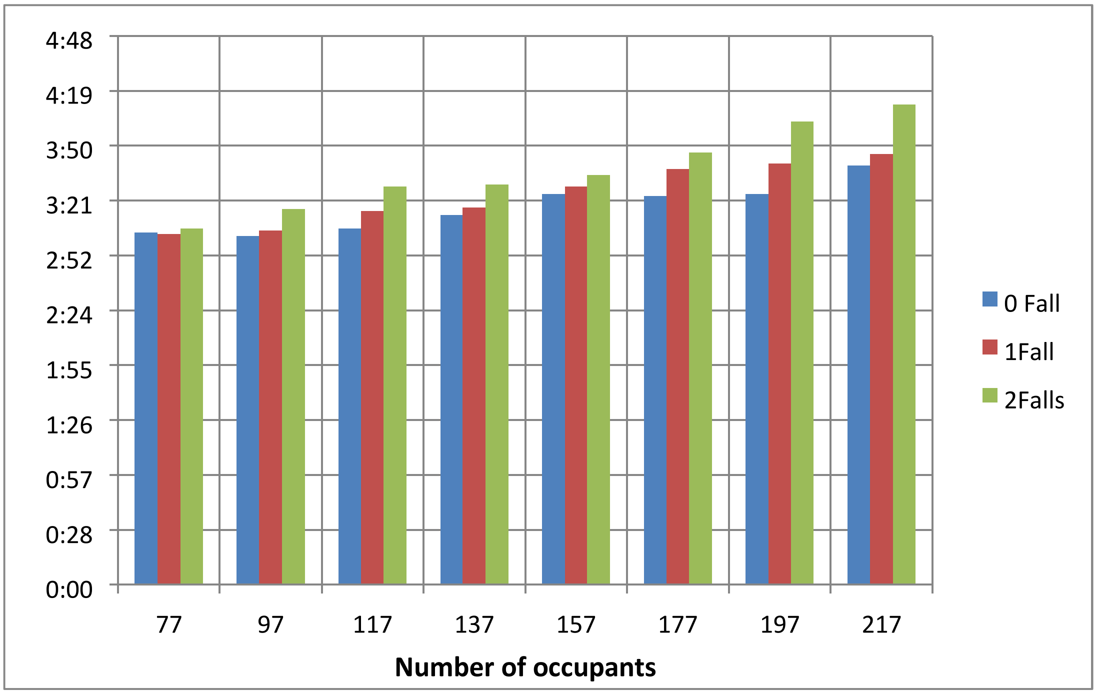
Max Congestion
90

Average movement time
135.62442396313364

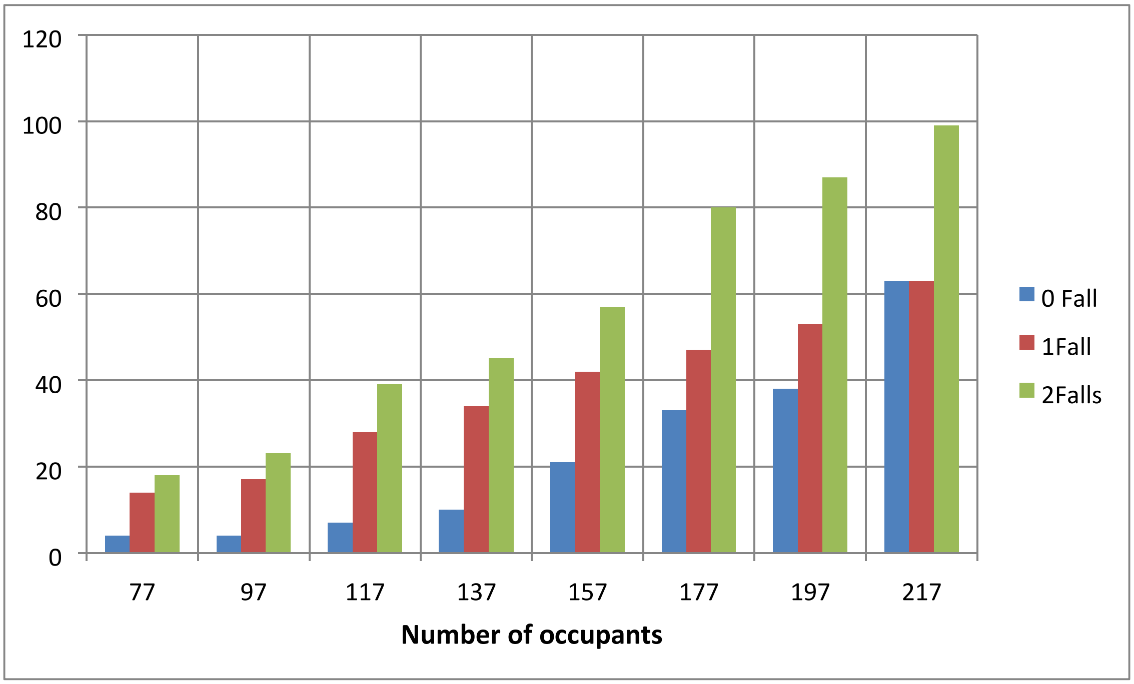
Figure 4-10: Simulation results from single run for evacuation considering 2 falls.



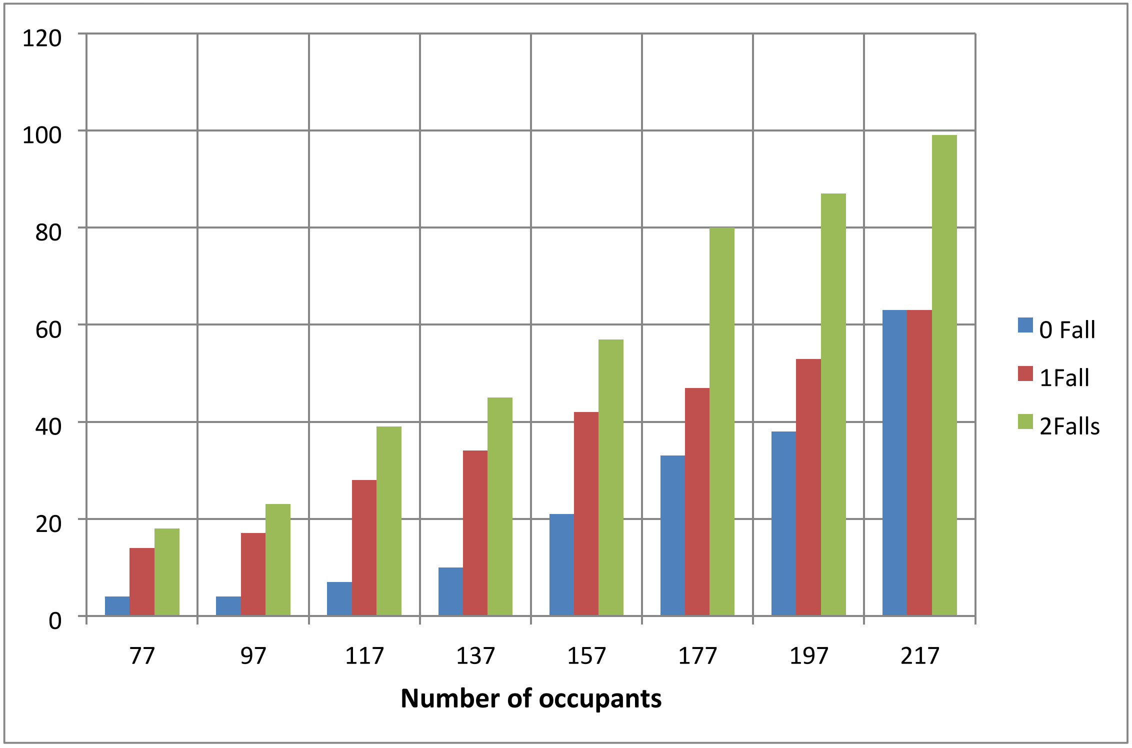
(a) Average movement time of each occupant for 3 fall scenarios



(b) Average total evacuation time of each occupant for 3 fall scenarios



(c) Average total evacuation time per run for 3 fall scenarios



(d) Number of occupants in congestion for each simulation run for 3 fall scenarios

Figure 4-11: Simulation results for 3 fall scenarios

4.2.5 Egress width

In a multi-storey building, the required egress width is calculated based on the greatest occupant load from any single floor, as presented in Figure 4-12. Thus, congestion occurs where the required egress width is insufficient. In this section, a series of experiments are designed to examine the effect of increasing egress width on egress performance. As can be observed in the experiments presented in previous sections, most congestion situations occur in staircases, and no obstructions are encountered while traveling in corridors. For this reason, only the egress width of staircases is tested in this section.

In this research, in order to compare the egress width, according to how much each width size reduces congestion, and the total evacuation time for older adults, a constant length of 0.5 m is assumed to be the difference of the staircases (1 m, 1.5 m).

It is important to note that this research provides a framework for the corridor width and staircase width assessment as well as the performance test through the proposed methodology. The purpose of this study is to provide an assistive performance test approach to improve egress performance based on simulation results. The simulation results offer an effective representation of what would occur in real life situations based on different staircase widths.

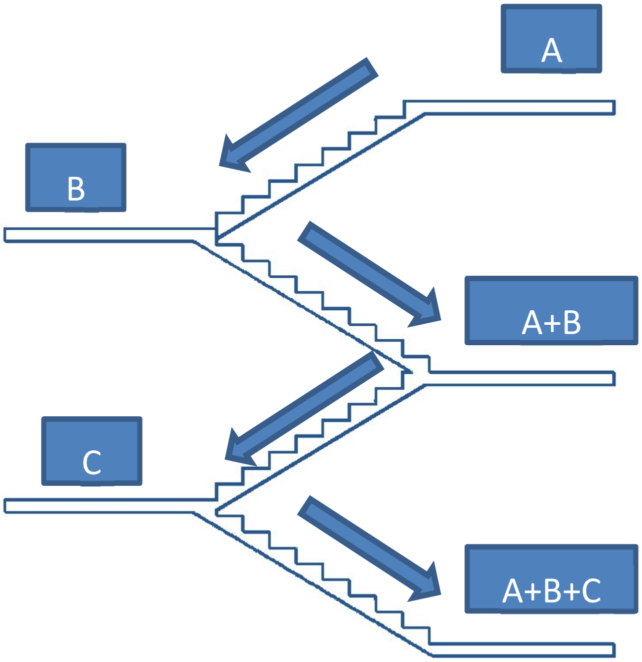


Figure 4-12: Occupant load merging on egress routes

Stair Width

Egress stair design is an important aspect of egress design, because the role exit stairs play in the overall safety of occupants between different floors in a building. Over time, the various model building codes have amended requirements for stairs to minimize potential hazards (for example tripping, falls, missteps) while maximizing the utility of the stair space. The results of experiments using a 1.5 m staircase width and various evacuation populations are presented in Table 4-8. The detailed results for the number of occupants in congestion situation during evacuation are presented in Figure 4-13. The example outcomes of one simulation run of the experiment are presented in Figure 4-14, and comparisons between the changed scenario and the base scenario are provided in Figure 4-15.

Table 4-8:

Simulation results of 1.5 m stair width

No. of occupants	Average movement time per person (min:sec)	Average total evacuation time per person (min:sec)	Average total evacuation time per run (min:sec)	No. of occupants in congestion
77	1:13	3:07	6:08	0
97	1:14	3:06	6:06	0
117	1:14	3:05	6:16	0
137	1:14	3:07	6:21	1
157	1:15	3:09	6:23	1
177	1:15	3:04	6:25	5
197	1:15	3:04	6:25	5
217	1:20	3:10	6:40	9

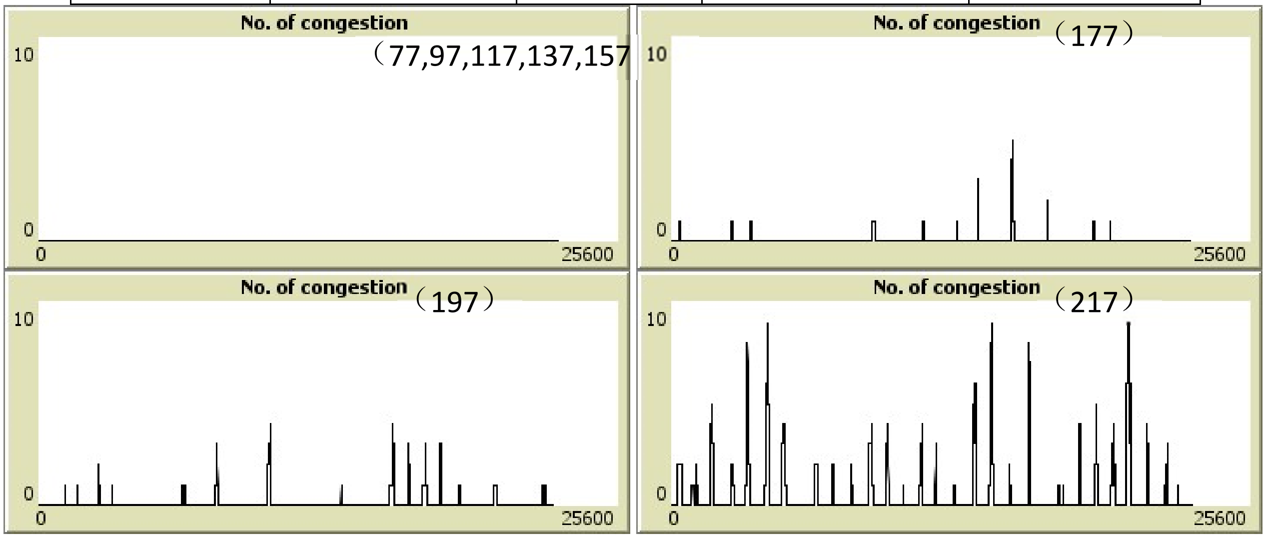
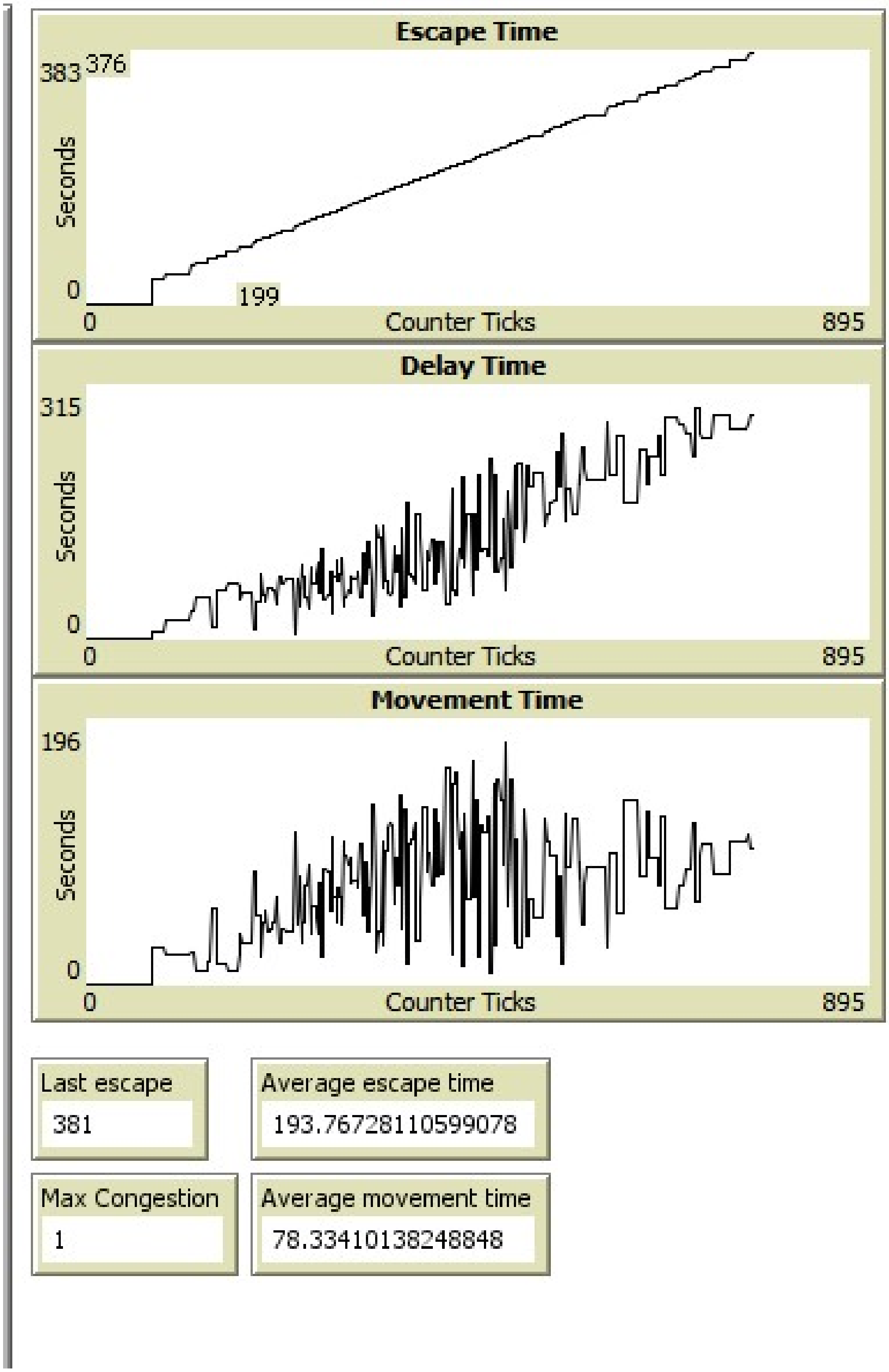


Figure 4-13: Simulation results for number of occupants in congestion situation during evacuation



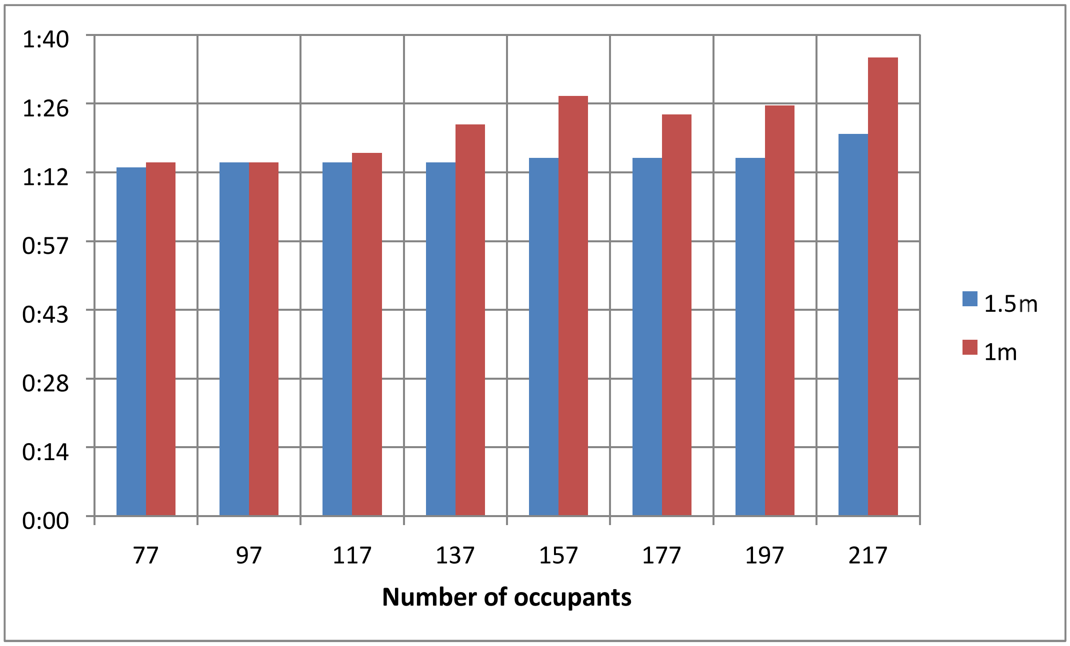
Last escape
381

Average escape time
193.76728110599078

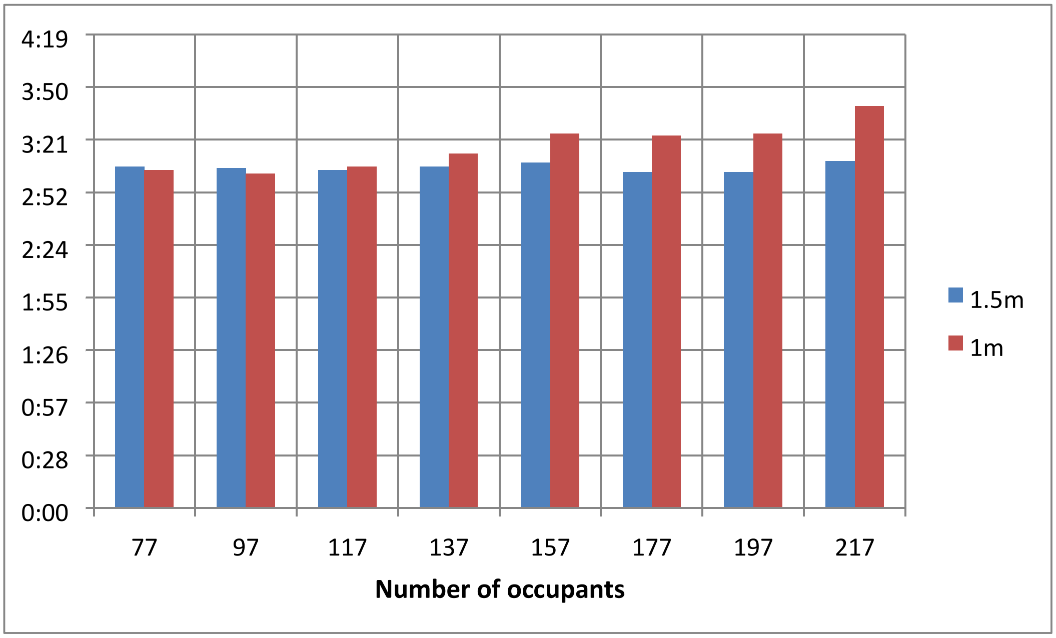
Max Congestion
1

Average movement time
78.33410138248848

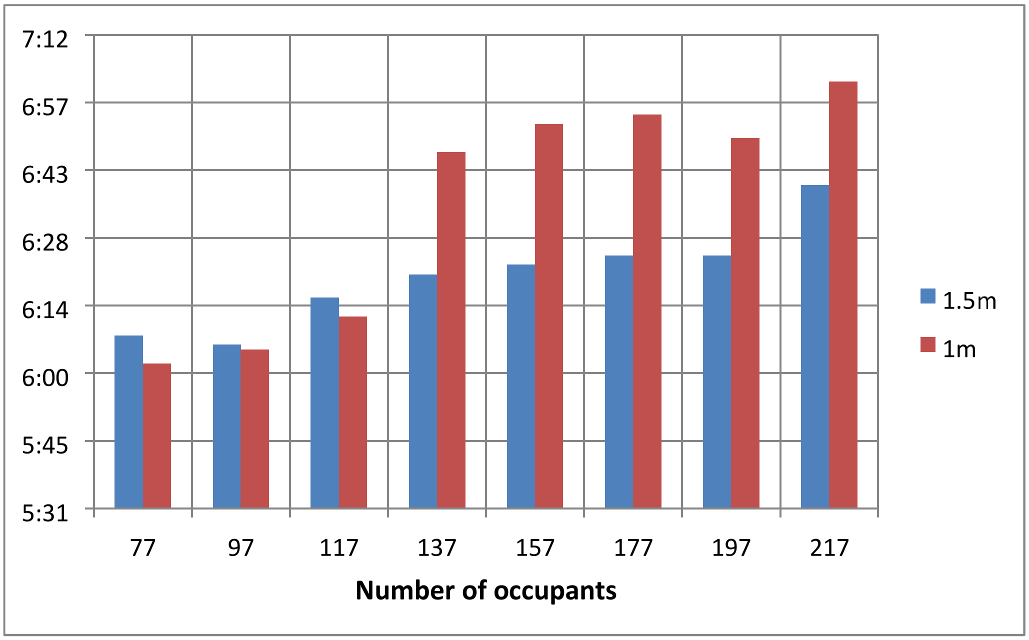
Figure 4-14: Outcomes of one simulation run of the experiment during evacuation



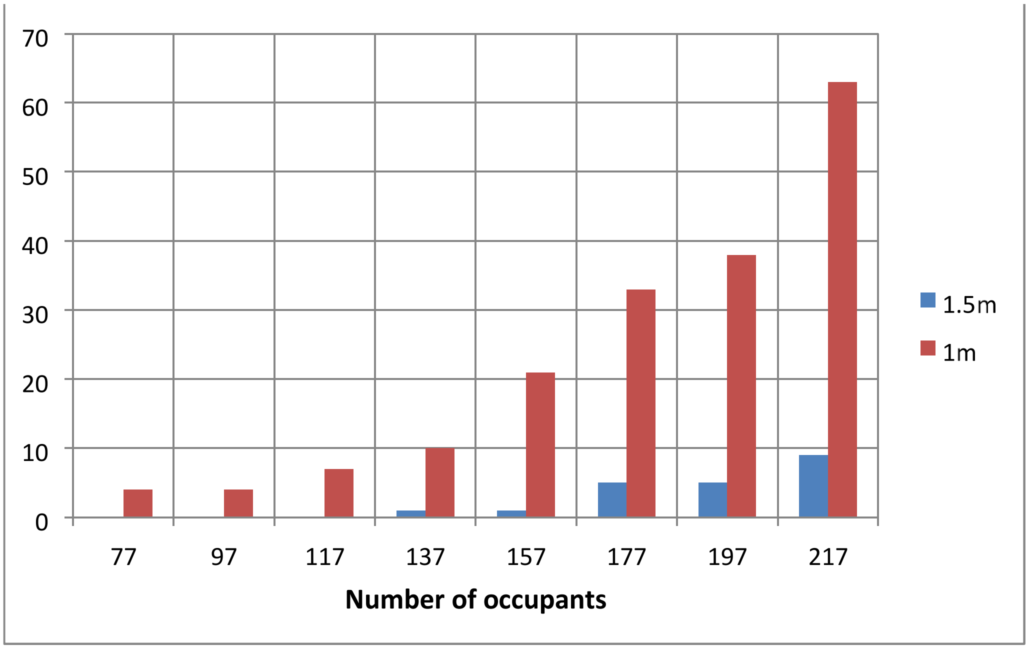
(a) Average movement time of each occupant for two staircase width scenarios



(b) Average total evacuation time of each occupant for two staircase width scenarios



(c) Average total evacuation time of each simulation run for two staircase width scenarios



(d) Number of occupants in congestion during each simulation run for two staircase width scenarios

Figure 4-15: Simulation results for two staircase width scenarios

From the comparisons, it is clear that the egress performance of the 1.5 m staircase scenario is superior to the original 1.0 m staircase scenario, especially in crowed situations. When the number of evacuees is 217, the average movement time per person decreases from 1:36 minutes to 1:20 minutes; the average total evacuation time per person decreases from 3:40 minutes to 3:10 minutes; and the average total evacuation time per simulation run decreases from 7:02 minutes to 6:40 minutes. Also, the congestion situation is largely improved by increasing the width of the staircase from 1.0 m to 1.5 m. When occupants travel in the wider staircase, the number of occupants in congestion situation remains less than 10 regardless of the increase in evacuation population.

4.2.4 Number of Staircase

As discussed in Chapter 2, a number of significant disasters have resulted from the inappropriate design of the means of egress. As a result, requirements of the critical factors have been developed to protect life safety. For example, IBC requires that for residential buildings that have only one means of egress (staircase, exit), the maximum occupant load per floor is a maximum of 10 persons (NFPA 2017). Most codes, including the IBC (2016) and NFPA (2017) require at least two exits from floors that are above or below grade. However, in some of the drills reported, it is notable that it is often the case that one staircase is out of order during the emergency evacuation process due to fire or other reasons.

In this research, in order to compare the number of required staircases according to how much a different number of staircases will influence the congestion and the total evacuation time for older adults, a scenario using all three staircases is designed and compared with the base scenario (two staircases in use). Figure 4-16 presents the simulation model of the three staircases scenario. The simulation results are collected in Table 4-9, and the example of the outcome of one simulation run is presented in Figure 4-17. Comparisons between the changed scenario and the base scenario are made in Figure 4-18.

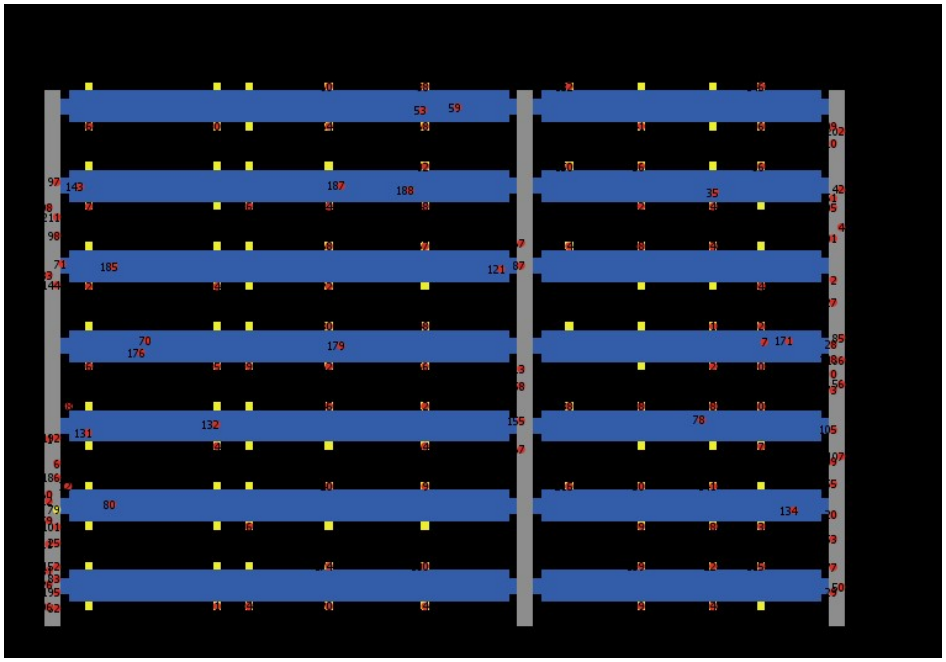
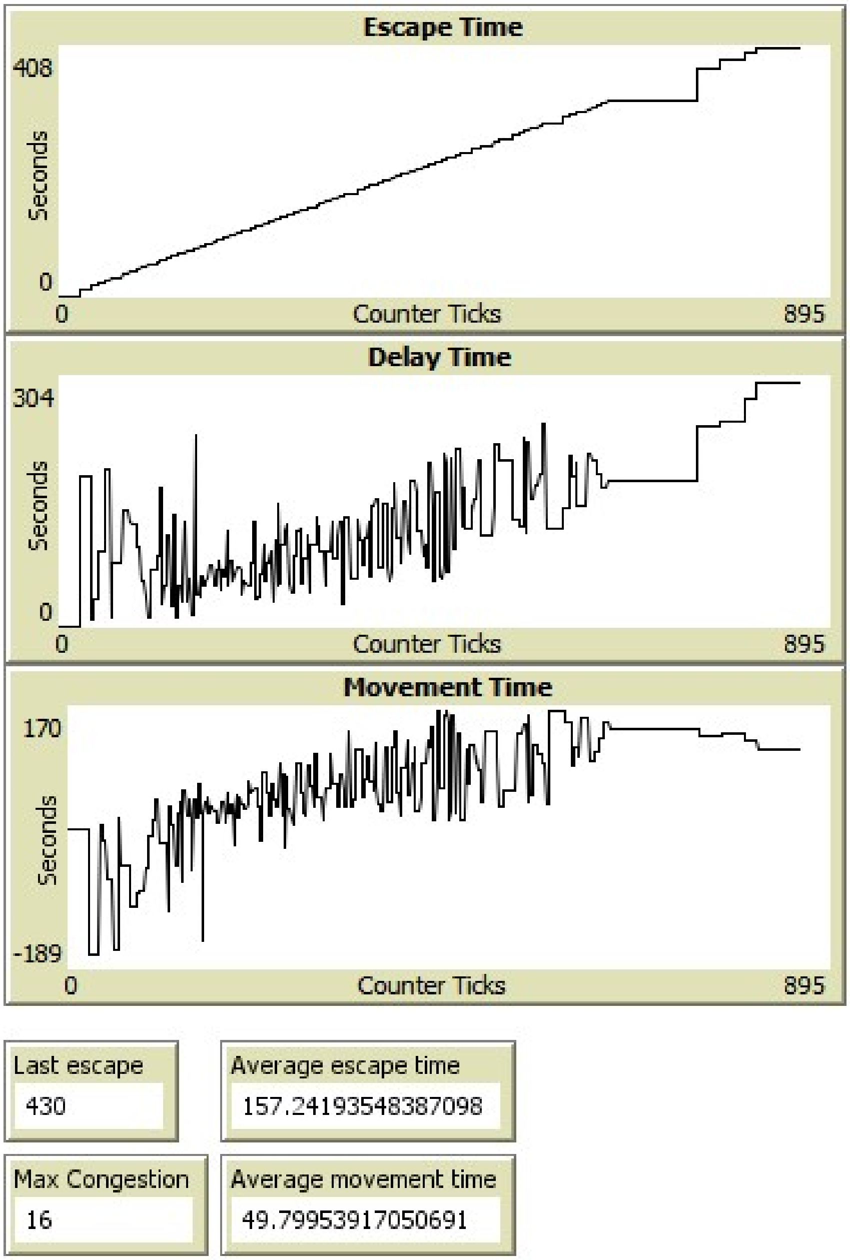


Figure 4-16: Simulation scenario of three staircases in use.

Table 4-9:
Simulation results of three staircases in use

No. of occupants	Average movement time per person (min:sec)	Average total evacuation time per person (min:sec)	Average total evacuation time per run (min:sec)	No. of occupants in congestion
77	0:39	2:29	5:43	0
97	0:39	2:35	5:58	3
117	0:38	2:28	5:44	3
137	0:36	2:28	5:45	3
157	0:40	2:32	5:56	5
177	0:41	2:32	6:08	8
197	0:43	2:29	6:18	10
217	0:47	2:38	6:25	20



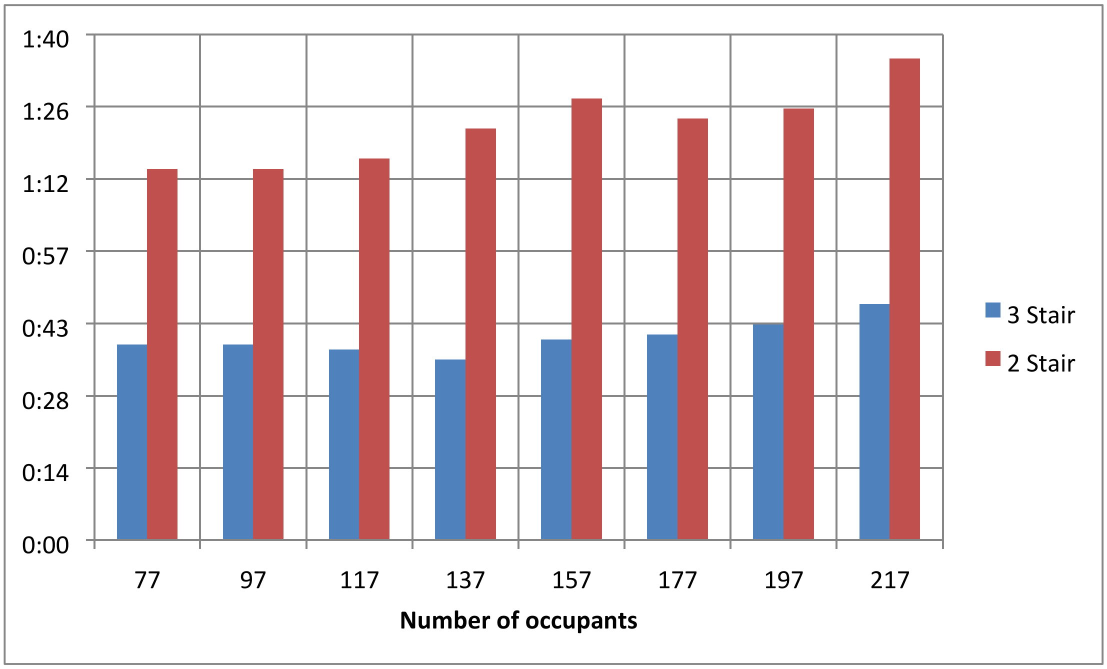
Last escape
430

Average escape time
157.24193548387098

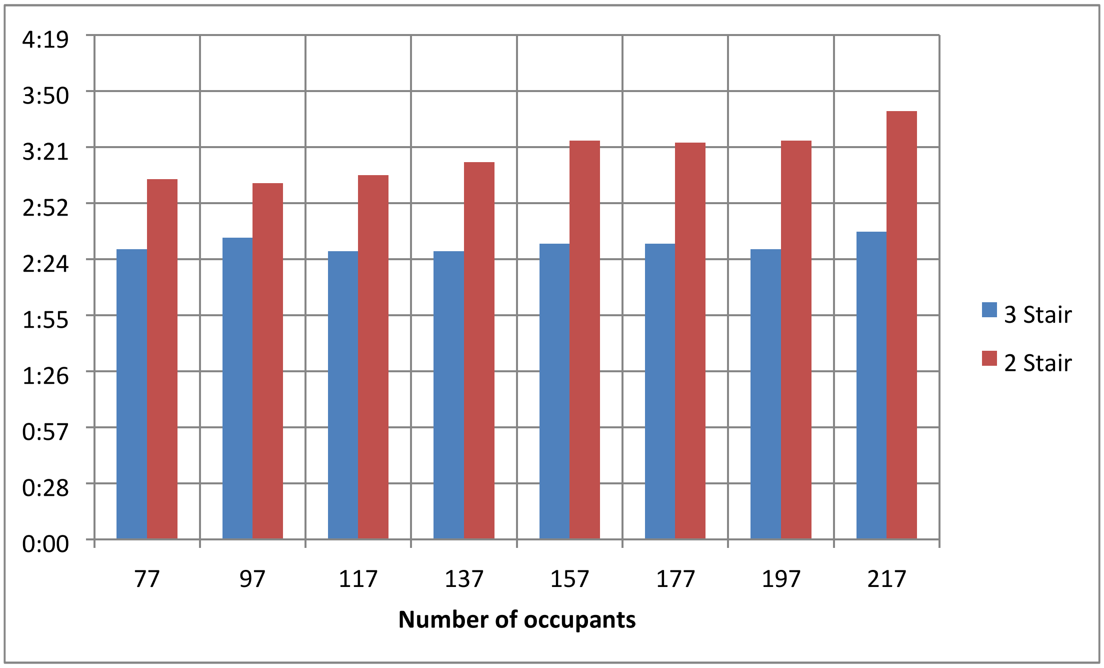
Max Congestion
16

Average movement time
49.79953917050691

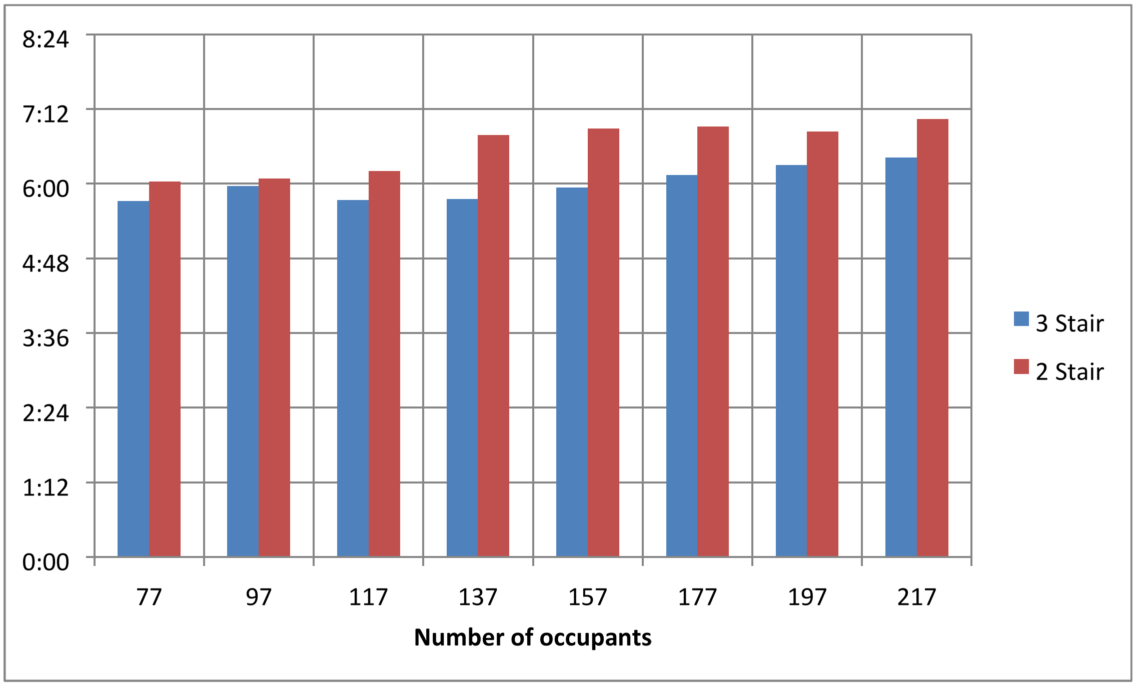
Figure 4-17: Outcomes of one simulation run of the experiment during evacuation



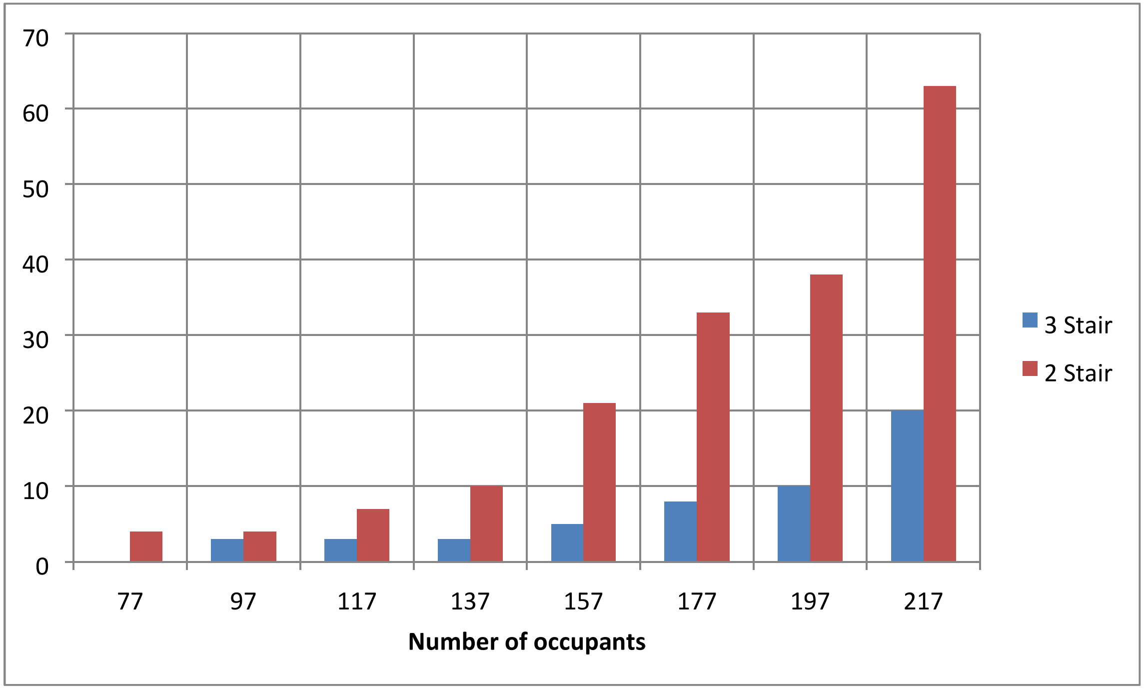
(a) Average movement time of each occupant for two staircase scenarios



(b) Average total evacuation time of each occupant for two staircase scenarios



(c) Average total evacuation time of each simulation run for two staircase scenarios



(d) Number of occupants in congestion of each simulation run for two staircase scenarios

Figure 4-18: Simulation results for two staircase scenarios

From the comparisons, it is clear that the egress performance of the scenario using three staircases is superior to the original scenario using two staircases, especially the average movement time per person. When the number of evacuees is 77, the average movement time per person decreases from 1:14 minutes to 0:39 minutes; when the number of evacuees is 217, the average movement time per person decreases from 1:36 minutes to 0:47 minutes, almost 1/3 of the original time. The average total evacuation time per person and per simulation run also decrease compared with the original scenario. For example, when the number of evacuees is 217, the average total evacuation time per person decreases from 3:40 minutes to 2:38 minutes. the average total evacuation time per simulation run decreases from 7:02 minutes to 6:25 minutes. Also, the congestion situation is greatly improved by increasing the number of staircases used from two to three. When occupants have more staircases to choose from, the number of occupants in congestion situation remains less than 10 when the evacuation population is less than 200. The number of people in congestion situation when the evacuees reach 217 is 20, much less than 63 in the original situation.

CHAPTER 5 CONCLUSIONS

As the need for senior apartments has been steadily increasing in recent years, research on egress process regarding fire safety has begun to receive increasing attention.

The previous chapters provide a literature review of egress design within a senior residential apartment environment and outline the MABS development and simulation of occupants' movements considering falls in multi-storey apartment buildings, as well as a MABS model for modelling the assisted egress methods. This research proposes an innovative assessment of factors that influence the egress process that aims to reduce the risk of falling for older adults (55 years and older). The assessment is developed by means of analyzing experiments on elderly fall behaviours. The main contributions of this thesis, the conclusions of the experiments, and the future work of the research are explained in the following sections.

5.1 Contributions

5.1.1 Apartment Egress Route Simplification and Application

In reality, the graphical model of a building can be as complex as engineering drawings or as simple as a brief sketch. Naturally, the level of details of the environment needs to be described in concert with the objective of the simulation. If the simulation is aiming to observe the detailed behaviour of agents when encountering graphical elements, a high level of detail about rooms, walls, corridors, obstacles, etc., is required. However, in situations where details of wayfinding behaviour 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. With the operation interface provided, this general platform can be applied to different building plans through adjusting the relevant parameters such as number of staircases, number of floors, length of corridors, length of staircases, average space between each apartment door, etc.

5.1.2 Occupant Evacuation Model Test and Application

As mentioned in previous chapters, this egress model is a probabilistic pedestrian dynamics model based on Markov chain and Monte Carlo methods. To simulate the wayfinding pattern of individual travel behaviour, an individual decision-making algorithm is applied to describe the process. By considering each individual as an "agent", a bottom-up occupant evacuation system is developed, which allows complex and unpredictable results to emerge after thousands of iterations.

The proposed system will enable the egress route designer to assess the proposed evacuation time according to the number of occupants and their desired delay time, and develop a way to reduce the risk of potential hazards during the egress process. Additionally, the developed simulation model can be used as a design tool to improve the fire safety design through applying alternative egress methods. However, it should be noted that the simulation model is a simplified model of reality such that the total evacuation time may exceed the simulated results. By using this MABS model, the effects of delay time, evacuee number, and fall accident were evaluated, as well as egress width and number of egress staircases.

One important advantage of the model is the flexible interface that allows users to change multiple parameters of the scenario, including elderly attributes, which therefore can be easily modified to simulate different senior apartment buildings with no need for coding. Another advantage is the simple but effective pedestrian dynamics model that is able to combine the randomness and purposiveness of pedestrian moving behaviour. Purposiveness of the model guarantees that every individual travels to the exit, randomness of the model allows the process during the evacuation to differ from one simulation run to another.

5.2 Conclusions

According to the presented case studies, some conclusions are made which may help improve evacuation plans. The variables such as delay time, number of evacuees, fall accidents, egress width, and number of staircases, are proven to have significant influences on the egress process, and thus have an important impact on egress safety.

Delay Time

The long delay time is suggested to have a significant influence on total evacuation time per person and per simulation run. It is recommended to identify any occupants that require a long period of time to respond to the hazard signal prior to starting to evacuate. Measures such as training and safe guard should be taken if any of the occupants are identified to be within the late delay group (LDG) in order to control the number of occupants with a long delay time. Record of the delay time required by each evacuee can be either acknowledged from the drill data, or collected from questionnaires.

Number of Evacuees

It is known that not all occupants participate in evacuation drills. In real emergency evacuations, the number of occupants that need to evacuate a building to reach a safe place varies from case to case. In the presented case study, it is proven that a larger number of evacuees will lead to longer total evacuation times, as well as more severe congestion situations. Methods to improve severe congestion situations are needed when the number of evacuees is large.

Fall Accidents

The elderly are at a higher risk of experiencing fall accidents in day-to-day life. From the case study, it can be observed that falls during the evacuation process have a significant influence on the congestion situation during evacuation, and of course, will lead to high potential of injury for the elderly people who have fallen down.

Egress Width

From the results presented in the case study, it is proven that increasing the width of the staircase can effectively improve the egress performance of the evacuation process when the number of evacuees exceeds half of the population living in the building. Through increasing the width of the staircase, more people are allowed to travel in the staircase rather than possibly experiencing delays if the staircase is crowded. By increasing the width of the staircase, the number of people in congestion situation is significantly decreased, and the total evacuation time per simulation when the number of evacuees is large is significantly shortened.

Number of Staircases

By increasing the number of staircases in use, the egress performance of the evacuation process is improved regardless of the number of evacuees. When one additional staircase can be chosen by the evacuees, some are then able to travel a shorter distance along the egress route, thereby reducing the evacuation time per person. Also, with three staircases in use instead of two, there are less of evacuees in each of the staircases, thus the congestion situation is also improved.

The MABS model now under development can possibly be applied to work as a supplement to evacuation drills to obtain more detailed information to help manage the building, and also to evaluate egress plan performance for a multi-floor building in order to determine the maximum number of occupants as well as the staircase design such as staircase width and number of staircases.

1. Updating, maintenance, and testing.

   An evacuation plan requires continual updating, maintenance, and testing. However, in reality, this is seldom carried out. One reason is that the cost to run evacuation drills is high, and is thereby unrealistic to run drills several times. The proposed model can work as a supplement to the drills. Through running the models multiple times, more detailed drill reports can be observed and suggested improvement methods can be tested in the model, resulting in a more cost-effective approach than drills.

2. Absence

   The drills can be imprecise since occupants are often not in the building due to work hours, meetings, meals, breaks, illness, vacation, or other activities. The population can be revised with this MABS model.

3. Variability in events

   It is important to identify potential emergencies and their duration; however, the dangerous situations seldom occur in drills, and limited information is provided for managers to evaluate the potential emergencies.

5.3 Limitations

One of the disadvantages of this model is the limited intelligence level of the simulated evacuees. High intelligence-level behaviours, such as communication, learning, and group organization, are not considered in this model. However, in scenarios where pedestrian density is low, these behaviours can be ignored as they appear to be the secondary factors that affect total evacuation duration.

Another limitation of the model is the pre-assumptions made during the experiments. As mentioned earlier, several design decisions and assumptions were made during the development of the framework, some of which affected the outcome. Also, several features and goals that were set early on in the framework development that were not substantially realized.

5.4 Future Works

This section covers some lessons learned, and offers recommendations for improving the overall framework. This framework is a project with a large scope, which contains several pre-assumptions and simplifications that were desired for the purpose of achieving the end result. As a result, little individual testing has been conducted. Thus far, most of the efforts are made to develop the fundamental framework; however, much of its implementation has yet to be completed.

5.4.1 Environment and Platform

The 3D environment building was developed and built after it was analyzed manually. When several buildings with complex floor plans need to be tested, the time and work required to develop the building models can be significant. Although the steps to build the building models are similar, which will save some time, the software could be developed to automatically read and identify the information needed to build the environment model from other documents, e.g., the CAD models. An MABS egress model able to receive inputs from other software, as a recommendation, would be beneficial to compile, run, and test multiple buildings as early in the development process and as frequently as possible.

5.4.2 Elderly Behaviours

The model in the research considers elderly behaviours primarily in two aspects: lower speed and fall potential. To achieve the results (total evacuation time), thes aspects are designed as determinstic inputs. Elderly people modelled in this research are simulated with a given speed, and the senario being tested is simulated with a given fall potential depending on the occupant’s group.

References

1. Abbott JL, Geddie MW. 2000. Event and venue management: Minimizing liability through effective crowd management techniques. Event Management. 6(4):259-70.

2. Adams A, Galea ER. 2011. An experimental evaluation of movement devices used to assist people with reduced mobility in high-rise building evacuations. In: Pedestrian and evacuation dynamics. Springer. 129 p.

3. Ali W. 2006. Developping 2D and 3D multiagent geosimulation, a method and its application: The case of shopping behavior geosimulation in square one mall (toronto). .

4. Askham J, Glucksman E, Owens P, Swift C, Tinker A, Yu G. 1990. Home and leisure accident research: A review of research on falls among elderly people. King's College; Age Concern Institute Gerontology.

5. Beard A. 1992. Limitations of computer models. Fire Safety Journal. 18(4):375-91.

6. Boyce MW, Al-Awar Smither J, Fisher DO, Hancock PA. 2017. Design of instructions for evacuating disabled adults. Applied Ergonomics. 58(Supplement C):48-58.

7. Buick JM. 1997. Lattice boltzmann methods in interfacial wave modelling. University of Edinburgh.

8. Cassol VJ, Testa ES, Jung CR, Usman M, Faloutsos P, Berseth G, Kapadia M, Badler NI, Musse SR. 2017. Evaluating and optimizing evacuation plans for crowd egress. IEEE Comput Graphics Appl. 37(4):60-71.

9. City of Edmonton. 2009. Residential infill guidelines: A manual of planning and design guidelines for residential infill in mature neighbourhoods. . 5 p. .

10. Conley D, Schultz AA, Selvin R. 1999. The challenge of predicting patients at risk for falling: Development of the conley scale. Medsurg Nursing. 8(6):348.

11. Cornes FE, Frank GA, Dorso CO. 2017. High pressures in room evacuation processes and a first approach to the dynamics around unconscious pedestrians. Physica A: Statistical Mechanics and its Applications. 484(Supplement C):28298.

12. Cote JN, Mathieu PA, Levin MF. 2002. Movement reorganization to compensate for fatigue during sawing. .
13. Cristiani E, Piccoli B, Tosin A. 2014. Multiscale modeling of pedestrian dynamics. Springer.

14. Day L, Fildes B, Gordon I, Fitzharris M, Flamer H, Lord S. 2002. Randomised factorial trial of falls prevention among older people living in their own homes. Bmj. 325(7356):128.

15. Duives DC, Daamen W, Hoogendoorn SP. 2013. State-of-the-art crowd motion simulation models. Transportation Research Part C: Emerging Technologies. 37:193-209.

16. Ferber J. 1999. Multi-agent systems: An introduction to distributed artificial intelligence. Addison-Wesley Reading.

17. Fujiyama T, Tyler N. 2004. An explicit study on walking speeds of pedestrians on stairs. 10th international conference on mobility and transport for elderly and disabled people; May 23–26, 2004; .

18. Fuller GF. 2000. Falls in the elderly. American Family Physician. 61(7):2159.

19. Gaines BR. 1979. General systems research: Quo vadis. General Systems Yearbook. 24(1):9.

20. Han LD, Yuan F, Chin S, Hwang H. 2006. Global optimization of emergency evacuation assignments. Interfaces. 36(6):502-13.

21. Hedman, Glenn. Stair descent devices: An overview of current devices and proposed framework for standards and testing. Fourth international symposium on human behaviour in fire, interscience communications.; 2009; .

22. Henderson LF. 1971. The statistics of crowd fluids. Nature. 229:381-3.

23. Hendrich AL, Bender PS, Nyhuis A. 2003. Validation of the hendrich II fall risk model: A large concurrent case/control study of hospitalized patients. Applied Nursing Research. 16(1):9-21.

24. IBC I. 2016. International building code. International Code Council, Inc.(Formerly BOCA, ICBO and SBCCI). 4051.

25. ICC [International Code Council]. 2016. Building department administration. .

26. J.J. Fruin. 1987. Pedestrian planning and design. Elevator World. :211.

27. Jennings NR, Sycara K, Wooldridge M. 1998. A roadmap of agent research and development. Auton Agents Multi-Agent Syst. 1(1):7-38.

28. Kirchner A, Nishinari K, Schadschneider A. 2003. Friction effects and clogging in a cellular automaton model for pedestrian dynamics. Physical Review E. 67(5):056122.

29. Klote JH. 1993. A method for calculation of elevator evacuation time. Journal of Fire Protection Engineering. 5(3):83-95.

30. Kuligowski E. 2003. Elevators for occupant evacuation and fire department access. Cib Report. :193-200.

31. Kuligowski E, Peacock R, Wiess E, Hoskins B. 2013. Stair evacuation of older adults and people with mobility impairments. Fire Saf J. 62:230-7.

32. Kuligowski ED, Peacock RD, Hoskins BL. 2005. A review of building evacuation models. US Department of Commerce, National Institute of Standards and Technology Gaithersburg, MD.

33. Larochelle B. 2009. Multi-agent geo-simulation of crowds and control forces in conflict situations. Universit Laval, Qubec. .

34. Li N, Becerik-Gerber B, Krishnamachari B, Soibelman L. 2014. A BIM centered indoor localization algorithm to support building fire emergency response operations. Automation in Construction. 42:78-89.

35. Lok N, Lok S, Canbaz M. 2017. The effect of physical activity on depressive symptoms and quality of life among elderly nursing home residents: Randomized controlled trial. Arch Gerontol Geriatr. 70:92-8.

36. Lord J, Meacham B, Moore A, Fahy R, Proulx G. 2005. Guide for evaluating the predictive capabilities of computer egress models. Nist Gcr. :6.

37. Manicaros MA, Stimson RJ. 1999. Living in a retirement village attitudes, choices and outcomes. Univ. of Qld.

38. Milazzo J, Rouphail N, Hummer J, Allen D. 1998. Effect of pedestrians on capacity of signalized intersections. Transportation Research Record: Journal of the Transportation Research Board. 1646:37-46.

39. MITSUBISHI ELECTRICAL CORPORATION. 2016. Passenger elevators machine-room-less system. .

40. Nakano M, Hagiwara I. 2000. Experimental study on starting time of evacuation in sleeping condition. Fire Safety Science. 4:263-74.

41. National Fire Protection Association. 2011. NFPA 101 life safety code. National Fire Protection Association.
42. Nelson HE. 1995. Emergency movement. SFPE Handbook of Fire Protection Engineering. :3.295.

43. NFPA [National Fire Protection Association]. 2017. Standard for fixed guideway transit and passenger rail systems. .

44. Parker C, Barnes S, McKee K, Morgan K, Torrington J, Tregenza P. 2004. Quality of life and building design in residential and nursing homes for older people. Ageing & Society. 24(6):941-62.

45. Pelechano N, Allbeck JM, Badler NI. 2008. Virtual crowds: Methods, simulation, and control. Synthesis Lectures on Computer Graphics and Animation. 3(1):1176.

46. Prot EY, Clements B. 2017. Preparedness in long-term care: A novel approach to address gaps in evacuation tracking. Disaster Medicine and Public Health Preparedness. 11(1):28-30.

47. Proulx G, Latour JC, MacLaurin JW. 1994. Housing evacuation of mixed abilities occupants. National Research Council Canada, Institute for Research in Construction, National Fire Laboratory.

48. Proulx G. 1995. Evacuation time and movement in apartment buildings. Fire Safety Journal. 24(3):229-46.

49. Proulx G, Pineau J. 1996. Review of evacuation strategies for occupants with disabilities. Internal Report, Institute for Research in Construction, National Research Council Canada. 712:19.

50. Proulx G. 2001. Occupant behaviour and evacuation. Proceedings of the 9th international fire protection symposium. 219 p.

51. Purser D. 2003. ASET and RSET: Addressing some issues in relation to occupant behavior and tenability. Fire Safety Science. :91-102.

52. Puts M, Hsu T, Szumacher E, Sattar S, Toubasi S, Rosario C, Brain E, Duggleby W, Mariano C, Mohile S. 2017. Meeting the needs of the aging population: The canadian network on aging and cancer—report on the first network meeting, 27 april 2016. Current Oncology. 24(2):e163.

53. Railsback SF, Grimm V. 2011. Agent-based and individual-based modeling : A practical introduction. Princeton University Press.

54. Russell S, Norvig P, Intelligence A. 1995. A modern approach. Artificial Intelligence.Prentice-Hall, Egnlewood Cliffs. 25:27.
55. Sharifi F, Fakhrzadeh H, Memari A, Najafi B, Nazari N, Khoee MA, Arzaghi SM, Bakhtiari F, Ghasemi S, Salavatian SN, et al. 2015. Predicting risk of the fall among aged adult residents of a nursing home. Archives of Gerontology and Geriatrics. 61(2):124-30.

56. Shkuratova N, Morris ME, Huxham F. 2004. Effects of age on balance control during walking. Arch Phys Med Rehabil. 85(4):582-8.

57. Sliwinski M, Buschke H, Kuslansky G, Senior G, Scarisbrick D. 1994. Proportional slowing and addition speed in old and young adults. Psychol Aging. 9(1):72-80.

58. Society of Fire Protection Engineers, (SFPE). 2003. Emergency egress from buildings part 1: History and current regulations for egress systems design. In: 7th

international conference on performance-based codes and fire safety design methods. Society of Fire Protection Engineers (SFPE). 2 p.

59. Sulistio A, Yeo CS, Buyya R. 2004. A taxonomy of computer-based simulations and its mapping to parallel and distributed systems simulation tools. Software: Practice and Experience. 34(7):653-73.

60. Tavares RM, Galea ER. 2009. Evacuation modelling analysis within the operational research context: A combined approach for improving enclosure designs. Build Environ. 44(5):1005-16.

61. Tavares RM. 2010. Design for horizontal escape in buildings: The use of the relative distance between exits as an alternative approach to the maximum travel distance. Saf Sci. 48(10):1242-7.

62. Toffoli T, Margolus N. 1988. Cellular automata machines. 3. pr. ed. Cambridge, Mass. u.a: MIT Pr.

63. Tubbs JS. 2007. Egress design solutions : A guide to evacuation and crowd management planning. United States: .

64. Weiss G. 1999. Multiagent systems: A modern approach to distributed artificial intelligence. MIT press.

65. Wilensky U, Rand W. 2015. An introduction to agent-based modeling. Cambridge, Massachusetts: The MIT Press.

66. Wood PG. 1980. A survey of behaviour in fires. Fires and Human Behavior. :83-95.

67. Wooldridge M, Jennings NR. 1995. Intelligent agents: Theory and practice. The Knowledge Engineering Review. 10(2):115-52.
68. Zeng Y, Song W, Huo F, Wei X. 2017. Effect of weibull distributed premovement time on evacuation. In: Fire science and technology 2015. Springer. 133 p.

69. Zhou S, Chen D, Cai W, Luo L, Low MYH, Tian F, Tay VS, Ong DWS, Hamilton BD. 2010. Crowd modeling and simulation technologies. ACM Transactions on Modeling and Computer Simulation (TOMACS). 20(4):20.