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An agent-based simulation framework for analysing fall risk among older adults in the evacuation procedures

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ABSTRACT

Poor performance during an emergency evacuation from a residential building can lead to serious injuries (even death) and loss of property. As a result, it is paramount that evacuation plans are designed to account for both the physical (or geometrical) limitations of the space, such as the stairway designs, and, more importantly, the physical condition of those living in the building. Generally, when egress planning is considered or modelled during the design phase of a building, it is assumed that its residents are sampled from an average population with an average mobility condition. As a result, older adults tend to be ignored or regarded as part of the average population in the evacuation simulations. Due to their vulnerability, it is common to see older adults suffer from falls, which may result in serious trauma, such as fractures, from which older adults often do not fully recover. Moreover, many of the adverse effects that can occur during an evacuation, including the risk of falling, is compounded when a larger number of individuals try to exit a building within a short time interval given the geometric constraints of the built environment and the (limited) physical capacity of the residents. To analyse the risk of falling among older adults in evacuation procedures, this paper proposes an agent-based simulation framework, which consists of three primary components: agent-based modelling, fall risk index establishment, and fall risk assessment for older adults in an evacuation scenario. A case study of an apartment-style seniors' residence in Edmonton, Canada is provided to demonstrate the applicability of the framework in evaluating fall risk among older adults. Furthermore, a sensitivity analysis is conducted to better understand how the number of evacuees and different designs of the built environment influence both the fall risk of individuals and the fall risk attributable to the built environment.

1. Introduction

Ensuring the physical safety of building occupants during emergency scenarios (e.g., fire, toxic gas release, or earthquakes) is an important issue to be taken into consideration in building design and building regulations, since the evacuation of building occupants introduces risks associated with falling, trauma, and potential loss of life. Generally, two primary constraints exist in the course of an evacuation, namely, a limited escape time window and the built environment (Zheng et al., 2009). In order to guarantee the safety of evacuees, the required safe escape time (RSET) should not exceed the available safe escape time (ASET) that is determined based on the structural design of the building and the properties of the construction materials used (Du et al., 2018; Purser, 2003). The RSET for each evacuee tends to include three parts: detection time (time for activating detection systems), delay time (time before starting to move), and movement time (the time for travelling to a safe location or to an exit) (Tubbs and Meacham, 2007). Clogging is a common phenomenon in evacuation procedures, especially in the case of an emergency. As evacuees rush, simultaneously, to escape from danger, pushing or trampling activities may occur, which may result in compression forces increasing to harmful levels. Considering temporal and physical constraints, evacuation drills and virtual field tests have been adopted to investigate human behaviour, evacuation time, and factors influencing wayfinding performance in evacuation procedures (Cheng et al., 2009; Lin et al., 2019; Proulx, 1995). However, the human subjects in both of the approaches may be restricted to a specific group since it is difficult to arrange participation of subjects having a diversity of features (e.g., age, gender, and physical condition) in such a prolonged experiment. Evacuation tests also tend to be time-consuming because they require preparation, execution, and

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analysis of results. Furthermore, evacuation drills and tests tend to be distant from real case emergencies where the presence of danger may trigger extreme and irrational individual behaviours. As a result, it is difficult to execute a test of the evacuation procedures immediately given that some parameters related to the evacuees or a part of the building design may not be correctly adjusted. As an alternative technique, simulation modelling has been applied to overcome the shortcomings of the above methods in evacuation analysis (Shen, 2005; Tan et al., 2015; Zheng et al., 2009). Furthermore, simulation can prove useful in the following scenarios: (a) to undertake an analysis where a full analytical (mathematical) formulation of the problem is practically impossible; (b) to gain better insight into the dynamics of behaviours; (c) to acquire knowledge in some situations where experiments expose the subjects to danger; or (d) to characterise interactions between human being and surroundings due to lack of data from the real world (Chen et al., 2018b; Shannon, 1976; Yang et al., 2005).

Although previous research studies are devoted to evacuation simulation for a specific building that is presented by means of a 2D or 3D model, most of these studies assume the subjects have an average physical capacity, while few studies conducted an analysis of a particular segment of the population, such as the elderly (Joo et al., 2013; Shen, 2005; Shi et al., 2009; Tan et al., 2015). In fact, population ageing is emerging as an unprecedented demographic challenge worldwide (Chen et al., 2019). The global population of people aged 60 years or over is predicted to rise to 2.1 billion by 2050, which is an increase of 1.3 times compared to the year 2015 and is predicted to account for 22% of the total population (United Nations, 2015). Due to changes in lifestyle, older adults are increasingly in favour of living in special residential apartments (e.g., age-restricted communities), where individuals of a similar age can more easily establish social interaction and thus enjoy a better quality of life and experience a higher level of overall life satisfaction (Chen et al., 2018a). As such, it is vital and meaningful to employ simulation modelling to evaluate evacuation procedures in this type of building due to the vulnerabilities of the older adult population, such as a slower gait speed and a greater potential for falling (Sharifi et al., 2015; Stevens, 2005). If satisfying the condition that the RSET should not exceed the ASET, the built environment becomes a major issue of concern in evacuation simulation. In terms of older adults, falling is the leading cause of injury-related visits to the emergency department at hospitals and the primary aetiology of accidental deaths (Fuller, 2000). Furthermore, it is common for older adults to have a fall and statistics show the risk of falling increases dramatically with age (Sharifi et al., 2015). For instance, a survey conducted in Newcastle, England demonstrated that fall potential among individuals aged 65–69 years was 22.4% and this percentage exceeded 35% for people aged 80 years or over. In the light of this, it is worth investigating fall risk of elderly evacuees and the dynamics of evacuation procedures. Taking a multi-disciplinary approach that integrates architecture, simulation modelling technique, and gerontology, the objectives of this paper are (a) to address the drawbacks of previous studies that overlook the elderly as specific human subjects in evacuation simulation analysis and fail to quantify their fall risk in a dynamic process, (b) to mimic the fall risk of the elderly in evacuation procedures considering various scenarios, and (c) to analyse the fall risk in a senior apartment complex combining parameters describing the individuals and those pertaining to the built environment.

The structure of the remainder of this paper is as follows. First, a literature review regarding falls among older adults and evacuation simulation models is presented. Then, a framework for fall risk simulation for evacuation of the elderly is proposed integrating three primary components: (i) an agent-based model; (ii) a risk index; and finally (iii) an integration of the first two components. The methodology is applied to analyse the fall risk of senior residents for a specific case in the Edmonton, Canada. Finally, the conclusions and future directions are summarised based on the results of this research.

2. Literature review

2.1. Falls among older adults

Currently, the studies regarding falls among older adults primarily focus on three topics: (i) causes for falls; (ii) risk factors for falls; and (iii) prevention strategies (Rubenstein, 2006; Stevens, 2005). From the study of Jensen et al. (2003), falls among older adults can occur due to many distinct causes, where the most frequently mentioned one is accidental or environment-related, followed by the next most common cause, which is attributed to gait problems and weakness. Usually, it is difficult to identify a single specific cause for a fall, since falls tend to be multifactorial in origin (Rubenstein, 2006). As such, many scholars prefer to investigate risk factors that contribute to having an increased likelihood of falling rather than simply classify the precipitating causes (Gillespie et al., 2003; Rubenstein, 2006). Furthermore, effective fall prevention strategies are formulated based entirely on risk factor identification and the corresponding risk points. The existing researches tend to divide these risk factors into two categories: (i) intrinsic risks related to individual health, and (ii) extrinsic risks related to environment (Fleming and Pendergast, 1993; Gillespie et al., 2003; Rubenstein, 2006; Stevens, 2005). Scott et al. (2001) identified and collected information from community-based fall prevention programs in Canada, and then categorised risk factors, which resulted in the following factors being the most frequent causes of fall-related injuries among older adults: (a) biological factors that pertain to the human body, natural ageing process, and health conditions; (b) behavioural factors related to human actions, emotions, or choices; (c) environmental factors that refer to an individual's surroundings; and (d) social and economic factors that include influences of and interactions between social conditions and the economic status of individuals at risk and the community's capacity to respond to the problem. In fact, the extent to which social and economic risk factors (e.g., low income, unemployment, and low education levels) contribute to falls is poorly understood, since these factors tend to have an indirect influence on risks of falling (Scott et al., 2001). Although the categories of risk factors are somewhat similar to those identified in previous studies, the specific factors used to describe each category vary due to differences in the research objectives.

Based on the identified risk factors, some assessment methods for fall risk have been developed for older adults, such as the Hendrich II fall risk model (Hendrich et al., 2003), the cumulative risk score (Dargent-Molina et al., 2002), the home assessment profile (HAP) (Chandler et al., 2001), an evidence-based assessment method (Afifi et al., 2014), and FROP-Com (i.e., falls risk for older adults in the community) (National Ageing Research Institute, 2010). These approaches for fall risk analysis tend to be applicable in the context of one or two categories of risk factors (e.g., biological, behavioural, or environmental factors), while a comprehensive evaluation approach that integrates all three categories of risk factors has yet to be developed. Furthermore, the environments in which fall risk among older adults is assessed are also diverse, such as in the community, rooms, or the staircase. The above assessment of fall risk is static based on information and data derived from individuals and the surroundings. In fact, the activities required of older adults (e.g., walking or evacuation in a building) are dynamic and continuous processes. Similarly, fall risk among older adults will change due to varying influencing factors from the start to the end of an activity. Based on this, the present study will propose an approach to quantify fall risk among older adults in the dynamic evacuation process by means of a comprehensive assessment index.

2.2. Agent-based models

Simulation, as a technique, is able to answer "what if" questions in order to achieve the goals of prediction, understanding, or exploration

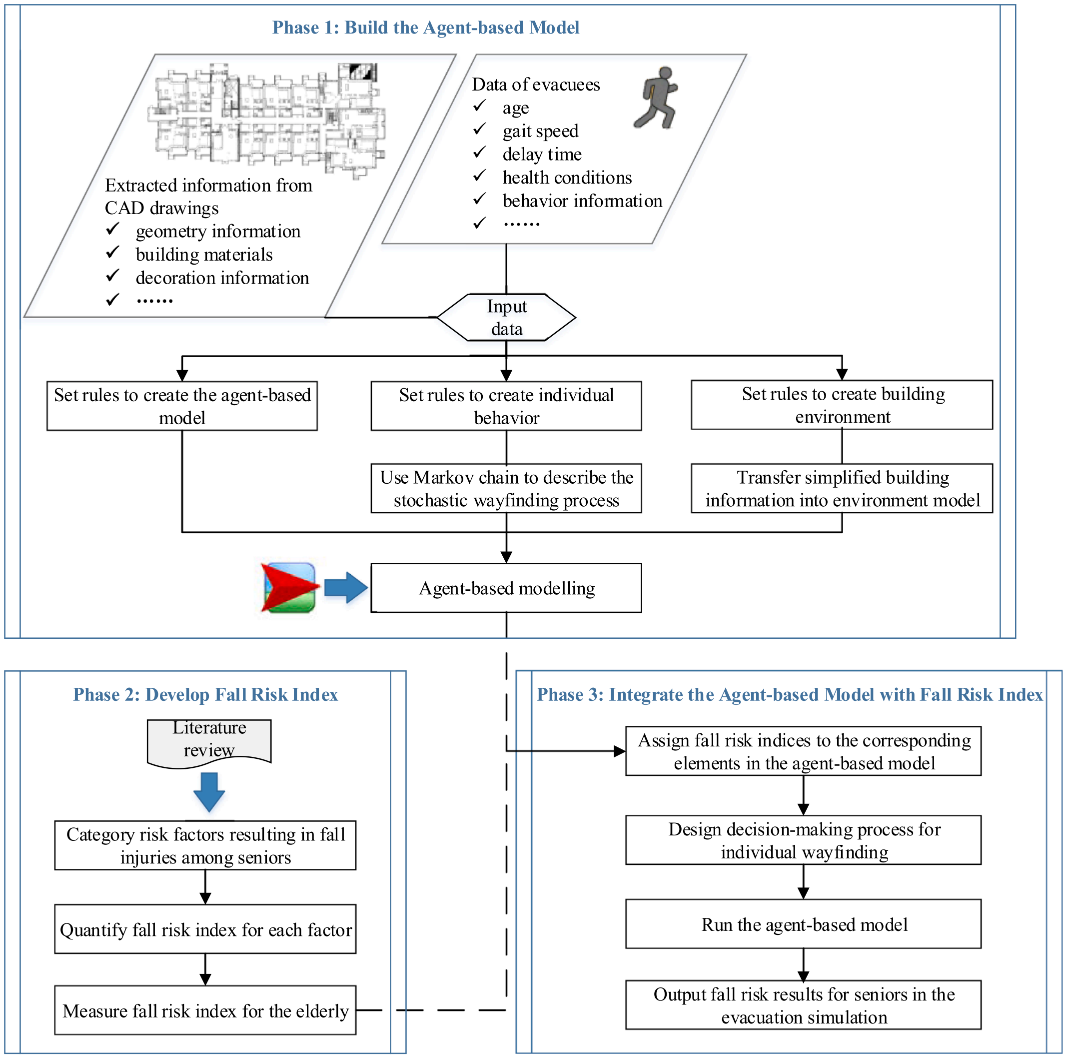


Fig. 1. A framework for fall risk simulation in the evacuation of older adults.

(Grüne-Yanoff and Weirich, 2010). In the context of research using simulation techniques, evacuation simulation models can be referred to as either macroscopic or microscopic. Macroscopic models regard a crowd of evacuees as a whole, while microscopic models treat evacuees in a crowd as individuals each subject to different factors based on their unique behaviour and decision-making as well as on the dynamics of their interactions with others (Pelechano and Malkawi, 2008; Zheng et al., 2009). Cellular automata models, social force models, and agent-based models, it should be noted, are the most widely used approaches in evacuation simulation. The first of these models divides the whole space into uniform grids and each grid-cell can be occupied by an evacuee. The rule that governs how the individual selects the next cell to move to is pre-designed in the simulation model. As such, following a set of local rules, the variables at each cell can be updated simultaneously based on the values of the variables in their neighbourhood at the previous time step (Wolfram, 1983). This approach developed for evacuation simulation mainly deals with the interaction between evacuees and neighbouring environments or the interaction among evacuees (Zheng et al., 2009). In terms of social force models, one classic model proposed by Helbing and Molnár (1995) is used to determine evacuee motion that is influenced by multiple factors (e.g., velocity, position, and the location of border), while Helbing et al. (2000) developed another model to mimic a panic situation where human crowd behaviour is described by a mixture of socio-psychological and physical forces. A common feature among the above two types of microscopic models is that evacuees are ideally treated as homogenous individuals, which goes against the reality in some situations. For instance, these evacuees represent a range of ages and gait speeds. To overcome this issue, agent-based models that build bottom-up social structures simulate complex interactions among evacuees in various situations (normal or emergency), taking into account that each evacuee will have unique behaviours. This makes the use of these models a powerful and reliable simulation approach to modelling heterogenous humans (Bonabeau, 2002; Zheng et al., 2009).

Some recent studies have adopted agent-based models to inform evacuation planning for different emergency situations, such as urban outdoor evacuation during an earthquake (D'Orazio et al., 2014), labour evacuation on construction sites (Marzouk and Daour, 2018), and passenger evacuation in a metro station (Shi et al., 2012; Zarboutis and Marmaras, 2007). In terms of modelling building evacuation, Rendón Rozo et al. (2019) designed a pedestrian simulation tool to mimic the behaviour of students attending a university class, in consideration of factors such as speed, gender, and obstacles, and then compared the evacuation time in different building evacuation plans. Similar research studies have simulated the evacuation of children and staff (or occupants) from schools (universities) during an emergency, considering agent attributes such as average body radius, speed, pre-movement time, and safety awareness (Marzouk and Mohamed, 2019; Poulos et al., 2018; Tan et al., 2015). Shi et al. (2009) developed a simulation model to analyse the dynamic egress progress of occupants in an indoor stadium under fire expansion. Liu et al. (2016) integrated a probabilistic description of building damage with a simulation model to investigate human evacuation behaviour and analyse the influences of a dynamically deteriorating environment on the egress process. These efforts, employing agent-based models to explore building evacuation, have focused on analysing evacuation performance (or time) considering different agent attributes and different types of emergency situations. However, in these studies an average physical capacity of the agents was assumed, while few research studies on evacuation procedures have been conducted that specifically investigate the elderly as a particular population of individuals with limited and varying physical capacities. Furthermore, besides evacuation time, fall risk of elderly evacuees is a key point that needs to be taken into account given its direct influence on the time metric. Therefore, after comparing the features of the evacuation simulation models and considering the research objectives of this study, the use of agent-based models is selected as the primary approach in mimicking the evacuation procedure of older adults for the purpose of analysing fall risk from an individual perspective.

3. Methodology

The proposed framework for fall risk analysis of older adults in an indoor emergency evacuation consists of three phases: (a) build an agent-based model to simulate evacuation procedures for older adults; (b) develop a fall risk index for older adults considering primary risk factors; and (c) integrate the agent-based model with the fall risk index to conduct an analysis of fall risk in the evacuation procedures of older adults. The overview of the framework is depicted in Fig. 1. The following subsections will give a more detailed introduction of each respective phase.

3.1. Build the agent-based model

To simulate the fall risk of older adults during the evacuation procedure in an apartment building, an agent-based model is built to capture the heterogeneity of agents (or evacuees) with regard to attributes such as age, velocity, and delay time in a virtual built environment with doors, hallways, stairwells, etc. Basically, the level of detail of the built environment should be aligned with the simulation objectives. In this study, a lower level of detail of the environment is suitable since fall risk analysis during the evacuation is the key task and a simpler environment can largely reduce the complexity of the model. As such, the graphic model of the building is simplified to fundamental egress components. Furthermore, the evacuation procedure of each evacuee in this study is simplified as follows: (a) appear at apartment doors after a certain delay at home (ready to evacuate); (b) make a decision on the selection of the stairwell; (c) travel along the hallway; (d) travel down the stairs; and (e) reach the exit. To achieve the above goal, NetLogo, which is visualisation software for developing the agent-based model (Wilensky, 1999), is selected to generate the environment conditions in its platform for testing simulation. A more detailed introduction to NetLogo can be found in Wilensky and Rand (2015).

3.1.1. Rules to create the agent-based model

Based on the CAD drawings of the building plans, the agent-based model can be built according to the following basic rules:

(a) The modelling method is derived from a partial behavioural model (Kuligowski and Peacock, 2005), which can simulate occupant movement and reflect specific features of human behaviour, such as delay time, walking speed, wayfinding, randomness of start points, and group.
(b) The built environment is simulated by means of fine network structure, which allows occupants to populate a discretised space with a lattice connecting discrete positions (small grid-cells).
(c) The model is designed to track occupants individually throughout the simulation and evacuees are represented by turtles with presetting attributes in NetLogo. Meanwhile, turtles move one step per clock tick, further estimating the entire evacuation time based on the total number of ticks (Wilensky and Rand, 2015).
(d) Evacuees in the simulation model have their own individual perspective in order to choose paths based on information available related to location and surrounding occupant density.
(e) Only low or medium occupant density is considered in the built model, thus ignoring push behaviour in the simulation.

3.1.2. Rules to create individual behaviour

To mimic individual behaviour in the agent-based model, some rules regarding occupant movement are presented as follows:

(a) Empty cell: Occupants will not move into an adjacent grid-cell unless it is empty.
(b) Occupant density: Considering the shoulder width of the 97.5th percentile for adult males is 0.51 m (NFPA, 2017), each occupant in this model is represented as a circle with a 0.25 m radius.
(c) Acquiring knowledge: Occupants in the simulation can acquire knowledge based on individual fields of vision from their own perspective.
(d) Probabilistic algorithm: To simulate individual travel behaviour, an individual decision-making algorithm is applied to account for the wayfinding actions performed during the evacuation procedure.

In a familiar environment, individuals in routine situations tend to move toward a given destination following a relatively fixed, and usually the shortest available, route. This rule will be violated, though, when people are in an emergency situation such as crowded evacuation in a building. In such cases, an individual's decision making for the selection of each step is influenced by multiple factors, such as individual priorities and empty patches surrounding the evacuee. As such, the escape route of an evacuee changes based on nearby crowd density and built environment-related factors.

Specifically, each occupant is equipped with four independent choices with the corresponding probabilities: go straight ($P_{Straight}$), go parallel ($P_{Parallel}$), go diagonal ($P_{Diagonal}$), and stop (P_{Stop}). An illustration for the three choices is shown in the legend in Fig. 5. Cristiani et al. (2014) found that pedestrians tend to continue in the same direction and move forward to the targeted destination if they are not forced to change directions; Meanwhile, there is no significant difference between the choice of moving parallel and that of moving diagonal when they need to change directions. For example, when pedestrian is going straight along the path, the priority level of four choices is: $P_{Straight} > P_{Diagonal} = P_{Parallel} \gg P_{Stop}$. Moving from one cell to the next can be viewed as transitioning from a given state to another the choice which is only dependent on the present location (i.e., state). Considering the above points, Markov chain is chosen to describe the stochastic wayfinding process in this model. In our previous studies (Du et al., 2018), it should be noted, the effectiveness of integrating simulation with Markov chain in modelling the evacuation analysis was verified. In this context, each occupant has step-count variables S_1, S_2, S_3. ..with the Markov property, the probability of moving to the next state (step count) depends only on the present state and not on the previous states.

$$\Pr(S_{n+1} = s | S_1 = s_1, S_2 = s_2, ..., S_n = s_n) = \Pr(S_{n+1} = s | S_n = s_n) \quad (1)$$

3.1.3. Rules to create the built environment

The detailed rules to build the simplified building plan derived from CAD drawings are as follows: (a) set the size of grid-cells (also called patches) as 0.5 m × 0.5 m each; (b) collect the hallways of each floor using the vertical plan of stairwells and build them in NetLogo using patches by rounding the length and width to 0.5 m accuracy; and (c) display each of the apartment doors connected to the hallway as two patches and specify it as the start point of the evacuation.

3.2. Develop fall risk index

The first step towards developing the fall risk index for older adults in an emergency evacuation is to identify risk factors that increase the likelihood of a fall. Based on the relevant literature reviewed in Section 2, this study focuses on primary risk factors derived from the biological/health, behavioural, and environmental categories in the context of evacuation procedures. Accordingly, the fall risk index for older adults is developed to quantify each category of risk factors.

3.2.1. Health

Hendrich et al. (2003) assessed more than 600 risk factors related to falling and investigated the data from 1135 patients in order to develop the Hendrich II fall risk model involving eight primary risk factors with a corresponding number of points. For instance, confusion/disorientation is assigned 4 risk points, while depression is assigned 2 risk points; in this system, the highest risk score possible for an individual if we add up the assigned values of the eight risk factors is 16. This model will output the total score summed from various health risk factors (0 to 16) where, the higher the value is, the greater the risk of falling will be. Furthermore, supporting evidence has been provided for choosing the Hendrich II fall risk model to identify patients aged 65 years old or over in terms of their risk of falling (Dessy et al., 2017; Ivziku et al., 2011). As a result, this model is also selected for use in the present study to assess the fall risk index in terms of the health of older adults. Considering a comparison among different fall risk indices, the value of each index should be normalised. To be consistent with other fall indices that consider “0” as high risk and “1” as low risk, the output score from Henrich II fall risk fall needs to be transformed into a similar scale. To achieve the goal of assessing fall risk, the normalisation method shown in Eq. (2) (i.e., linear conversion) is used to calculate the fall risk index for health in this study based on the total score derived from the Hendrich II fall risk model. In other words, when risk points from the Hendrich II fall risk model are equal to 0(16), the fall risk index for health in the present study is equal to 1(0).

$$I_{Health} = -\frac{1}{16}TP + 1 \tag{2}$$

where $I_{Health}(0 \leqslant I_{Health} \leqslant 1)$ is the fall risk index for health; $TP(0 \leqslant TP \leqslant 16)$ is the total number of points obtained according to the Hendrich II fall risk model. If $I_{Health} = 1$, it indicates the individual is in sufficiently good health condition such that no fall would be caused, and$I_{Health} = 0$ indicates the maximum risk for a fall being triggered.

3.2.2. Behaviour

Evacuation is a dynamic process taking place during a limited time period; therefore, fall risk factors with respect to individual behaviour are influenced primarily by the gait speed of the evacuees themselves and the amount of congestion surrounding each evacuee. Both of these variables are dynamic and continuously changing in the course of an evacuation, since the number of evacuees surrounding a given evacuee varies in time and, in turn, influences the evacuee’s gait speed and choice of escape route. As such, the corresponding fall risk indices for behaviour are developed as described below.

- Gait speed

Gait speed is incorporated as one of the main factors influencing a fall of an older adult (Stevens, 2005). Numerous studies have demonstrated that, among older adults, there exists a strong relationship between a decrease in gait speed in usual conditions and the risk of falling, because slowing gait may reflect both damaged systems and a high energy cost of walking (Brach et al., 2005; Studenski et al., 2011; Verghese et al., 2009). In terms of fall risk, Dargent-Molina et al. (2002) presented the weights associated with different gait speeds among older adults: (a) the weight is equal to 0 for fast speeds (those faster than 1.4 m/s); (b) the weight is equal to 1 for normal speeds (those between 1.0 m/s and 1.4 m/s); (c) the weight is equal to 2 for slightly slower speeds (those between 0.6 m/s and 1.0 m/s); and (d) the weight is equal to 3 for slow speeds (those slower than 0.6 m/s). It can be seen a greater weight is associated with an increased risk of falling at the corresponding gait speed. Since the present study follows the principle that, the lower the value is, the greater the potential for falling will be, all the weights mentioned above need to be converted into values representing fall risk. Thus, 0, 1, 2, and 3 (the weights) in Dargent-Molina’s study are replaced by 1, 0.75, 0.5, and 0.25, respectively, to match the range of fall risk values in the present study. Meanwhile, the fall risk values are determined using linear conversion for gait speed at different speeds. Accordingly, in this study fall risk indices for gait speeds by type are calculated using Eq. (3), where, in order to have a better understanding of linear conversion, the constants are not simplified.

$$I_{Gait} = \begin{cases} 1 & , \quad \text{if } V \geqslant 1.4 \\ (0.75 - 0.5)(V - 0.2)/0.4, & \text{if } 0.6 \leqslant V < 1.4 \\ 0.25V/0.6 & , \quad \text{if } V < 0.6 \end{cases} \tag{3}$$

where $I_{Gait}(0 \leqslant I_{Gait} \leqslant 1)$ is the fall risk index for gait speed; and V is gait speed of evacuees.

- Congestion:

The traditional approach used to measure the level of congestion in human crowds is crowd density, which is described as persons/m^2. In general, a density of 5–6 persons/m^2 is regarded as a threshold above which prompt actions should be taken to avoid accidents (Helbing and Mukerji, 2012). This extreme situation (corresponding to immediate life-threatening danger) is not considered in this study, since in the agent-based model each patch holding an evacuee is adjacent to eight patches and the maximum density in this total area (9 patches in total) is equal to 4 persons/m^2, i.e., 9 persons/(1.5 m × 1.5 m). Feliciani and Nishinari (2018) classified the crowd density below the threshold into three categories (low, medium, and high) and stated there was no friction among pedestrians in the cases of low or medium density. Based on this, we select medium density (1.95 persons/m^2) as the threshold below which the fall risk index for congestion is equal to 1 (i.e., no fall risk). In this case, the total number of evacuees on 9 patches is equal to 4 (i.e., 1.95 × 1.5 × 1.5), meaning that no more than 3 evacuees can be in adjacent patches when the crowd density is at a medium level. The index is set to 0 (i.e., the maximum fall risk) when the surrounding eight patches are occupied. As for other situations, the amount of congestion is calculated using the following linear conversion.

$$I_{Congest} = \begin{cases} 1 & , \quad \text{if } N_E < 4 \\ (8 - N_E)/4, & \text{if } 4 \leqslant N_E < 8 \\ 0 & , \quad \text{if } N_E = 8 \end{cases} \tag{4}$$

where $I_{Congest}(0 \leqslant I_{Congest} \leqslant 1)$ is the fall risk index for congestion, and N_E is the number of evacuees (or agents) in adjacent patches. Here a lower value of $I_{Congest}$ signifies a higher fall risk for this evacuee.

After integrating two fall risk indices I_{Gait} and $I_{Congest}$ with the same weight (0.5), the fall risk index corresponding to the behaviour ($I_{Behavior}$) of a given evacuee is then calculated using Eq. (5).

$$I_{Behavior} = (I_{Gait} + I_{Congest})/2 \tag{5}$$

3.2.3. Environment

During an evacuation procedure, older adults first prepare (or delay) in their own room, travel along the hallway towards the staircase, and then travel down the stairs to reach the exit on the ground floor. As such, fall risk factors due to the built environment are

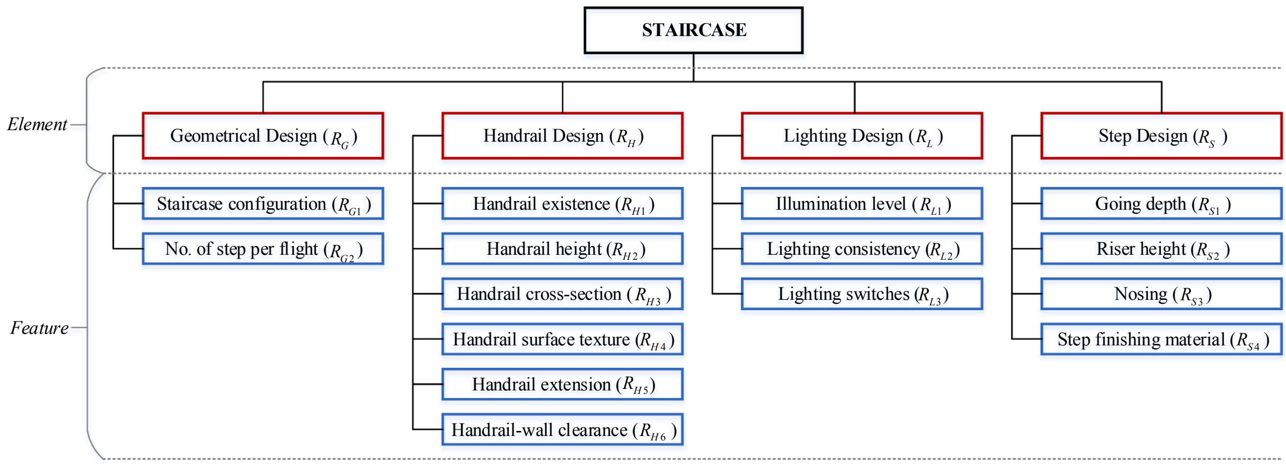


Fig. 2. Staircase elements and feature analysis.

determined at three different locations: staircase, hallway, and room.

- Staircase:

Afifi et al. (2014) adopted an evidence-based assessment method to investigate fall risks of older adults due to the architectural design of staircase elements and presented ratings for each feature of a certain element in different design scenarios. The score for each feature is rated between 0 and 1, and the lower the value, the higher the fall risk. The staircase elements and the corresponding features can be seen in Fig. 2. The symbol in parentheses refers to the rating for the corresponding element (or feature). Take the instance of a handrail as an example: if the staircase has two handrails (i.e., one handrail on each side), the rating for this feature (R_{H1}) is equal to 1; if the staircase has one handrail on one side, R_{H1} is equal to 0.67; if there is no handrail on either side, R_{H1} is equal to 0. For a detailed look at the rating standards for the fall risk of each feature pertaining to each element in different design scenarios, the interested reader can refer to Afifi et al. (2014).

If the ratings of the underlying features of a given element are known, the rating for this element is described by the mean of the ratings of all of its features (Afifi et al., 2014). For instance, the rating for geometrical design $R_G = (R_{G1} + R_{G2})/2$. Similarly, after the other three elements are rated, the fall risk index for a staircase ($I_{Staircase}$) is defined in this study by Eq. (6). The value of $I_{Staircase}$ is displayed using the original rating scale (0–1), rather than mapped onto the range 0–100 as was the case in the study by Afifi et al. (2014).

$$I_{Staircase} = (R_G + R_H + R_L + R_S)/4 \tag{6}$$

- Hallway:

In general, the basic components in hallway design include the floor, side walls, and lighting. These elements can also be similarly found in staircase design. At this point, the fall risk rating of each feature pertaining to each element in hallway design can be derived from that in staircase design (as shown in Fig. 3), where the rating for floor finishing material (R_{F1}) and for side wall surface (R_{SW1}) in different scenarios are the same as R_{S4} (step finishing material) and R_{H4} (handrail surface texture), shown in Fig. 2, respectively.

Similarly, the ratings for elements (R_F, R_L, and R_{SW}) are equal to the mean of ratings of the corresponding features. Subsequently, in this study, the fall risk index for the hallway ($I_{Hallway}$) is defined as per Eq. (7).

$$I_{Hallway} = (R_F + R_L + R_{SW})/3 \tag{7}$$

- Room:

The HAP developed by Chandler et al. (2001) is a quantitative, performance-based home assessment instrument to evaluate how an older adult functions in the home environment, where four types of rooms are selected as evaluation objects including living room, kitchen, bedroom, and bathroom. All the potential hazards in each type of room have been listed, including lighting, flooring, storage, furniture, and the corresponding detailed features to be assessed. The HAP scoring system is composed of two parts: hazard scores in three ranks (0, no risk; 1, low to mild risk; 2, moderate to high risk), and the frequency with which each hazard is encountered on 0–5 rating scale. In fact, the assessment procedure using the HAP is similar to the procedure involved in evaluating person–environment interactions during representative activities within each used area of the home (Chandler et al., 2001). With respect to the evacuation procedure and fall risk ratings, some hazards should be ignored in each room in this study, such as storage and furniture, according to their assessment guidelines. Furthermore, hazard scores can already reflect potential risk of falling and evacuation is a one-time activity, so the frequency rating of each hazard is ignored in this study in order to be consistent with the approaches to measure fall risks for hallways and staircases. Subsequently, the total hazard score for each room can be obtained by using Eq. (8). The interested reader will find a detailed description for hazards and their corresponding rating details by referring to Chandler et al. (2001).

$$HS_i = \sum_{j=1} \sum_{k=1} HS_{ijk} \tag{8}$$

where HS_i is the total hazard score for room of type i ; and HS_{ijk} is the hazard score of hazard j pertaining to feature $k$in this room.

In order to determine the fall risk index for each type of room (I_{Room_i}), the score HS_i in this study is applied according to Eq. (9) to determine the value of I_{Room_i} between 0 and 1. The smaller the value of I_{Room_i}, the greater the risk of falling in this room.

$$I_{Room_i} = 1 - HS_i/HS_{\max_i} \tag{9}$$

The fall risk index for rooms (I_{Room}) is then calculated using Eq. (10), where N_R refers to the number of rooms involved in the home assessment of each evacuee.

$$I_{Room} = \sum_{i=1} I_{Room_i}/N_R \tag{10}$$

3.2.4. Fall risk index for the elderly

After the fall risk index for each factor is calculated using Eqs. (3)–(10), an integrated algorithm described in Eq. (11) is then built in order to measure the fall risk index for each evacuee per step. This equation integrates the quantified values of three primary fall risk

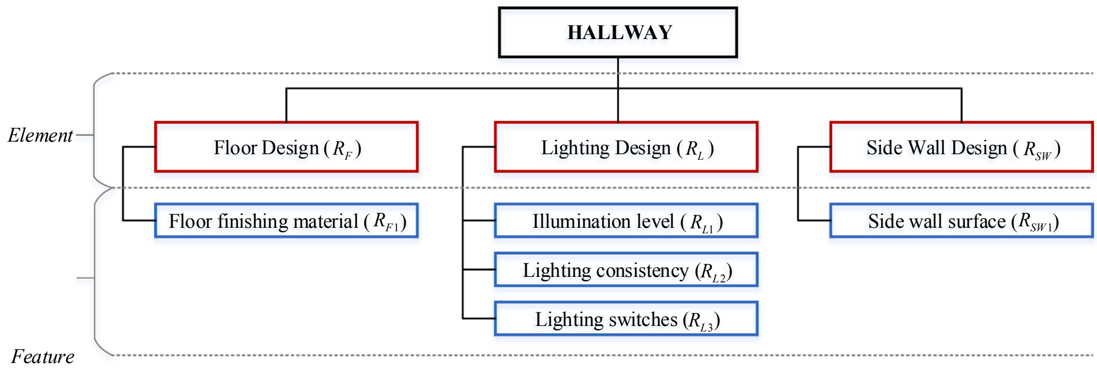


Fig. 3. Hallway elements and feature analysis.

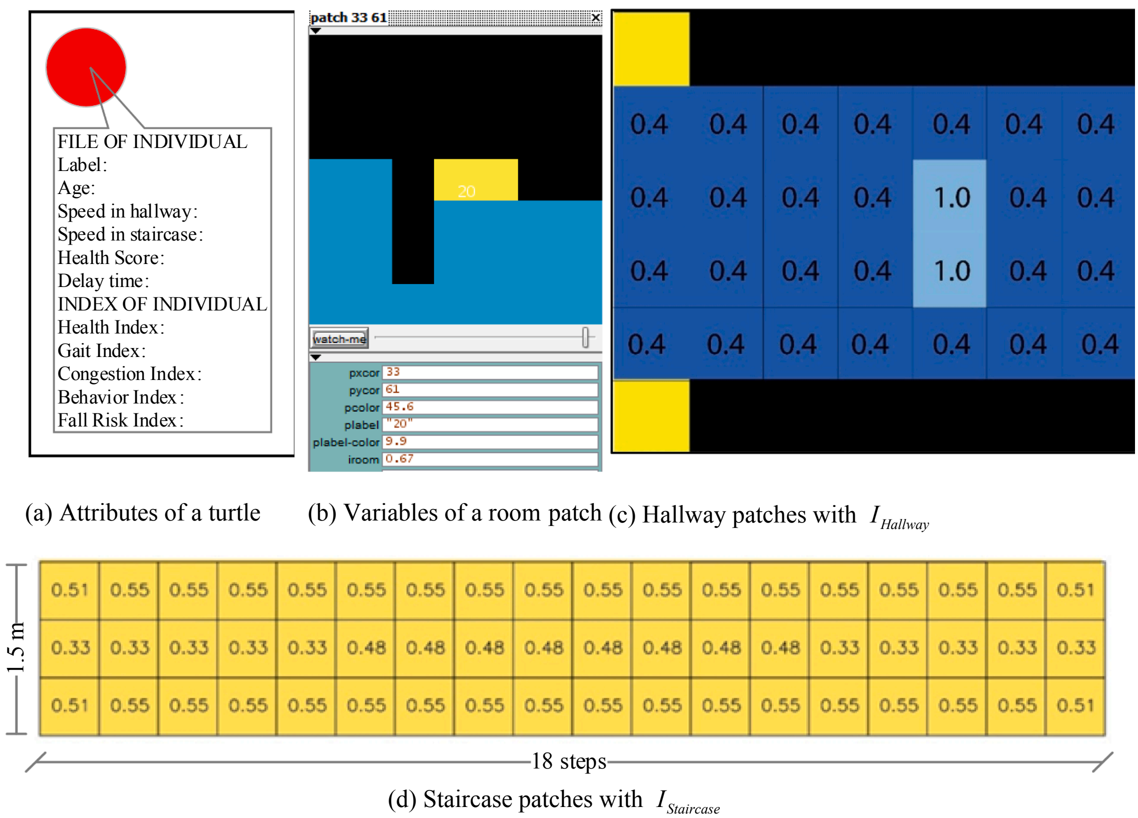


Fig. 4. Examples for attributes of a turtle and fall risk indices for environment.

factors (health, behaviour, and built environment). Since all the fall risk indices are measured under the same principle (i.e., the range is [0,1], where a lower value signifies a higher fall risk), it becomes possible to conduct a comparative investigation such as comparing fall risk among all evacuees. Furthermore, the fall risk index (I_{Fall_t}) is measured per step, and this ensures that the simulation model for fall risk analysis allows the essence of what occurs in a real emergency evacuation to be captured, since fall accidents are sudden events that happen when individuals transition from a given cell to the next. In this respect, the integrated algorithm could enhance the applicability and accuracy of the proposed simulation framework for fall risk analysis of older adults in evacuation scenarios.

$$\begin{cases} I_{Fall_t} = a_1 \times I_{Health} + a_2 \times I_{Room}, & if\ t \leqslant T_{delay} \\ I_{Fall_t} = b_1 \times I_{Health} + b_2 \times I_{Behavior} + b_3 \times I_{Hallway}(I_{Stair}), & if\ t > T_{delay} \end{cases} \tag{11}$$

where a_1, a_2, b_1, b_2, and b_3 are the weights for these fall risk indices; I_{Fall_t} ($0 \leqslant I_{Fall_t} \leqslant 1$) is the fall risk index of each evacuee at time t; T_{delay} is the number of ticks (i.e., the time) after which an evacuee finishes preparation and starts to move forward toward the exit. If $t \leqslant T_{delay}$, the evacuee is still at home; otherwise, the evacuee is travelling through the hallway or on the stairs. A value of I_{Fall_t} relatively close to 0 is indiciative of a higher fall risk, whereas values that are close to 1 correspond to a lower fall risk.

Throughout the evacuation procedure, the fall risk index for each evacuee (I_{Fall}) is then calculated using Eq. (12), where N_T is the number of ticks (or the total time) required by this evacuee to complete the evacuation. Here the meaning of the value of I_{Fall} is the same as that of I_{Fall_t}.

$$I_{Fall} = \sum_{t=1} I_{Fall_t}/N_T \tag{12}$$

In addition, we define the value of I_{Fall_t} belonging to a certain patch (I'_{Fall}) as equal to the mean of I_{Fall_t} for all the passers-by (N_P) at time t in order to visualise the fall risk of evacuees in the built simulation model,

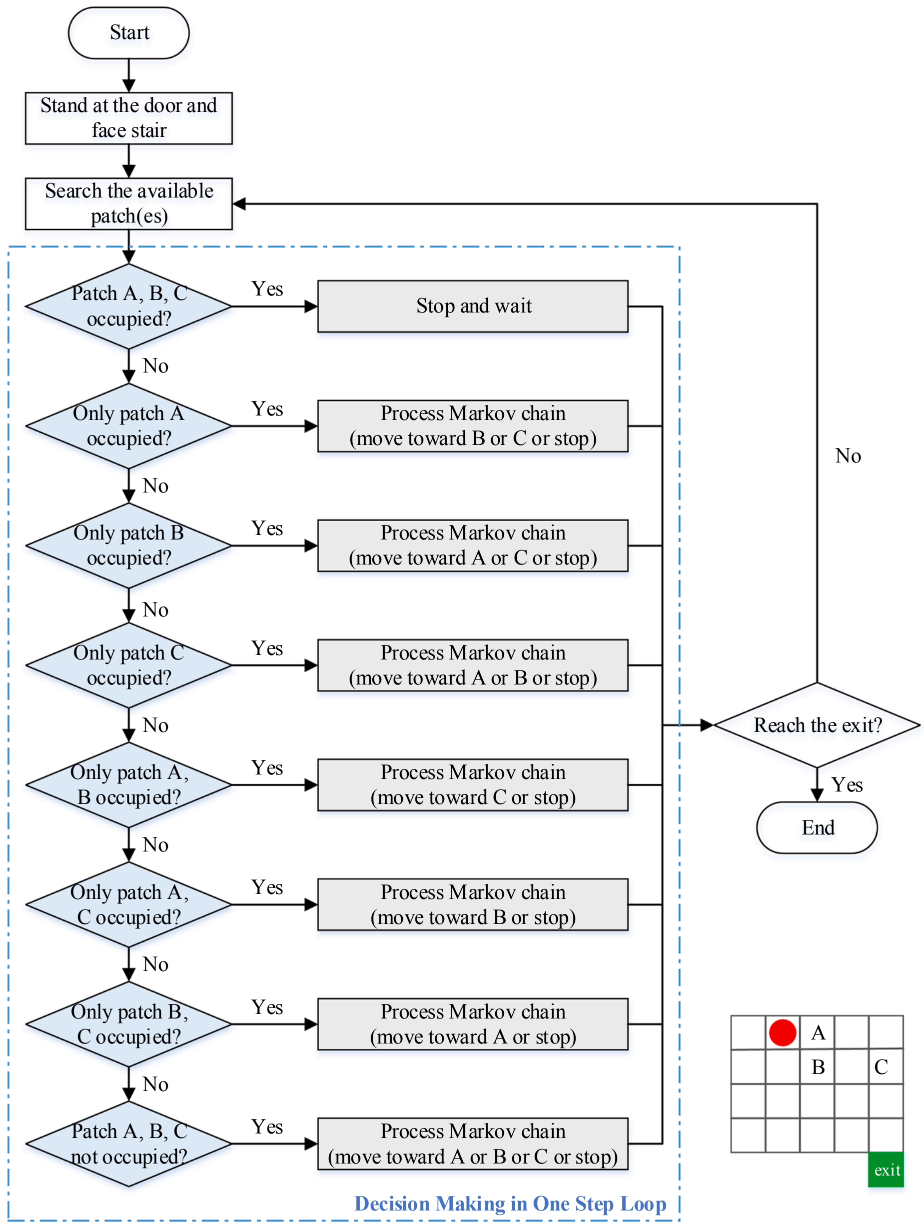


Fig. 5. The decision-making process for individual wayfinding.

as shown in Eq. (13). Similarly, the meaning of the value of I'_{Fall} is the same as that of I_{Fall}.

$$I'_{Fall} = \begin{cases} \sum_{p=1} I_{Fall_t}/N_P, & \text{if } p > 0 \\ \text{otherwise}, & 0 \end{cases} \tag{13}$$

3.3. Integrate the agent-based model with fall risk index

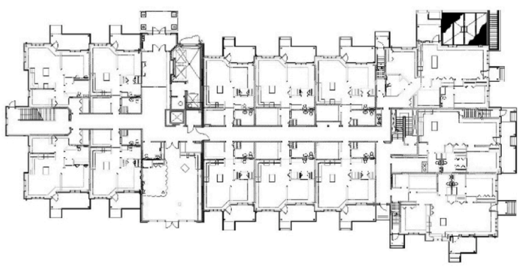
Before simulating the elderly evacuation based on the agent-based model, all the attributes that one turtle owns to identify a senior resident must be established, while the fall risk index for the environment (e.g., $I_{Staircase}$, $I_{Hallway}$, or I_{Room}) need to be assigned to patches that represent certain building elements. For example, as shown in Fig. 4(b), a variable "Iroom" is given to each room patch, which refers to I_{Room} and is calculated using Eqs. (8)–(10). Once the simulation starts, the interactions begin between the fall risk assessment of turtles and patches. The weighted graph made of the environment patches will display the real-time fall risk index (I_{Fall_t}) when a turtle passes a series of patches. Meanwhile, the fall risk index (I_{Fall}) will be determined after each turtle representing an evacuee reaches the exit.

In the course of evacuation, the wayfinding actions of evacuees are influenced by the surrounding environment and occupant density, which further affect fall risk possibility (i.e., the values of $I_{Fall_t}$and I_{Fall}) of each evacuee. Based on the built Markov chain described in Section 3.1, the decision-making process for individual wayfinding is presented in Fig. 5.

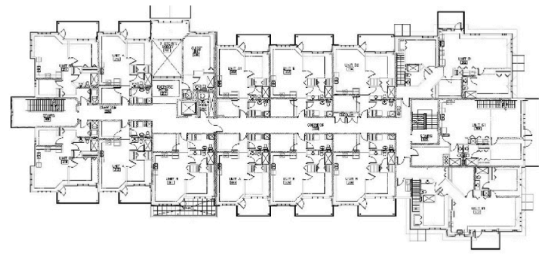
4. Case study

4.1. Environment model

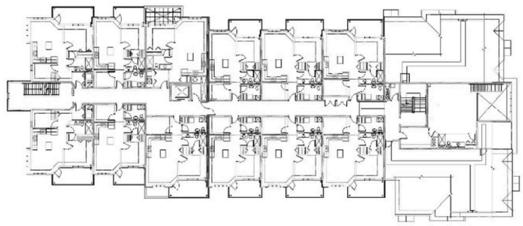
A 4-storey seniors' residence (apartment building) to be built in



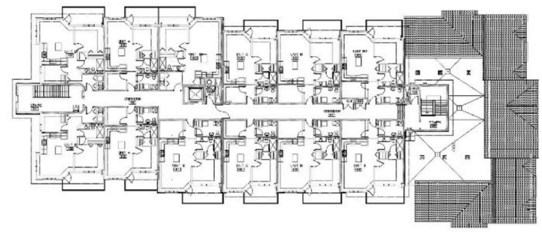
(a) Floor 1



(b) Floor 2

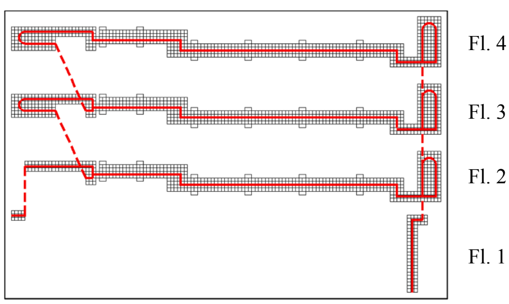


(c) Floor 3

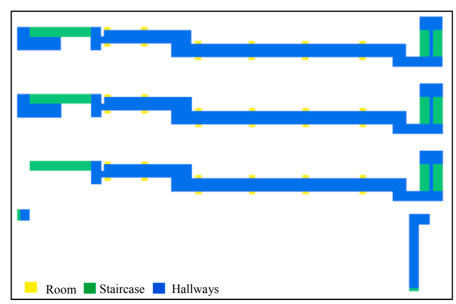


(d) Floor 4

Fig. 6. Floor plans of the apartment building.



(a) Building with grids and travel paths



(b) Building components shown in colour

Fig. 7. Simplified plan of the building.

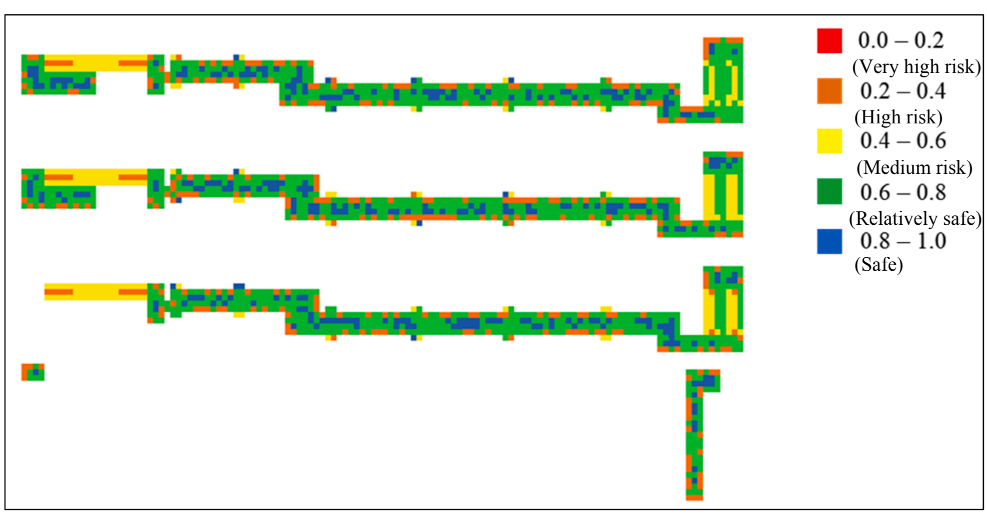


Fig. 8. Fall risk index map for environment components.

Table 1
Parameters for turtles in the evacuation simulation.

Parameter	Notation	Unit	Value	Reference
Fall risk index for health	I_{Health}		Uniform (0,1)	Assumption
Gait speed	V	m/s	In hallways: Triangular (0.5, 0.8, 0.65) On stairs: Triangular (0.2, 0.4, 0.3)	Bukowski (2008), Du et al. (2018)
Number of total turtles	(n/a)	No.	72	Two residents in each room
Delay time	T_{delay}	second	Triangular (0, 300, 90)	Du et al. (2018), Proulx et al. (1994)
Probabilities in Markov chain				
when the nearest target (e.g., the corner or the exit) is straightforward or nearly straightforward	$P_{Straight}$		0.7	Du et al. (2018)
	$P_{Parallel}$		0.125	
	$P_{Diagnoally}$		0.125	
	P_{Stop}		0.05	
Probabilities in Markov chain				
when the nearest target (e.g., the corner or the exit) is diagonal or nearly diagonal	$P_{Diagnoally}$		0.425	Du et al. (2018)
	$P_{Straight}$		0.425	
	$P_{Parallel}$		0.1	
	P_{Stop}		0.05	

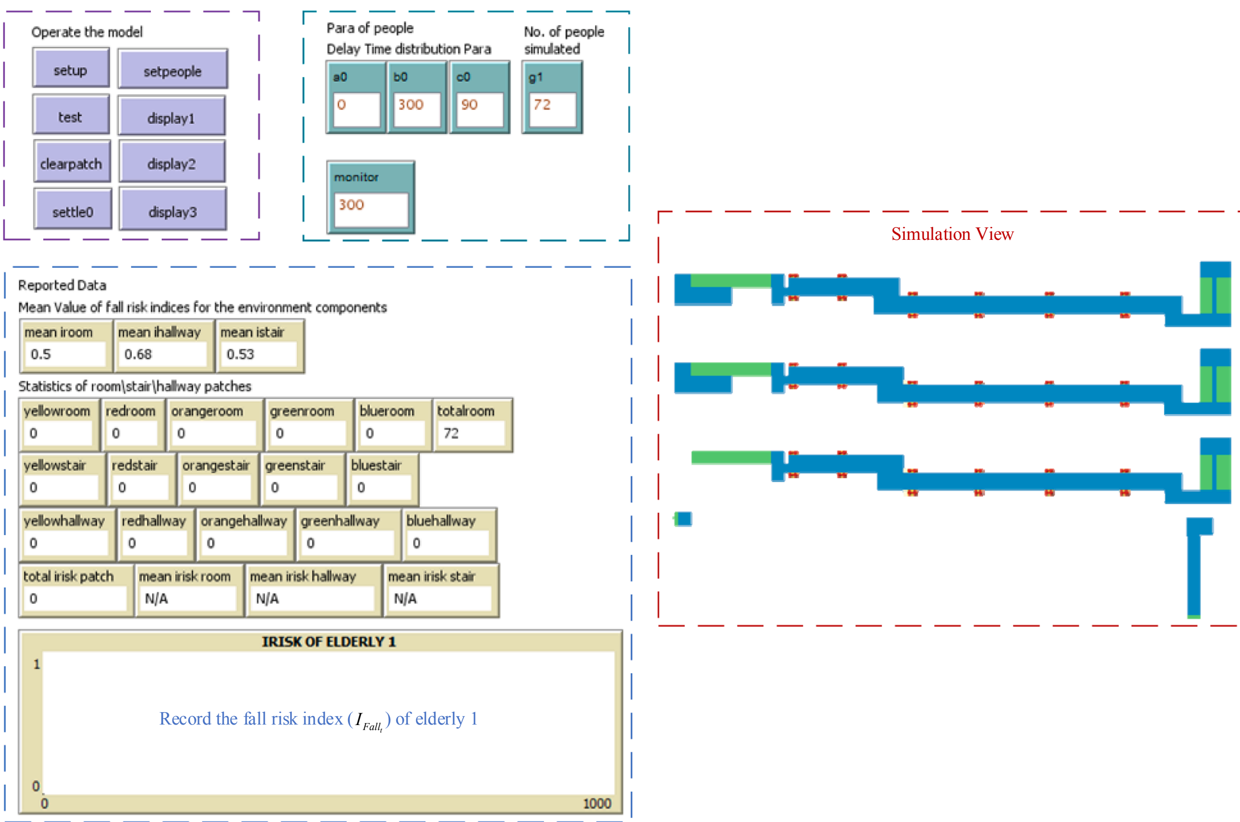


Fig. 9. The agent-based model for fall risk simulation.

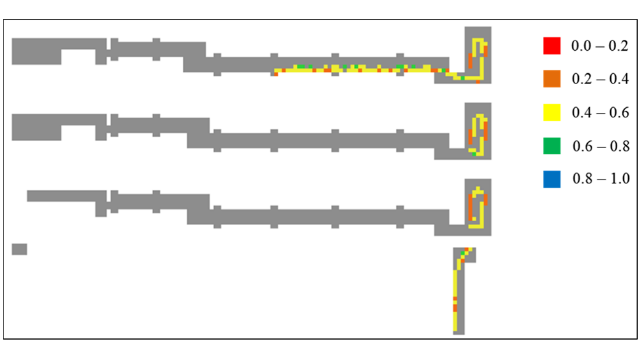


Fig. 10. Fall risk index (I_{Fall_t}) map for one evacuee.

Edmonton, Canada is selected for the case study to demonstrate the application of the proposed framework. The CAD drawings of the floor plans of this building are shown in Fig. 6. Based on the floor plans, this apartment was manually simplified into fundamental egress components as described in Section 3.1, where primary building elements are distinguished by pixels of a different colour. The simplified plan of this building is shown in Fig. 7. The image file, shown in Fig. 7(b), was then imported into NetLogo, which results in the desired patches being indicated automatically by the corresponding colour.

Using the environment model developed in NetLogo and the CAD drawings of this building, we can calculate fall risk indices for the environment components (i.e., rooms, hallways, and stairs) following the equations shown in Section 3.2.3. The values of the fall risk index of

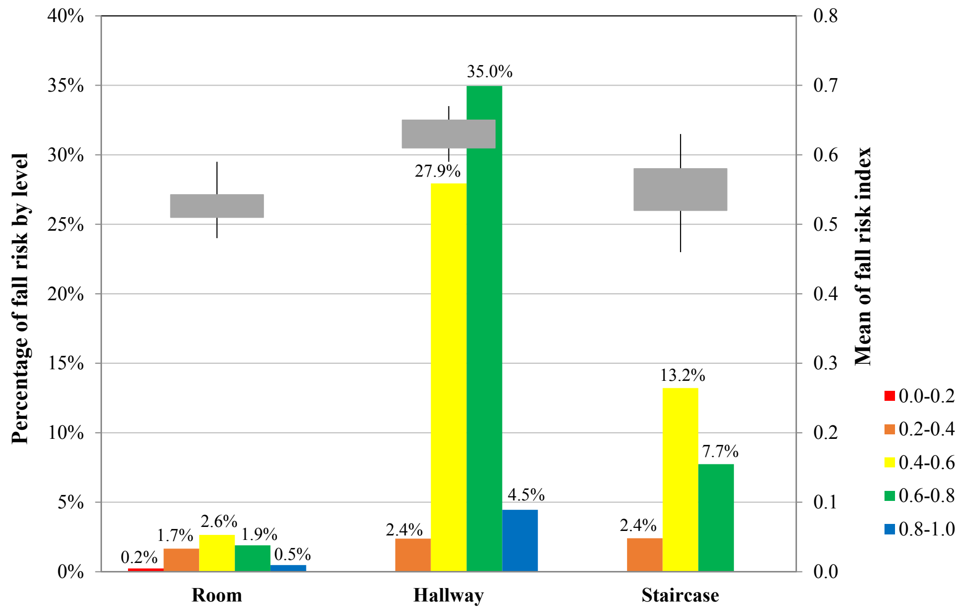


Fig.11. Fall risk of evacuees with respect to different building elements.

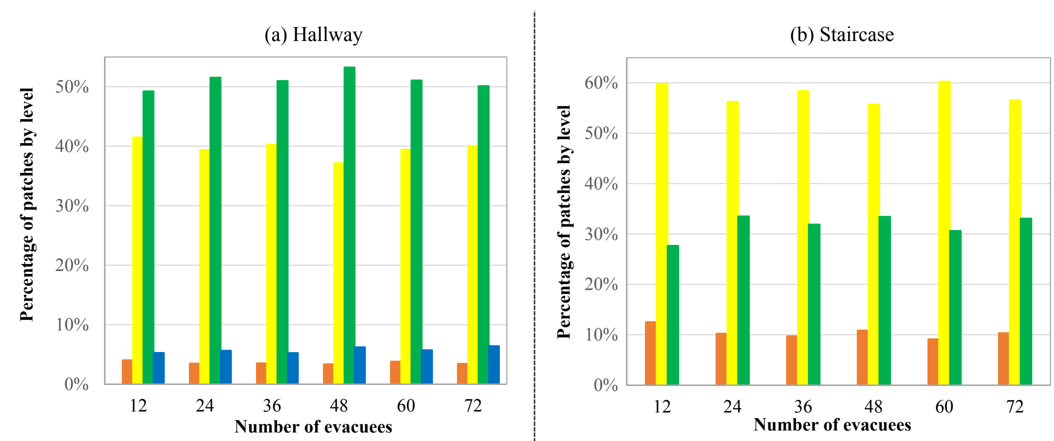


Fig. 12. Distribution of patches by fall risk level.

each patch are shown in Fig. 8. It can be observed that there is a relatively high fall risk in this apartment building in the area of the staircase, while the fall risk is lower for travelling along hallways except in the case of some patches close to the walls.

4.2. Turtles representing older adults

In the simulation model, turtles representing older adults aged 55 and over are marked with a red circle. In this case study, all the occupants of this seniors' residence are independently-living older adults. Since this seniors' residence apartment building will be developed in future, the relevant parameters used to describe the residents are represented in Table 1 and are based on relevant literature. Also, we assume each evacuee will only target one staircase and not change it during the remainder of the evacuation procedure; the weights in Eq. (11) are assumed to be equal, that is, the fall risk indices for health, behaviour, and environment have the same degree of importance. The evacuation time considered in this study consists of delay time and movement time in terms of each evacuee, since the detection time is assumed to be negligible, representing an ideal situation where the alarm system detects the emergency instantaneously.

4.3. Fall risk analysis

After the environment model is constructed and information of turtles is known, the agent-based model for fall risk of older adults can be processed in NetLogo. The operation interface for the developed model in this study is shown in Fig. 9, where the "display1" function is designed to show the fall risk map for environment components, the "display2" and "display3" functions are used to display the fall risk index map for all patches with and without values, respectively, and the monitor function is designed to control the simulation time (in seconds). Other parameters for turtles such as gait speed and fall risk for health are assigned in the code. Furthermore, a portion of the output data is directly reported in the operation interface. For example, the fall risk index of a given evacuee can be recorded as time goes by. The simulation view shows that all residents are in their own rooms and ready for evacuation after we click the functions "setup" and "set-people".

First, we assume that only one senior resident travels through the

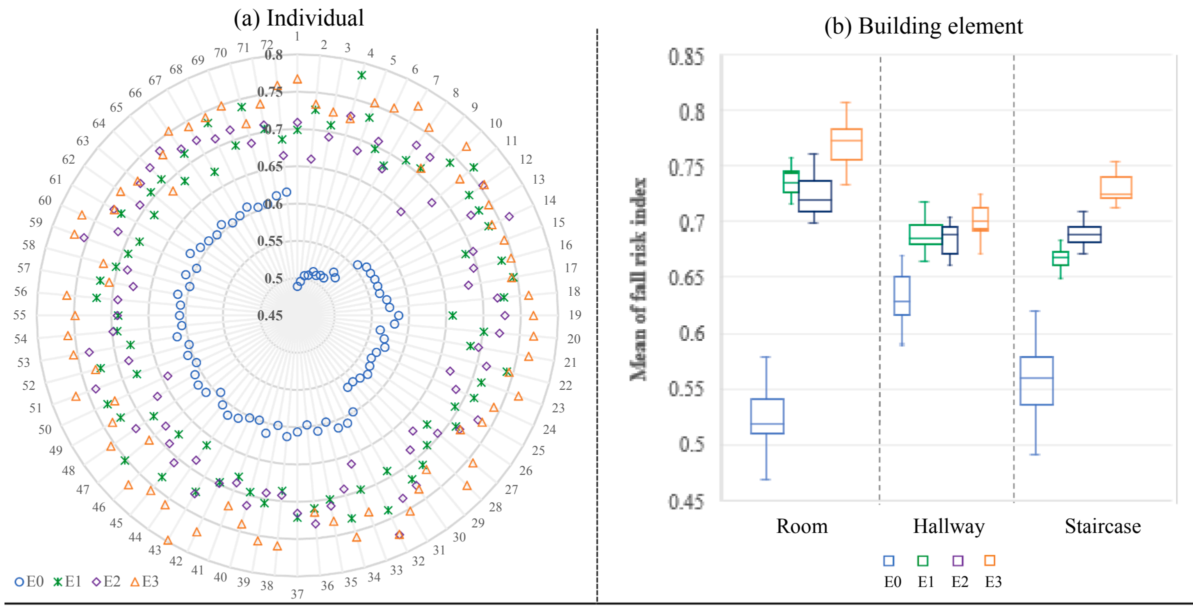


Fig. 13. Average fall risk for different building design plans.

apartment, so the real-time fall risk index (I_{Fall_t}) for this evacuee can be traced as per Fig. 10, where red patches indicate a high fall risk while blue patches denote a situation with little fall risk. Meanwhile, all the coloured patches represent the path that the turtle chose. Based on this simulation, we can grasp that the fall risk index for this turtle (I_{Fall}) is equal to 0.46 throughout the evacuation procedure by means of Eq. (12).

Similarly, if, during the course of the evacuation, more than one turtle passes through a particular patch, the simulation model will output the values of I_{Fall} for each turtle. In order to conduct a statistical analysis of the fall risk index, we ran this simulation model 1000 times. The results of I_{Fall} for all 72 evacuees in total for each simulation are shown in Fig. A1, and the mean of I_{Fall} falls in the range [0.49, 0.62] in terms of each evacuee. In this simulation model, the total evacuation time is less than 10 min, which satisfies the safety condition: RSET $<$ ASET (where ASET is greater than 30 min for fire emergency response when the occupant load is more than 30 persons in residential buildings) (Du et al., 2018; Purser, 2003).

In order to have an overall understanding of the process in the building (i.e., which zones represent a high risk to trigger a fall), we also monitor the simulation from the perspective of each environmental patch. According to Eq. (13), the evolution process of fall risk for all patches can be traced in Fig. A2 (take a one-time simulation as an example). The fall risk index map for all evacuees is shown as output in Fig. A2(j). The value assigned to each patch in this figure is equal to the mean of values during this experiment. It can be seen that there are more red patches in the staircase than in the hallways, while evacuees have more potential for falling in the left staircase compared with the right staircase (more red and orange patches).

After running the simulation 1000 times and obtaining fall risk indices for each patch belonging to the corresponding building element as per Eq. (13), the fall risks corresponding to different elements are determined as shown in Fig. 11, where the bar chart displays the percentage of patches by fall risk level in relation to different building elements as a proportion of all patches, such that the sum of all the percentage values is equal to 1. The box plot, meanwhile, gives the mean of fall risk index of room patches, hallway patches, and stair patches after all simulation experiments. Overall, it is found that this apartment is not well suited to older adults, since the areas with a fall risk index higher than 0.6 account for around 50% of the entire observed plan. Meanwhile, the minimal mean of fall risk index (I'_{Fall}) of room patches, hallway patches, and stair patches is close to or slightly above 0.5. It should also be noted that older adults tend to have a higher fall risk on stairs compared to in hallways, since the minimal value of the box plot for hallways is larger than the maximum value of the box plot for stairs (where a lower value of I'_{Fall} corresponds to a higher fall risk).

4.4. Discussion

In the above experiment, we consider that the seniors' residence apartment is fully occupied by 72 residents, while details about the built environment are derived from the original design plan for the building. To explore influence of the number of evacuees and of different building design plans on the fall risk of older adults, a sensitivity analysis is conducted by resetting the population in the building as [12, 24, 36, 48] and making adjustments to the built environment in order to observe the corresponding changes to the fall risk. The occupied rooms in the model are selected randomly during each run of the simulation. The comparison of fall risk for different numbers of evacuees and of different building design plans is described from the perspective of individuals and the built environment, respectively.

- Different numbers of evacuees

For a given number of evacuees, the fall risk index (I_{Fall}) is gathered for each evacuee for all the simulations, but the findings show that there is not a large variation among the means of I_{Fall} for different sizes of the population. This implies, counterintuitively, that as the number of evacuees increases, the fall risk index does not increase accordingly. After the delay time, evacuees move towards the exit in which case I_{Fall_t} depends on three primary risk factors. As such, we collect the number of patches categorised by fall risk level (as shown in the legend in Fig. 11) in terms of hallway and staircase, then calculate the percentage for each fall risk level after each simulation, and then average the percentages derived from all the simulations. Fig. 12 shows the distribution of patches by fall risk level in hallway and staircase as the number of evacuees increases.

Among the building components, there are some common points for all the simulations. Overall, the percentages of patches of different fall risk levels have a similar distribution, although the percentage fluctuates slightly for a certain level of patches. For example, the yellow patches are prominent in the patch distribution for staircase, followed by the green and orange patches. Specifically, the patches with moderate fall risk (i.e., yellow patches) account for the largest percentage of the total patches through which the evacuees travel on the staircase, meanwhile there are no patches with the lowest or highest fall risk. By contrast, the average fall risk of all patches along hallways seems to be lower than that of staircase, since nearly 50% of patches are labelled by the green colour and older adults on 6% of patches have the lowest fall risk. Based on the results, some suggestions are given in order to decrease the percentage (or number) of orange patches: (a) partly modify the component design for hallways and staircase (refer to Fig. 2 and Fig. 3) in order to improve safety and mitigate potential fall risk; and (b) provide an evacuation guide for the residents, mentioning a detour around those patches with higher fall risk.

- Different building design plans

For the case seniors' residence apartment fully occupied by 72 residents, three new building design plans are considered in order to reduce fall risk associated with built environment-related factors. In building design plan (a), according to the original fall risk index map for environment components (Fig. 8), all the patches with lower values (i.e., red, orange and yellow patches) are changed into patches with environment-related fall risk indices of 1. In building design plan (b), based on the results shown in Fig. 11, the fall risk index for environment is set to 1, in terms of all the patches with the lower value (i.e., red, orange, and yellow patches). In building design plan (c), all the patches in building elements are assigned environment-related fall risk indices of 1. After all the simulations, the fall risk indices for individuals (I_{Fall}) and for patches (I'_{Fall}) are collected for each experiment, and from this we can obtain the average fall risk of each evacuee and of differernt building elements. In Fig. 13, E0 refers to the orginal building design plan, where E1, E2, and E3 corrrespond to the proposed building design plans (a), (b), and (c), respectively.

In terms of individuals, the mean of the average fall risk of all evacuees is 0.58 (i.e., below the safety threshold of 0.6) for E0, while the values for E1(E2) and E3 are found to exceed the threshold at 0.71 and 0.75, respectively. Although a few evacuees (e.g., Agent 9 and Agent 11) have a higher average fall risk in E3 compared to the other improved building designs, the fall risk is significantly reduced among most older adults. Furthermore, there is not a significant difference between E1 and E2 in terms of variations in average fall risk from the individual perspective.

For the building elements, the average fall risk in staircases is reduced when the environment is improved in part or all of patches, where the mean of the fall risk index in E3 grows by 31% compared to E0, while the performance in E2 improved based on the simulation results is better than that modified based on the original environment (i.e., E1). The mean of the fall risk index in hallways increases by 11% in E3, while the average performance in E2 is similar to that in E3. In contrast, a more significant improvement is observed in the mean of fall risk index in rooms, with the percentages of all new design plans exceeding 38%. The above results also verify that partial modifications of the design of the built environment can enhance older adults' safety and reduce potential fall risk.

5. Conclusions

This study was designed to quantify the fall potential among older adults by analysing and visualising fall risk and thereby minimising this potential by improving the identified risk zones when, during an emergency evacuation, they travel along a spatial path inside a building. To achieve this goal, a novel framework is outlined in this study based on the agent-based simulation. Using this approach, the safety level of the building in terms of fall risk for each resident of a seniors' residence is evaluated. Meanwhile, the locations in the building where there is a high probability of fall risk can be made known to evacuees, so more attention can be paid when passing by these specific locations. The main contributions of this study include: (a) a set of methods are integrated to quantitatively define a comprehensive fall risk index for older adult evacuees that includes health, behavioural, and environmental factors; (b) agent-based modelling is used to simulate the evacuation procedure and analyse fall risk of older adults; (c) a helpful tool is provided to trace and visualise the real-time fall risk for different groups of people, different building plans, and different components of a building. The proposed framework is validated by a real-world case study (an apartment-style seniors' residence in Edmonton, Canada) to show the applicability of fall risk analysis to evacuation procedures. The framework can also be applied to analyse fall risk of other population groups after establishing a fall risk index for the studied population and adjusting the parameters in the agent-based model.

The present study is also subject to certain limitations. First, in this study the weights for fall risk indices of staircases (Eq. (6)) and hallways (Eq. (7)) and the weights of the three primary risk factors in Eq. (11) are treated equally. A future study can consider determining these values from an experimental (or evidence-based) study. In addition, the virtual built environment for the agent-based model is created after importing the simplified building plan derived from CAD drawings into NetLogo. In future, we can integrate agent-based modelling with building information modelling (BIM) in order to transform a 2D model into a 3D model and output the information pertaining to the built environment (e.g., rooms, hallways, and staircases) in real time. Finally, this study uses agent-based models to analyse the fall risk of older adults during an evacuation but does not consider the risk of a fall accident due to high crowd density. A future study can incorporate fall accidents in building the simulation model and investigate the impact of this on the individual fall risk and evacuation results, as well as identify the optimal route for rescuing occupants who have fallen during evacuation procedures.

Appendix A

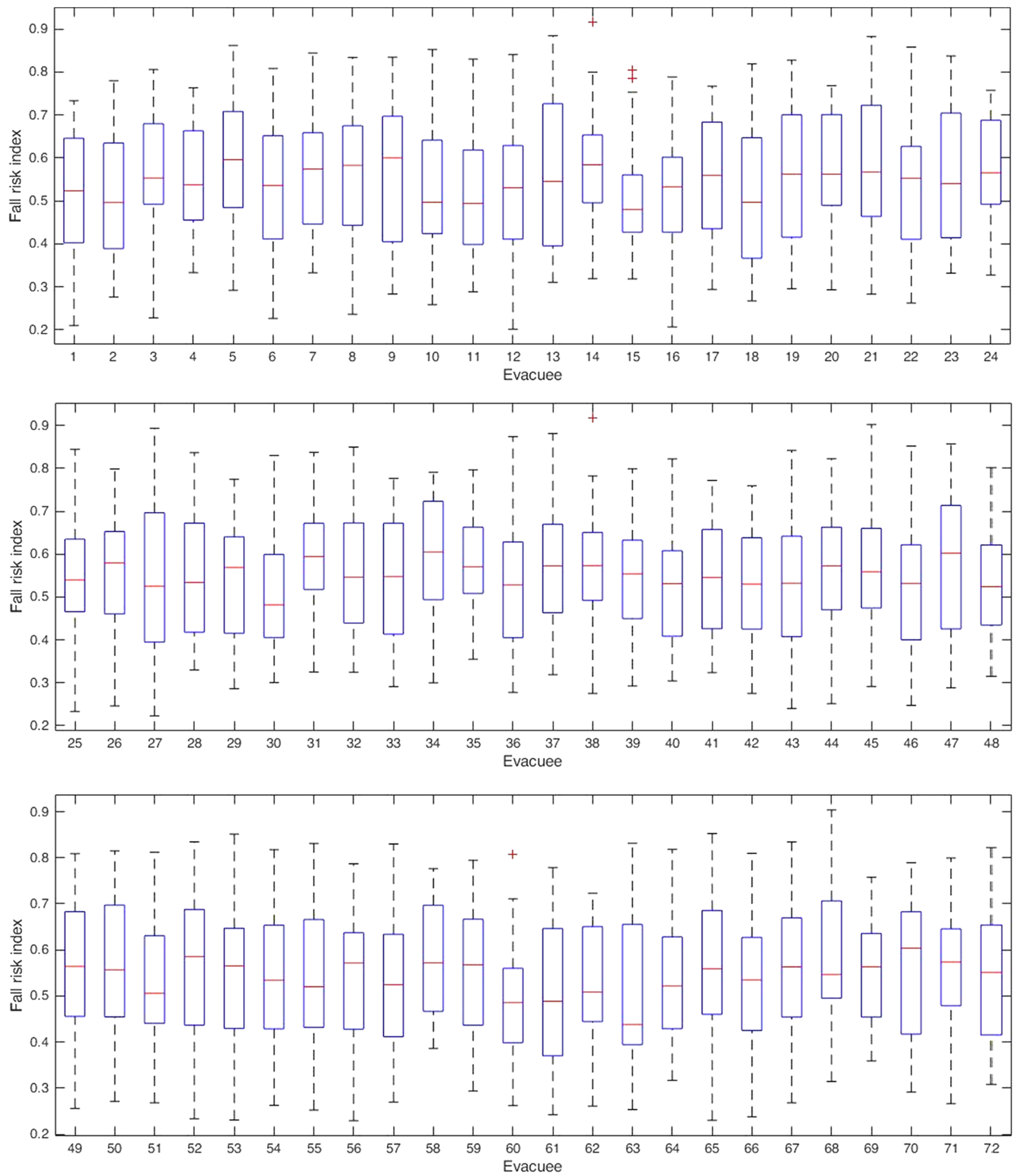


Fig. A1. Fall risk index (I_{Fall}) of 72 evacuees.

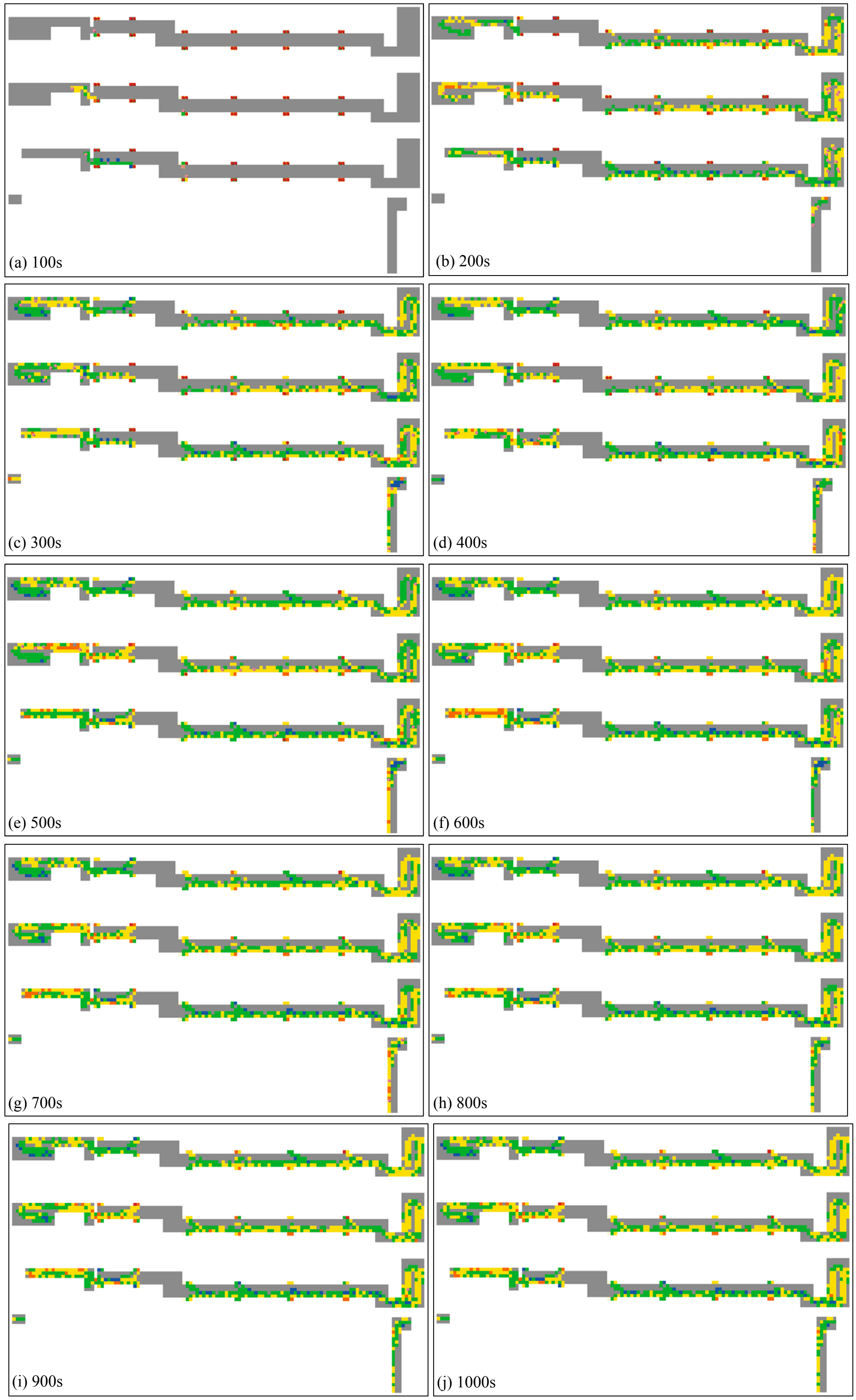


Fig. A2. Evolution process of fall risk in the simulation.

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