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Evaluating building egress safety for the elderly under different urgent-level circumstances in high-density cities: based on ABEM-enabled simulation

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Abstract: In high-density cities, people usually live in mid-rise or high-rise residential buildings where indoor environments are quite complicated. Safety risks exist not only within homes, but also on the way to egress from residential buildings. As the aging issue becomes severer, it is essential to provide safe egress plans particularly for the elderly who are more fragile to risks and obstacles. Kinds of emergencies might occur in reality, some are hard to predict and extremely dangerous, while some can be warned in advance and would not cause damages immediately. However, previous research seldom considered the different urgent levels of circumstances during the egress process of the elderly. Consequently, this study contributes to proposing an agent-based egress model (ABEM)-based evaluation of building egress safety for the elderly under different urgent-level circumstances by introducing absolute and relative indicators. Absolute indicators evaluate building egress safety for the elderly, relative indicators reveal whether buildings hinder safe egress of the elderly compared with ordinary residents, and indicator weights are decided by

AHP method to compute building egress safety index (BESI) as the evaluation results. Case study shows BESI scores of 8.696, 8.941 and 6.290 under three circumstances. BESI scores are valuable references for old home buyers to make decisions. Furthermore, this evaluation approach offers an effective tool to help designers to improve design schemes for safer egress, to assist property managers in updating egress plans and facilities based on new occupancy status in the operation stage, eventually to facilitate the development of healthy residential buildings.

Keywords: egress safety; the elderly; agent-based egress model; urgent level; residential building.

1. Introduction

People generally spend approximately 90% of their time indoors, and almost 70% of that time is spent at home (Brik *et al.*, 2021). Current modes of working and living have changed dramatically, prolonging the time people spend at home, especially in the post-pandemic era (Awada *et al.*, 2022). Working from home and aging in place have become more and more common. It reminds us that residential buildings should be flexibly adapted to different circumstances without compromising residents' well-being. Consequently, the healthy performance of the building began to attract more attention than before. Owing to declining mobility and functional impairment, the elderly have to stay at home most of the time, making them more sensitive to the healthy performance of residential buildings (Zhang *et al.*, 2021). In high-density cities, residents usually live in mid-rise or high-rise buildings with more complicated indoor risks. The risks would exist not only within homes, but also in the process of daily egress from the building (Du *et al.*, 2018), especially the high-rise buildings (Aleksandrov *et al.*, 2019).

Besides, residents have to face with diverse threats from kinds of emergencies, such as earthquakes, fires, floods, explosions, as well as viruses. When emergencies happen, all residents have to evacuate from their residential buildings quickly. However, the urgent level of emergencies would be various. For instance, fire and earthquake are the most common emergencies with extremely high-level of urgency and danger. These emergencies are hard to be predicted in advance, so residents must egress from buildings as quickly as possible to survive from emergencies. Meanwhile, techniques can help predict and alert some emergencies in advance, like hurricanes, floods, virus spread, and other predictable emergencies. The advanced alert provides residents a limited period for evacuation before harms occur actually. So, the urgency of emergencies caused by predictable dangers is considered lower. Currently, many countries and regions are faced with the epidemic threat from COVID-19. It is scientifically proved that COVID-19 can spread widely within the same building through public areas, elevators, wastewater plumbing systems, ventilation systems (Gormley *et al.*, 2020). Once the virus is found to spread within the building, all residents will require to leave in a limited time for interrupting transmission. For instance, the local governments of Hong Kong[1] and Japan[2] have evacuated residents to prevent the infection of COVID-19 in high-risk buildings.

Injuries and casualties usually occur during the egress process from buildings, regardless of under normal circumstances or emergencies, especially the people with reduced ability to egress. At present, the egress abilities of residents are becoming more varied with the building populations, typically including individuals with impairments or the elderly or generally less mobile (Geoerg

[1] https://www.news.gov.hk/chi/2020/06/20200604/20200604_180615_179.html
[2] https://www.town.niseko.lg.jp/resources/output/contents/file/release/2890/32347/hinan.pdf

et al., 2019). Even a single fire may cause a considerable number of casualties in high-rise buildings (Aleksandrov *et al.*, 2019). Therefore, it is necessary to analyze the egress safety considering elderly with physical impairments and declining mobility which increase their risks in the egress process.

Previous research has pointed out the efficient evacuation of particular groups is a problem to be solved for quite a long time (Institute for Accessibility Development Tsinghua University, 2020). However, only a few studies have analyzed building egress safety from the perspective of the elderly, and have seldom noticed the impact of different urgent levels of circumstances on egress safety of the elderly. Consequently, this study aims to develop a simulation-based evaluation approach of building egress safety for the elderly under different urgent-level circumstances. An agent-based egress model (ABEM) is developed to simulate the egress process in mid-rise or high-rise residential buildings. The building egress safety index (BESI) is computed by absolute and relative indicators based on the simulation results. Finally, the significant effects on building egress safety for the elderly can be explored. This ABEM-based evaluation approach and its results of BESI provide residents, designers, and developers convincing results to guide the improvements of building egress safety for the elderly.

2. Literature review

2.1 Occupants' egress from buildings

Under normal circumstances, occupants always need to go in and out of buildings (Fu *et al.*, 2021). The egress routes within buildings in daily life generally rely on the building circulation design. Since the main indoor movement method is walking, researchers used the concept of "indoor walkability” to measure the building circulation performance by checking whether occupants can direct their movement and reach their destination conveniently (Natapov *et al.*, 2015). The indoor walkability was evaluated in several dimensions, including distance, simplicity, accessibility, and pedestrian-friendly circulation environment (Lee *et al.*, 2020), and the index of indoor walkability can be computed based on rich digital data of buildings derived from BIM (Shin and Lee, 2019). Other researchers further mentioned that indoor walkability is not only determined by the built environment, but is also associated with occupants’ feelings and preferences (Maghelal and Capp, 2011, Fu *et al.*, 2021a).

Besides the normal circumstance, the egress under emergency circumstances, also called emergency evacuation, is the focus of research as well. Generally, the emergency evacuation determines the occupants’ life safety heavily. Similar to the normal egress from the building, the built environment and occupants’ characteristics are also regarded as the main factors affecting the efficiency of emergency evacuations. Some studies concerned the effects of particular building features, like emergency signage assisting in the wayfinding process (Gerges *et al.*, 2018, Fu *et al.*, 2019), alternatives of escape routes for blockages or high congestion (Rendón Rozo *et al.*, 2019), building plane complexity, and other internal factors (Qu *et al.*, 2019). Meanwhile, occupants’ characteristics play roles in the process of emergency evacuations, such as age, gender, obesity (Spearpoint and MacLennan, 2012), physiological and psychological characteristics (Hanapi *et al.*, 2017), and individual movement characteristics (Li *et al.*, 2020). Moreover, occupants’ acquired information of evacuation procedures (Gerges *et al.*, 2018), spatial knowledge of building planes (Lin *et al.*, 2020), exit familiarity, and neighbor behavior (Kinateder *et al.*, 2018) significantly assist them in the decision-making of escape routes. Besides the research about the general emergency situation, as a typical emergency situation of buildings, fire evacuation has been discussed more in particular. The fire would destroy building structures and building materials once the temperature is beyond their fire resistance (Banerji and Kodur, 2022), and the rapid spread of fire and smoke in buildings can hinder the evacuation process (Kodur *et al.*, 2020; Fu et al., 2021b) by generating several toxic gases like carbon monoxide, hydrogen cyanide and phosgene gas (Kodur *et al.*, 2019) and affecting movement speed and exit choice of occupants (Ronchi *et al.*, 2018; Gerges *et al.*, 2018). The location of stairway within the building and the floors at which the fire starts (Kodur *et al.*, 2020) are significant variables under the fire situation, as well as situational awareness which allows occupants and first responders to know the severity of the fire, such as the nature of fire growth (Kodur *et al.*, 2020).

For guaranteeing individual safety, the whole time of the emergency evacuation should be optimized as little as possible (Du *et al.*, 2020). The time of emergency evacuation can be divided into several parts, containing pre-evacuation time (detection time and delay time) and travel time (exit selection and movement time) (Tubbs and Meacham, 2007, Rahouti *et al.*, 2020). Researchers have proposed several strategies to reduce targeted types of evacuation time. For instance, the pre-evacuation time refers to the period after the emergency occurs and before occupants begin to escape, usually including information exchanges, attachment to belongings and people, coming and going (D'Orazio *et al.*, 2015). In order to reduce this pre-evacuation time, individual interactive system for care homes and hospitals was developed to identify the motions and alert the dangers by individual wearable devices (D'Orazio *et al.*, 2015). Assistance tools were proposed to help evaluate the actual building egressibility conveniently, such as "Egress Enabler" (Smedberg et al., 2022a).

In fact, it is impossible to create an actual emergency to verify the feasibility of hypotheses or proposed strategies, and researchers usually adopt controlled experiments or computer simulations as the main alternatives to actual events (Selamat *et al.*, 2020). The controlled experiments need to recruit volunteers as participants, and computer simulation is more flexible to set diverse egress scenarios. Even kinds of emergencies are likely to occur in residential buildings, only a few researchers have studied the effects of urgency levels on the quality of egress (Haghani *et al.*, 2020).

2.2 The elderly's egress from buildings

Previously, the majority of previous studies seldom distinguished the egress behavior of the elderly from the general people (Du *et al.*, 2018). The egress behavior of particular groups, like the patients (Haghpanah *et al.*, 2021, Yazdani *et al.*, 2021), children (Yao and Lu, 2021), the disabled (D'Orazio *et al.*, 2014), and the elderly (Hanapi *et al.*, 2017, Folk *et al.*, 2020), gained concerns recently due to their unique features of egress. As mentioned in the introduction, compared with able-bodied adults, the elderly may have mobility impairments and memory loss, decreasing their functional capability to egress from buildings (Spearpoint and MacLennan, 2012) and also their willingness to evacuate (Dostal, 2015). So, the elderly would have many difficulties and dangers in escaping under emergency circumstances (Li *et al.*, 2020), and usually require longer times and more assistance to egress from buildings (Lui and Tong, 2010, Rahouti *et al.*, 2021). Quite similar to the general egress, the egress process and behavior of the elderly have been observed and evaluated via actual drills, experiments or computer simulations. For instance, unannounced and announced drills were conducted in the retirement homes to evaluate the evacuation performances of the elderly (Rahouti et al., 2021) and the agent-based model was developed to simulate and evaluate the flood evacuation behaviors of the elderly (Nakanishi et al., 2019).

The elderly declare a lack of reliance on the physical environment and supports from other people during the evacuation (Smedberg *et al.*, 2022b). Improving the physical environment and additional assistance are two main ways to augment the elderly's egress in previous studies. The elderly generally spend much time on pre-evacuation and wayfinding, especially those with cognitive disorders. The building design of escape routes was checked whether suitable for the elderly to reduce the time delay of evacuation (Hanapi *et al.*, 2017). For reducing wrong choices of egress way, a robust wayfinding system based on photo luminescent material tiles was used to provide proper information of escape routes for the elderly (Bernardini *et al.*, 2017). The egress modeling and simulation were widely applied to optimize the building design based on the simulation results (Folk *et al.*, 2020). On the other hand, the actual data from Sweden has proven that more than half of the elderly rely on evacuation assistance from neighbors, first-responders or homecare personnel for survival (Runefors *et al.*, 2021). Kinds of guidance systems or devices were developed to assist the elderly in the egress process (D'Orazio *et al.*, 2014, D'Orazio *et al.*, 2015, Bernardini *et al.*, 2017). The interactive guidance system and matched wearable device can help the elderly reduce 30% of the total egress time (D'Orazio *et al.*, 2015). Meanwhile, the elderly's evacuation time is also prolonged with the proportion increment of dependent elderly, and there is a controllable critical value for the proportion of dependent elderly, which can help properly arrange the distribution of elderly accommodation and safe evacuation of the aged care institutions (Li *et al.*, 2020).

Fall risk is regarded as a major barrier in the elderly's daily life, and researchers concentrated on developing techniques for detecting the indoor and outdoor fall risks efficiently and automatically (Sixsmith and Johnson, 2004, Forbes *et al.*, 2020, Kyriakopoulos *et al.*, 2020, Mrozek *et al.*, 2020). The elderly's fall risk would be extremely high when plenty of residents try to egress from buildings within a short time at the same time (Du *et al.*, 2020).

Table 1 summarizes the main circumstances and objectives that previous studies focused on and concludes their strengths and weaknesses. Even though there were already some researchers who paid attention to the research about the elderly's egress, previous relevant studies are still not as sufficient as the general egress. Most relevant studies only concerned the elderly's special egress behavior under particular emergencies, like fire, but ignored the egress behavior of the elderly would change with different circumstances, since individual evacuation behavior varies with the level of perceived urgency (Haghani *et al.*, 2020). Potential risks would appear during their egress change as well. Furthermore, different egress behavior between the elderly and ordinary residents lead to different egress safety, but seldom research has studied egress safety by comparing it with ordinary residents. Therefore, this study proposes ABEM and indicators of BSEI for the elderly, to explore how building egress safety changes with different residents and different urgent-level circumstances.

Table 1 The summary of characteristics of main relevant studies

Topic	Literature	Circumstance	Research objective	Strength	Weakness
Occupants' egress from buildings	Natapov et al., 2015	Normal	Improving the building circulation	Focus on the building circulation and walkability	Don't distinguish different circumstances
	Shin and Lee, 2019	Normal	Building circulation analysis by indoor walkability index		
	Lee et al., 2020	Normal	Building circulation analysis by indoor walkability index		
	Fu et al., 2021a	Normal	Walkability evaluation of building circulation		
	Kinateder et al., 2018	General evacuation	Influence of exit familiarity and neighbor behavior on the exit choice in the evacuation	Analyze the factors that influence the evacuation	Only consider the general emergency circumstances
	Fu et al., 2019	General evacuation	Influence of emergency signage on the evacuation		
	Lin et al., 2020	General evacuation	Influences of spatial knowledge on the evacuation		
	Kodur et al., 2020	Fire evacuation	Critical factors influencing the fire evacuation		
	Fu et al., 2021b	Fire evacuation	Critical factors influencing the risky decision in the fire evacuation		
	Gerges et al., 2018	Fire evacuation	Human behavior during the fire evacuation	Analyze human behavior during the evacuation	Only a few studies concern the impacts of different circumstances on human behavior
	Rendón Rozo et al., 2019	General evacuation	Designing the building evacuation plans based on human behavior		
	Rahouti *et al.*, 2020	Fire evacuation	Human behavior during the fire evacuation drills		
	Haghani et al., 2020	**High and low levels of urgency**	Evacuation behavior under different urgency		
	Kodur et al., 2019	Fire evacuation	Assessing fire hazards in buildings	Assess the building performance during the evacuation	Only consider the general emergency circumstances
	Smedberg et al., 2022a	General evacuation	An instrument to assess the egressibility		
Egress of the elderly	Lui and Tong, 2010	Fire evacuation	Fire safety in residential care homes	Analyze the factors that	Ignore the impacts of the

	Spearpoint and MacLennan, 2012	General evacuation	The effect of aging and less fit population on the ability to egress buildings	influence the evacuation of the elderly	urgency of circumstance
	Li et al., 2020	General evacuation	Effect of the Distribution of Dependent Elderly on the evacuation		
	Runefors et al., 2021	Fire evacuation	Factors on survival and evacuation of the elderly		
	Dostal, 2015	General evacuation	Willingness and ability of homebound older adults to evacuate		
	Nakanishi et al., 2019	Flood evacuation	Simulating the flood evacuation behavior	Assess the evacuation of the elderly	Ignore the urgency of the circumstance in the assessment
	Rahouti et al., 2021	General evacuation	Assessment of the evacuation performance of elderly evacuees		
	Smedberg et al., 2022b	Fire evacuation	Egressibility of the elderly		
	Bernardini et al., 2017	Fire evacuation	Indoor evacuation wayfinding for the elderly based on photoluminescent material	Develop the assistances to help the evacuation of the elderly	Do not develop for circumstances with different urgencies
	Hanapi et al., 2017	General evacuation	Suitability of escape route design for the elderly		
	Folk et al., 2020	Fire evacuation	Emergency egress design for the elderly		
	D'Orazio et al., 2014	General evacuation	Designing guidance system for the elderly based on the evacuation simulation		
	D'Orazio et al., 2015	Fire evacuation	Proposing an interactive system to reduce the pre-movement time of the elderly		
	Du et al., 2018	General evacuation	Fall accidents during evacuation	Focus the fall risks	Do not analyze other types of risks during the evacuation
	Du et al., 2020	General evacuation	Fall risks in the evacuation		
This study: ABEM-based BESI of the elderly		Normal, low-urgent, and high-urgent circumstances	1. Simulating the egress process under circumstances with **different urgencies**; 2. **Comparing the egress** of the eldrly and ordinary residents; 3. Evaluating the building egress safety for **the elderly**.		

3. Research methodology

In order to compare the building safety performances for the elderly's egress under different circumstances, we propose research methodology containing three main steps: (1) developing ABEM to simulate the process of residential egress from the building; (2) setting diverse egress circumstances with different urgent levels; (3) proposing a series of indicators and determining weights to compute the BESI for the elderly based on physical features of the building and simulation outputs. The logic of this research methodology is illustrated in Figure 1.

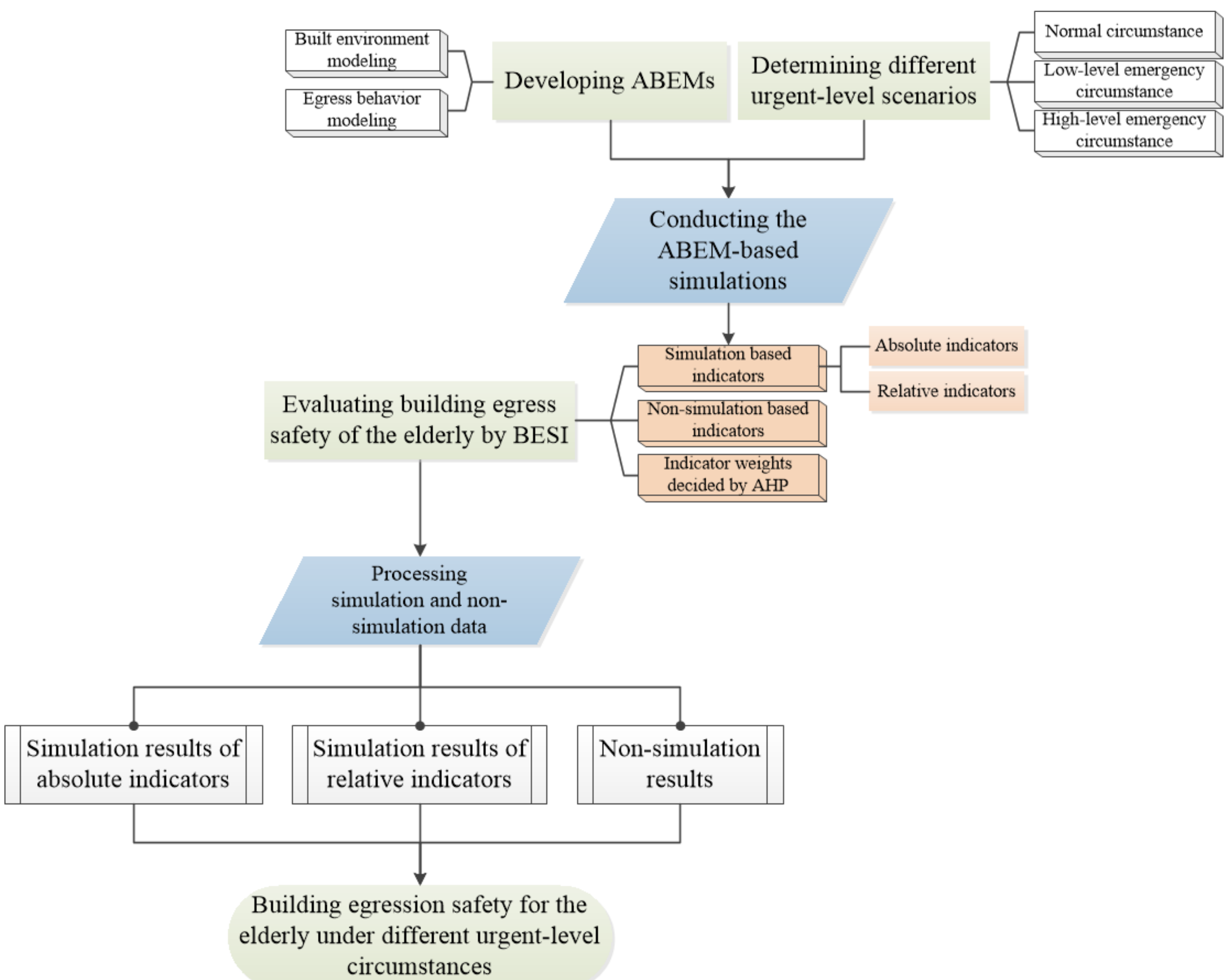


Figure 1 The logic map of the research methodology

3.1 Developing agent-based egress models (ABEMs)

The agent-based model is a class of computational models for simulating the actions and interactions of autonomous agents with a view to assessing their effects on the system as a whole. Due to its ability to randomly simulate individual behavior and interactions with other individuals and environments, the agent-based model is widely used to model complex systems containing considerable agents (Marzouk et al., 2019), such as emergency simulations of buildings and infrastructure.

Due to its good adaptability to kinds of circumstances and different population groups, Anylogic is adopted to develop the ABEM, and its pedestrian library is helpful to simulate dynamic pedestrians based on physical rules. In order to develop ABEM in the Anylogic, the physical environment and individual behavior logic are required to be established. The way to model the physical environment and the egress behavior logic of the elderly and ordinary residents under different urgent-level circumstances and to extract simulation results from the software are elaborated as follows.

3.1.1 Built environment modeling

The built environment should be consistent with the actual building. By importing the CAD drawings, scales of building components can be modeled in the software, including exterior walls, interior walls, floors, doors, elevator rooms, stairs, and any other necessary building details associated with the egress process. Other components and advanced information without direct relations to residents' egress can be left out in the built environment modeling, like pipe, HVAC, detailed material, structure. Furthermore, the built environment modeling should follow several rules:

a. Besides the common exit, another emergency exit is required to set on the first floor of buildings. This emergency exit is closed normally, and should open for quick evacuation under emergency circumstances.

b. When modeling the built environment of multistory residential buildings, each floor can be regarded as an agent in the Anylogic. It is one quick way to model the built environment of mid-rise or high-rise buildings by duplicating or extending the floor agent.

c. Each agent of single floor, except the ground floor, should contain the ground of this floor and the stairs to the lower floor. So, two height levels are set in the agent of each floor: the upper level is located at the height of current floor, and the lower level is at the end of the stairs, also at the same height of the lower floor.

3.1.2 Egress behavior modeling

In the egress behavior modeling, features of egress agents and egress logics need to be defined. Generally, there are two basic ways to egress from buildings: taking the stairs or the elevator. Even though the detailed egress logic would vary with different buildings, but the logic of taking the stairs and the elevator are similar. Thus, the logic of two basic egress ways is provided as shown in Figure 2.

a. Egress agents: the elderly and ordinary residents

Besides the agent of single floor in the built environment modeling, other agents are essential to represent residents in the egress behavior modeling. Since the egress process of the elderly is inevitably affected by ordinary residents, both the elderly and ordinary residents must be considered in the egress behavior modeling. As a result, two kinds of agents are developed for "the elderly" and "ordinary residents". According to the population report of United Nations (United Nations, 2019), the elderly refers to the resident over 65 years old, while the ordinary resident refers to the normal adult living in the buildings. Compared with ordinary residents, the elderly generally have a lower gait speed, longer response time and different choices of egress behavior due to their declining physical conditions. Even though the gait speed of the elderly varies with individual age, weight, height, gender, health condition and other features, the gait speed cut-off of the elderly is usually set as 0.8 meters per second (Mendes *et al.*, 2018). Apart from the gait speed, further human physical parameters of agents are considered by taking advantage of Anylogic software. The agents of the elderly and ordinary residents are set up based on the pedestrian library, which assists in assigning each agent with individual properties (appearance, size, height), preferences, and states and simulating agents' movement according to the social force model (Bina & Moghadas, 2021). More specifically, the detailed features of the two agents should be assigned according to actual applications and egress plans under different urgent-level circumstances as elaborated in 3.2.

b. Egress behavior: taking the stairs

As shown in Figure 2(a), the logic is modeled to realize agent's egress via the stairs by utilizing the process modeling library and the pedestrian library of the Anylogic. Generally, there are two types of situations to enter the stairs of each floor except the ground floor, one is the resident who lives in units of the current floor needs to enter the stairs, and the other is the resident who comes from the upper floor needs to pass by the stairs of current floor. Therefore, during modeling the egress behavior of taking the stairs, the agents of residents are set to go to the beginning step of the stairs, then reach the final step of the stairs, changing their location from the upper level to the lower level in the agent of current floor. Once they arrive the lower level of current floor, residents are set to immediately exit the agent of current floor and enter the agent of the next floor.

c. Egress behavior: taking the elevator

The logic of egress via the elevator can be developed by integrating process modeling library, pedestrian library, agent palette, and statechart, as shown in Figure 2(b). When egressing from buildings via the elevator, residents would directly go to the elevator room of their floor, and the units of these floors would be pedestrian sources of the elevator. After residents arrive at the elevator room, they should queue up to wait for the elevator. Once the door of elevator opens, residents enter the elevator in order of arrival. Then the door would be closed and more residents should stop entering when the number of residents in the elevator has reached the maximum elevator capacity or no more residents arrive and queue up within 5 seconds. This logic is realized by setting the blocks of “queue” and “hold” in the process modeling library, the variable to record the enter time of last resident, the event for automatic updating, and Java code of conditional statements in the statechart in Figure 2(b). The elevator operation is represented by “delay” block in process modeling. Residents are delayed in this block to simulate the time period that the elevator moves from the current floor to the ground floor. Finally, exiting refers to exiting the agent of the current floor, meanwhile, entering the ground floor.

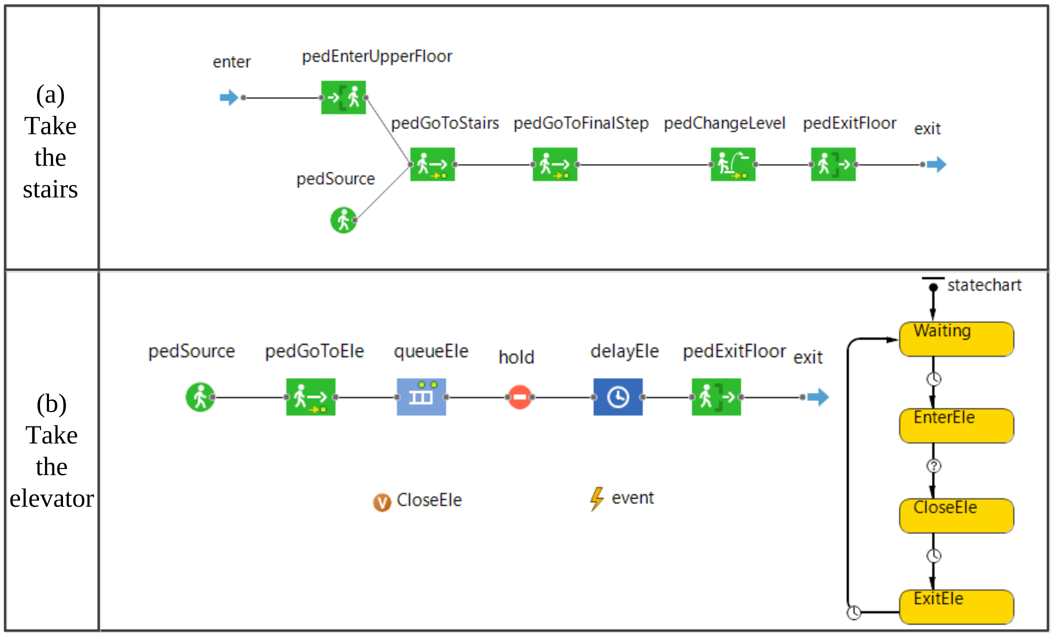


Figure 2 The basic logic of egress behavior via elevators and stairs

3.1.3 Data statistics, collection and export

The successful development and running of the ABEM is not the end of simulation. The final step is to export required simulation results after conducting the ABEM. In terms of the evaluation of "BESI" which is explained in 3.3, the necessary data should contain the beginning time and the end time of egress of each resident, real-time records of the flow rate of the elevator room and the stairs on specific floors, and real-time records of the density of the elevator room and the stairs on specific floors. Figure 3 illustrates the extraction process of the simulation results and presents examples to extract flow rate and density data.

In order to record and export the beginning time and end time of the whole egress process for each resident, variables of time and agent ID are created to assign data, datasets are set to store these real-time records temporarily, and java codes are inserted in specific blocks to collect, assign and export the real-time records. For instance, when one resident begins to egress, the actual time and its ID is assigned to variables “time” and “id” by java codes “t=time(); id=p.getId();”; then these data are added to datasets by java codes “dataset.add(t,id);”; finally when the simulation ends, all data in the dataset are exported to the excel file by “excelFile.writeDataSet(dataset,1,1,1);” which refers to write data of “dataset” in “excelFile” starting at the first sheet, the first row, and the first column. Since the flow rate and density are two important indicators of “BESI”, real-time flow rate and density in the elevator rooms and the stairs are recorded by graphical markups of “Pedestrian Flow Statistics” and “Polygonal Node” respectively. As shown in Figure 3, variables of time, flow rate and density are created, and datasets are built to store the time series data. Events with Java codes are executed every second to collect the real-time flow rate and density data and added to datasets.

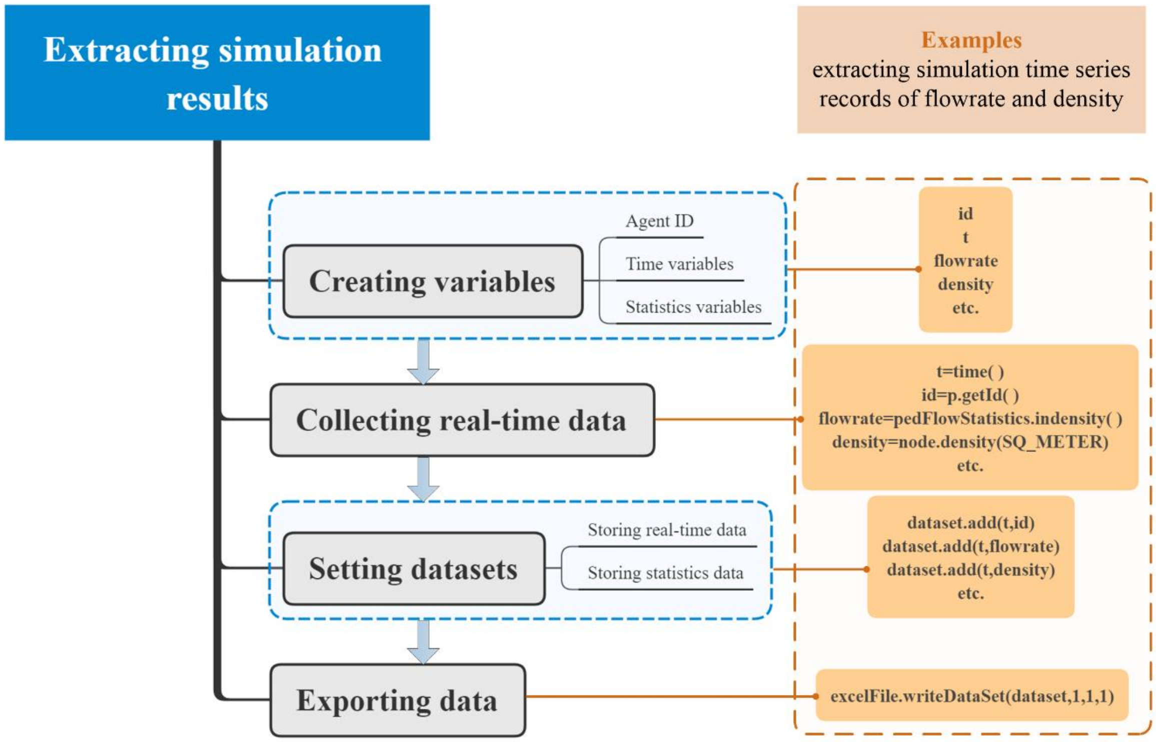


Figure 3 The flowchart of the simulation results extraction process

3.2 Determining different urgent-level circumstances

In reality, residential egress behavior, even the built environment of residential buildings, would be various with different urgent-level circumstances. Circumstances with three levels of urgencies are defined and egress plans are set to guide residents to egress from buildings quickly under different circumstances.

a. Normal circumstance

The normal circumstance means the usual circumstance in daily life without unusual things happening. Owing to their declining capacity, the elderly generally rely on elevators to egress buildings in their daily lives. Generally speaking, ordinary residents living on higher floors would also take elevators to egress, while ordinary residents on lower floors usually prefer to take the stairs. The residential egress is a random action in the whole day. The Poisson's distribution is widely used distribution to measure how many times random events are likely to occur within a certain time, which is quite suitable to describe the random egress of residents. So, it supposes that the departure time of all residents coincides with the Poisson's distribution of quite a lower parameter.

b. Low-level emergency circumstance

As mentioned above, a limited time would be available for residents to evacuate from their homes under low-level emergency circumstance. The dangers would not threaten residential lives immediately, and the elevator can operate normally. Under this circumstance, the elevator usually is reserved for the elderly, while ordinary residents without impaired mobility should take the stairs to egress. All emergency exits should open to help quick egress. Before the emergency occurs, residents' location, behavior, condition and other elements would affect the departure time of residents to egress within a limited period. Since these elements of residents are random as well, we can suppose their departure time from homes is also the Poisson's distribution and their interarrival time coincides with the exponential distribution with higher parameter, due to the limited period for egress.

c. High-level emergency circumstance

When high-level emergency occurs in residential buildings, like fire, earthquake, explosion, or other extreme dangers, residents should leave the building as soon as possible to survive from the emergency. Due to the unstable building condition, the elevator is unsafe to operate. Once notice the notifications or alerts of emergencies, all residents should follow the egress plans and emergency exit signs and go downstairs via the stairs quickly. Similar to low-level emergency, locations, behavior, condition and other elements of residents are random before they begin to egress, so residential departure time should follow Poisson's distribution as well. Since high-level emergency is more dangerous, residents must leave their homes immediately and their departure time follows the Poisson's distribution with extreme high parameter. Owing to different reaction times to alerts, the interarrival of departure time of the elderly and ordinary residents would be different. Thus, we suppose the interarrival time of ordinary residents coincides with the exponential distribution with higher rate parameter than the interarrival time of the elderly.

3.3 Evaluating building egress safety for the elderly by BESI

Several indicators have been proposed to evaluate building safety performance in the process of residential egress in previous research, such as critical features of built environment and simulation results. Consequently, the indicators widely used in safety evaluation are summarized into two main types. One type of indicators assesses the safety performance based on the physical environment or other objective facts of residential buildings, like the floor plan, exit sign, egress drill, segregation facility. One type of indicators is based on the results of simulations or experiments, which means the evaluation data need to be obtained from simulations or experiments, such as egress time, congestion index, conflicting points, level of service (LOS) (Singh and Jain, 2011, Ashraf Tashrifullahi and Hassanain, 2013). Even though the simulation can be conducted efficiently to present the whole egress process on the computer, the egress simulation cannot consider all elements and factors and essential assumptions are inevitable. It is hard to reveal exact safety degree of built environment only by simulations and experiments. Therefore, this study decides to integrate indicators of ABEM-enabled simulation and indicators of non-simulation as supplements to evaluate building egress safety for the elderly.

Based on the summary of indicators used previously, expert interviews are conducted to (1) ensure the effectiveness of proposed indicators in this study, (2) provide valuable advice on indicators for the elderly, (3) express opinions on indicator weights under each circumstance and thresholds of BESI. Regarding opinions of expert participants, two principles should be considered to judge the effectiveness of potential indicators: the indicators with similar concepts should be removed, and the indicators should be suitable to be applied in different circumstances. For instance, “safety margin” is calculated based on actual egress time and available egress time. It is unnecessary to adopt actual egress time and safety margin simultaneously. Since there is no limit to available egress time normally, safety margin is only suitable for assessing egress performance under emergency circumstance. Thus, the actual egress duration is adopted rather than the safety margin. Besides the absolute indicators, experts confirmed the significance of relative indicators to judge whether the building is friendly to the elderly’s egress, like the increment of egress duration of the elderly compared with ordinary residents. The final indicators to evaluate building egress safety for the elderly and their scoring standards are listed in Table 2. Furthermore, indicators play different roles in the egress safety for the elderly under different circumstances, so it is essential to determine indicator weights scientifically based on experts’ opinions. The analytic hierarchy process (AHP) method, a frequently used method in MCDM problems, is adopted to collect the experts’ opinions through the questionnaire and transfer these opinions to quantitative data. Finally, BESI can be computed by scores and indicator weights to uncover how safe the building is for the elderly, and the thresholds should be set to help comprehend and apply BESI in practice.

Table 2 Building egress safety indicators for the elderly

Domain	Indicator	Description	Scoring standard	Source
Simulation	Average egress duration	The average total egress duration of the elderly on each floor.	10: Egressing within 2 minutes. Deleting 2 scores each more minute.	(Shen, 2006; Marzouk and Mohamed, 2019)
	Increment of average egress duration	The average increment of total egress duration of the elderly compared with ordinary residents.	10: No increment. Deleting 2 scores each more minute.	Interview
	Proportion of the later half egress	The proportion of the elderly who are the later half of residents to egress building among all elderly.	10: Zero percent. Deleting 1 score each more 10% increment.	Interview
	Increment of the proportion of the later half egress	The increment of the proportion of later half egress of the elderly compared with ordinary residents.	10: No increment. Deleting 2 scores each more 10% increment.	Interview
	Ratio of low/medium/high flow rate	The ratios of low, medium and high flow rate (person/minute/meter) in the elevator room and the stairs of each floor (Flow rate of LOS A/BC/DEF refer to low/medium/high for the elderly according to the Appendix).	10: 100% low flow rate. Deleting 1 score per 10% high flow rate, 0.5 scores per 10% medium flow rate.	(Marzouk and Mohamed, 2019)
	Ratio of low/medium/high density	The ratios of low, medium and high density (person/square meter) in the elevator room and the stairs of each floor (Density of LOS A/BC/DEF refer to low/medium/high for the elderly according to the Appendix).	10: 100% low density. Deleting 1 score per 10% high density, 0.5 scores per 10% medium density (Coefficients: the elevator room-1.0, the stairs-0.8)	(Ashraf Tashrifullahi and Hassanain, 2013)

Non-simulation	Periodical egress drills	The exercise or training organized regularly, in which residents practice what they should do under emergency circumstances.	10: Regular. 5: Seldom. 0: Never.	(Marzouk & Mohamed, 2019)
	Exit signs	The signs placed on the wall or the ground to give information about the exit direction.	10: Clear sign. 5: Unclear sign. 0: No sign.	(Marzouk & Mohamed, 2019)
	Segregation facilities	The facilities set to separate people from dangers.	10: Yes. 0: None.	(Marzouk & Mohamed, 2019)

4. Case study and results

4.1 Case description and modeling

A common residential building is chosen as the study case to develop the ABEM to ensure its feasibility and validity. As the typical residential building, this case contains ten floors with the same floor plan except for the ground floor, two elevators with the maximum capacity of 5 people, and two staircases. The detailed floor plan is illustrated in Figure 4. There are four residential units on each floor, and a fire-proof door is set in the hallway between entrances of two staircases to segregate dangers. In terms of the exit signs, when high-level emergencies happen, residents in units A and B should egress from the left staircase and residents in units C and D from the right staircase.

As mentioned in 3.1, the built environment of residential buildings and the egress behavior of residents should be modeled in the ABEM development for the study case. At first, according to the floor plan of this building, the built environment of egress can be modeled in the Anylogic (Figure 5). Secondly, two types of agents are defined, containing agent appearances, populations, gait speeds, and departure time distributions. We suppose the overall residents of the building are 180, and the ratio of the elderly to ordinary residents is one to four. Considering the actual situations, the gait speed of the elderly is definitely different from ordinary residents, the normal gait speed of residents is also different from gait speed under emergencies, and the distributions of interarrival time of residential departure change with circumstances. The circumstance is more urgent, the gait speed is faster, and the distribution of residential departure time is more concentrated. Therefore, the normal walking speed is set as the egress speed under the normall circumstance, the quick walking speed is set as the egress speed under the low-level emergency, the indoor running speed is set as the egress speed under high-level emergency, and all the speeds are measured by 20 participants who were selected randomly. In order to take the gender and age differences into the model, the participants should be diverse to contain 5 old males, 5 old females, 5 adults males, and 5 adult females. People who apply ABEM and BESI in their own cases are recommended to refer to the speed data of this study and collect speed data for their cases. In section 3.2, we supposed the residential departure time follows the Poisson's Distribution, and the elderly would show longer reaction time than ordinary residents under the high-level emergency. So, the exponential distribution can be used to define the distribution of interarrival time of residential departure. Due to the restriction of data collect, the parameter is set based on the interview and observation of participants. A series of basic settings for residential agents are supposed in Table 3.

At last, the different circumstances should be defined. According to National Building Standard, buildings must prepare egress plans for occupants in advance to cope with emergency circumstances. The field survey shows only ordinary residents living under the fourth floor prefer to egress via the stairs, while ordinary residents would like to take the elevators to egress. According to the actual condition, the egress plan for three circumstances of the case is illustrated in Figure 6, and the detailed egress logics of ABEMs can be modeled by expanding basic logics based on the egress plan and floor plan of study case.

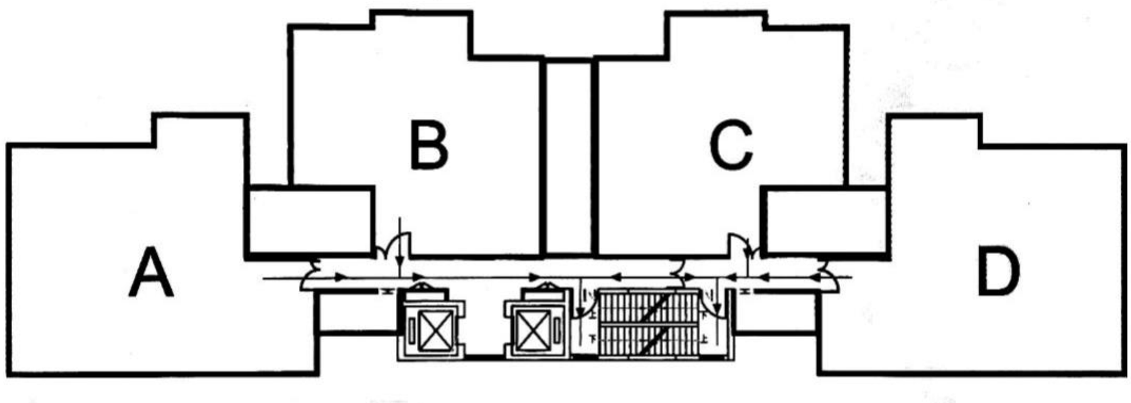


Figure 4 The floor plan of the study case (second floor and above)

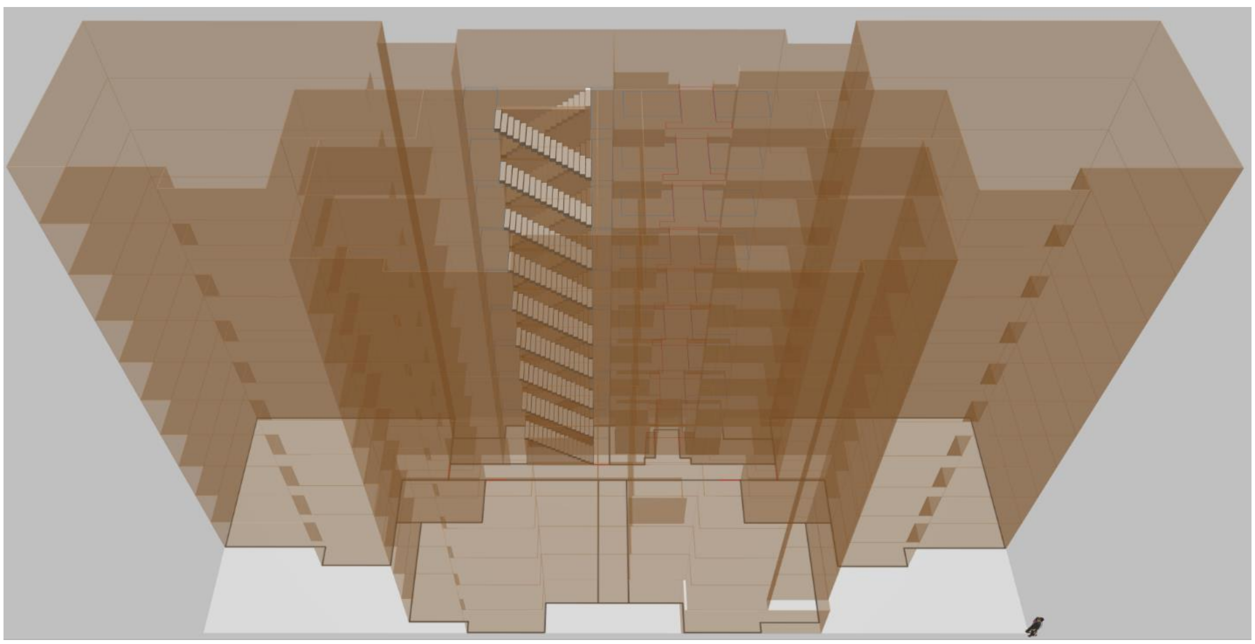


Figure 5 The built environment modeling for ABEM

Table 3 Basic settings of ABEM under diverse circumstances

Parameter \ Diverse circumstance	Normal	Low-level emergency	High-level emergency
Distributions of interarrival time of residential departure	*X*~*E*(0.2)person/min	*X*~*E*(1)person/min	Ordinary residents: *X*~*E*(3)person/min The elderly: *X*~*E*(1.5)person/min
Egress speed of the elderly	*U*(0.8-1.0)m/s	*U*(1.1-1.3)m/s	*U*(1.6-1.8)m/s

Egress speed of ordinary residents	U(1.0-1.2)m/s	U(1.5-1.7)m/s	U(2.2-2.5)m/s

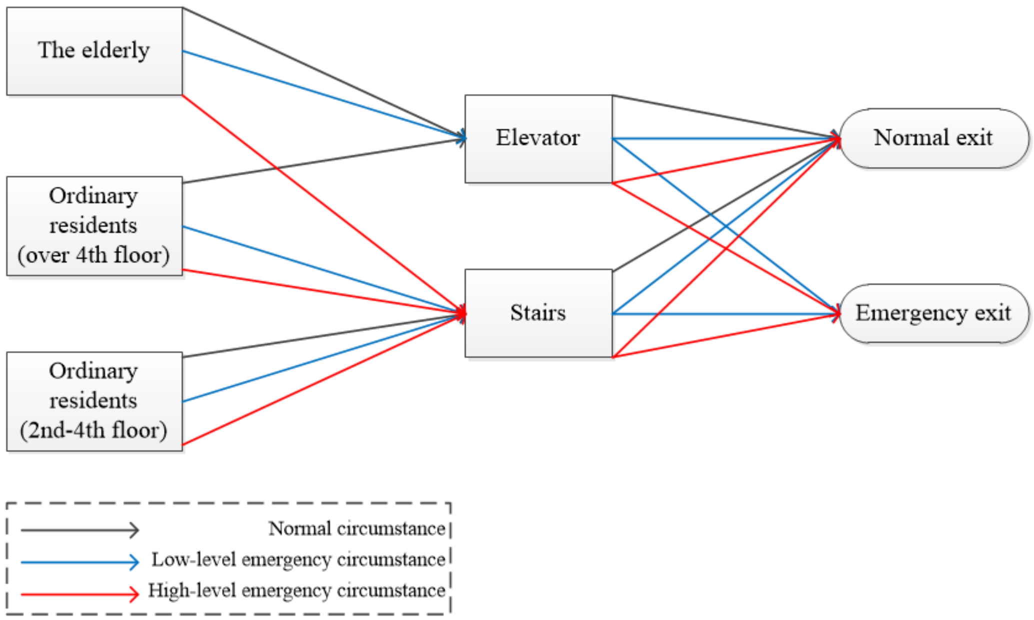


Figure 6 The egress plan of the study case

4.2 Simulation results of the ABEM

The completed ABEM under diverse circumstances is developed in the Anylogic based on the information and actual condition of the study case, containing its physical environment, the egress logic, parameters, variables, events, datasets, java codes, and other essential settings. In order to verify the ABEM, the simulation based on the ABEM have been conducted ten times and extracted the simulation data every time. Since the agent behavior are random following the restriction rules, the simulation results would not be exactly the same every time. By comparing all simulation results, it is convenient to ensure the stability of ABEM. The simulation results are recorded and exported directly after running ABEMs. These exported data include the ID number, floor number, beginning time of egress and end time of egress of each resident, also real-time flow rate and density of the elevator room and the stairs on each floor during the whole egress process. According to these exported data, we illustrate the simulation results under three circumstances in Figure 7, 8, 9 and 10. Figure 7 presents the average egress time of residents on each floor, figure 8 presents the proportion of later half egress on each floor, figures 9&10 present the distribution of density and flow rate in different building spaces.

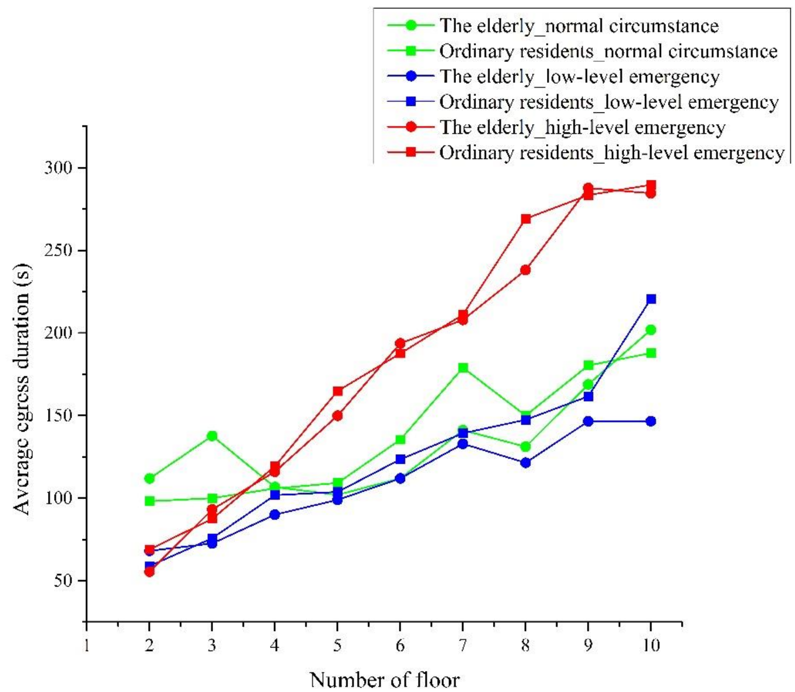


Figure 7 The summary of average egress time under diverse circumstances

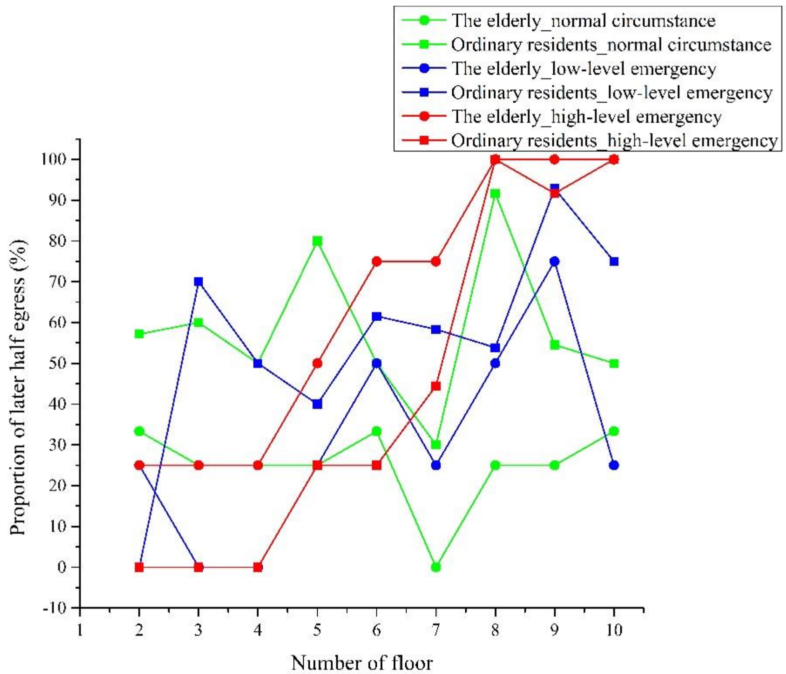
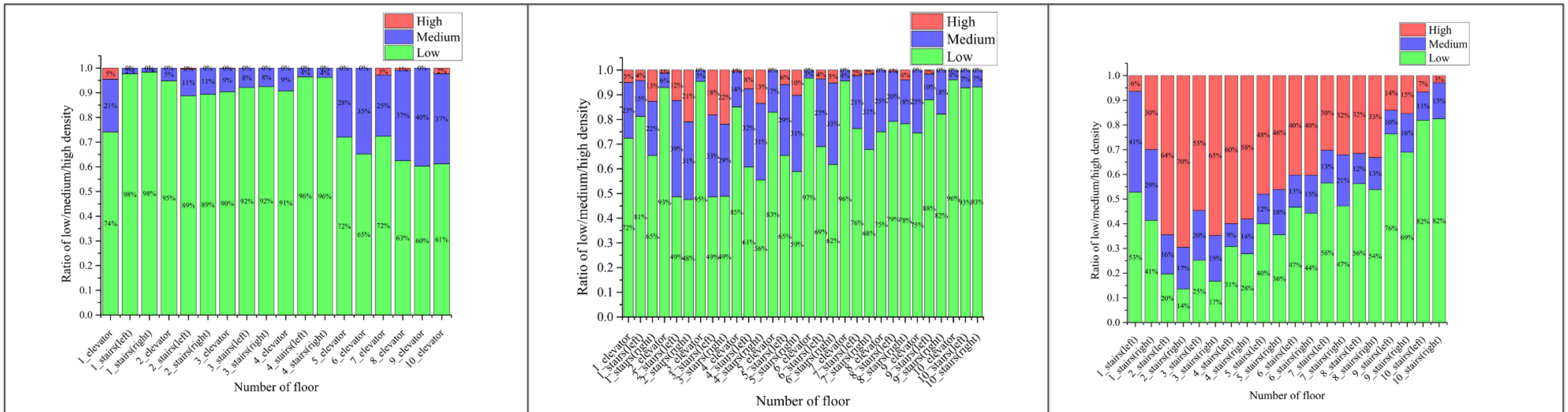
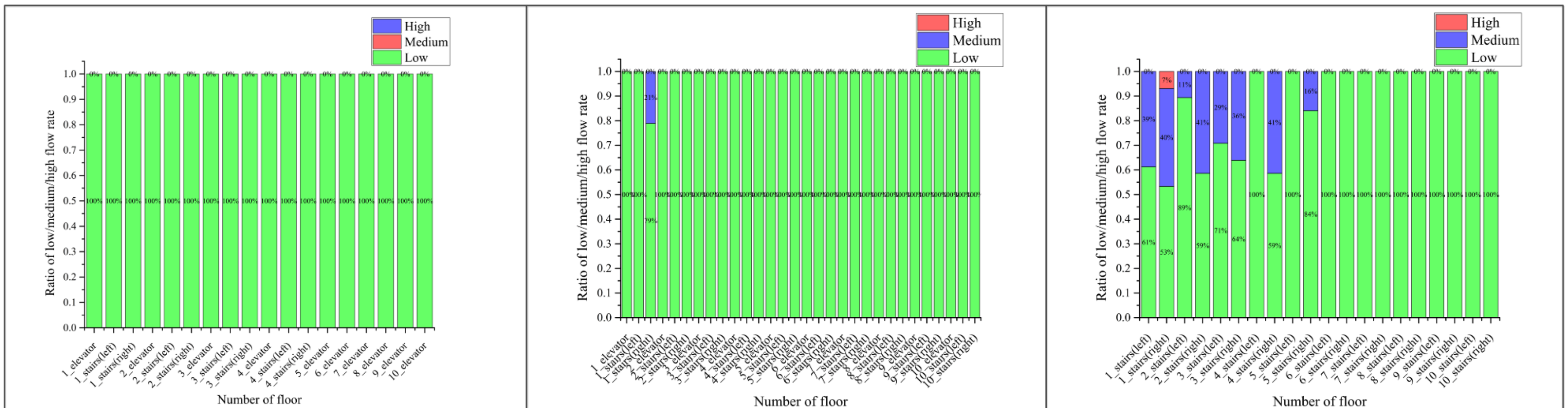


Figure 8 The summary of later half egress under diverse circumstances



(a) Density performance under the normal circumstance | (b) Density performance under the low-level emergency | (c) Density performance under the high-level emergency

Figure 9 The summary of density in the building under diverse circumstances



(a) Flow rate performance under the normal circumstance | (b) Flow rate performance under the low-level emergency | (c) Flow rate performance under the high-level emergency

Figure 10 The summary of flow rate in the building under diverse circumstances

4.3 Results of indicator weights and BESI of building and each floor

Eight experts with sufficient experience were invited to express their opinions on the importance and validity of indicators in overall building egress safety for the elderly. The basic information of experts is shown in Table 4. All experts were asked to mark symbols to make pairwise comparisons based on their knowledge and experience. The results of indicator weights are calculated by the AHP approach, as shown in Table 5. The weights indicate that indicators have various importances in the evaluation under different circumstances. The importance of non-simulation-based indicators increases as the urgent level of circumstance increases, because only simulation results are hard to reflect the influence of other building facilities, especially when emergencies occur. More specifically, building egress safety of the elderly normally relies on performances of egress duration, increment of egress duration compared with ordinary residents, and exit signs in the building; when low-level emergency happens, egress duration, density, flow rate, and exit sign are more critical to the elderly's egress; and when high-level emergency happens, their earlier egress, increment of earlier egress, essential segregation facilities and egress drills become more critical.

Table 4 Basic information of experts

Category	Type	Percentage
Age	<30	12.5%
	30-60	62.5%
	>60	25%
Degree	Bachelor's degree	25%
	Master's Degree	25%
	Doctoral Degree	50%
Occupation	Professor	37.5%
	Researcher	37.5%
	Official	25%
Work experience	<5 years	25%

	5-10 years	37.5%
	>10 years	37.5%
Expertise field	Building Technology	50%
	Disaster reduction	25%
	Property management	25%

Table 5 The weights of indicators of building egress safety for the elderly

Indicator \ Circumstance	Normal	Low-level emergency	High-level emergency
Simulation-based indicator	0.875	0.889	0.800
Average egress duration	0.211	0.235	0.024
Increment of average egress duration	0.438	0.449	0.032
Proportion of the later half egress	0.030	0.027	0.282
Increment of the proportion of the later half egress	0.025	0.051	0.500
Ratio of low/medium/high density	0.091	0.161	0.077
Ratio of low/medium/high flow rate	0.205	0.077	0.085
Non-simulation-based indicator	0.125	0.111	0.200
Periodical egress drills	0.240	0.221	0.297
Exit signs	0.550	0.711	0.164
Segregation facilities	0.210	0.068	0.539

Meanwhile, experts are required to show their opinions about how to set the threshold of BESI for convenient application in actual cases. Based on experts' advice, the thresholds of acceptable and good BESI are set as 6 and 8, signifying that the building with a BESI score over 6 is regarded to provide an acceptable egress safety for the elderly, and a BESI over 8 means the building with good egress safety for the elderly. The BESI can be calculated based on simulation results, building information, and indicator weights. Figure 11 illustrates the building egress safety indexes for the elderly under three circumstances, and Table 6 shows the detailed scores of all indicators.

The overall BESI is highest under the low-level emergency, that under the normal circumstance is slightly lower, and both two BESIs are regarded as good egress safety, while the building performs worst under high-level emergency is much lower, but still acceptable. It indicates this residential building can provide a quite safe egress process for the elderly unless an emergency with high urgency happens. More specifically, the building performs much better in the simulation-based indicators under normal circumstance and low-level emergency than those under high-level emergency. If only considering the simulation-based indicators, the building egress safety is even unacceptable under the high-level emergency. By comparing the detailed scores of simulation-based indicators, residential building gets the highest scores of most indicators under the low-level emergency, except the two indicators about the later egress; but the building scores of most indicators are lowest among scores under the high-level emergency. In the domain of non-simulation, the score of each indicator would not change with circumstances, but the same score would play different roles under different circumstances. As shown in Figure 11, the BESI score of this building is highest under high-level emergency, which is just an acceptable score, even unacceptable under low-level emergency. This residential building is equipped with good segregation facilities, which are important to segregate dangers only when an emergency occurs, while the poor drill and exit signs weaken the building egress safety under low-level emergency.

Furthermore, as shown in Figures 7-10, each floor of the building might perform quite dissimilarly, such as the average egress time of the elderly vary with the floor where they live on, and differences in the egress process between the elderly and ordinary residents also change with the floor. Therefore, the BESI can be computed for each floor to assist the elderly in judging the safety of the floor they live on. Figure 12 presents the changes of BESI with the floor of the building case.

It is found that this building of study case is able to provide good egress safety for the elderly on the most floor under the normal circumstance and low-level emergency, but the egress process is not stable and safe enough for the elderly living on floors higher than fourth when an extreme emergency happens. According to sub-scores of BESI, the elderly are recommended to choose units on the lower three floors of this building for their later lives.

Table 6 The detailed scores of simulation-based indicators under diverse circumstances

Domain	Indicator	Circumstance		
		Normal circumstance	Low-level emergency	High-level emergency
Simulation	Average egress duration	8.667	9.111	7.111
	Increment of average egress duration	9.111	9.778	9.333
	Proportion of the later half egress	7.000	6.667	3.333
	Increment of the proportion of the later half egress	10.000	9.667	7.444
	Ratio of low/medium/high density	8.200	8.800	3.378
	Ratio of low/medium/high flow rate	10.000	10.000	6.458
Non-simulation	Periodical egress drills		5	
	Exit signs		5	
	Segregation facilities		10	

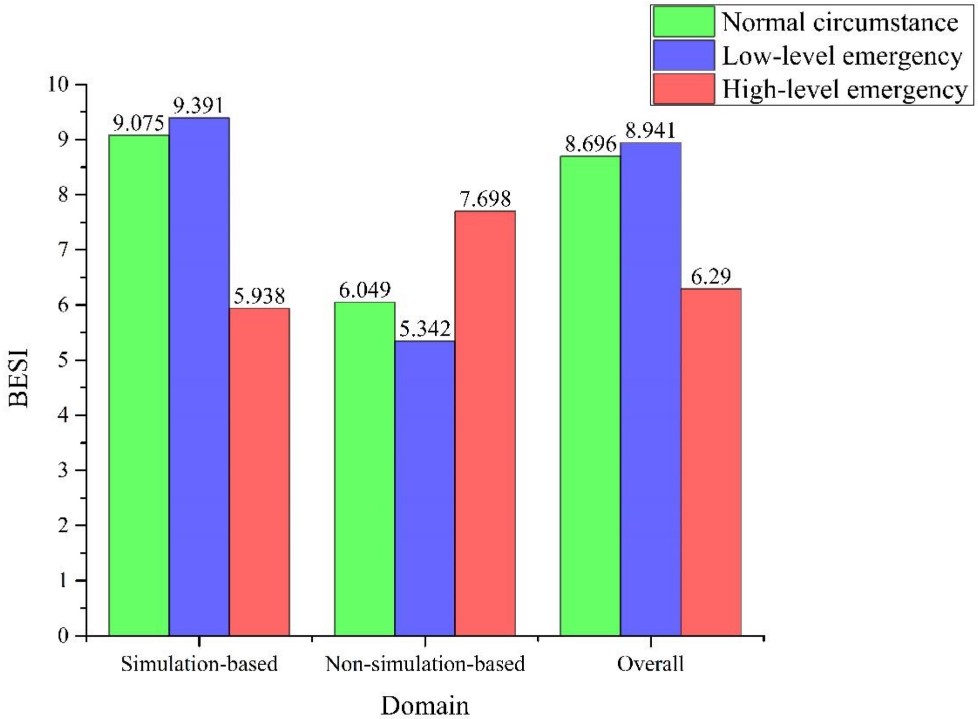


Figure 11 The building egress safety index for the elderly under diverse circumstances

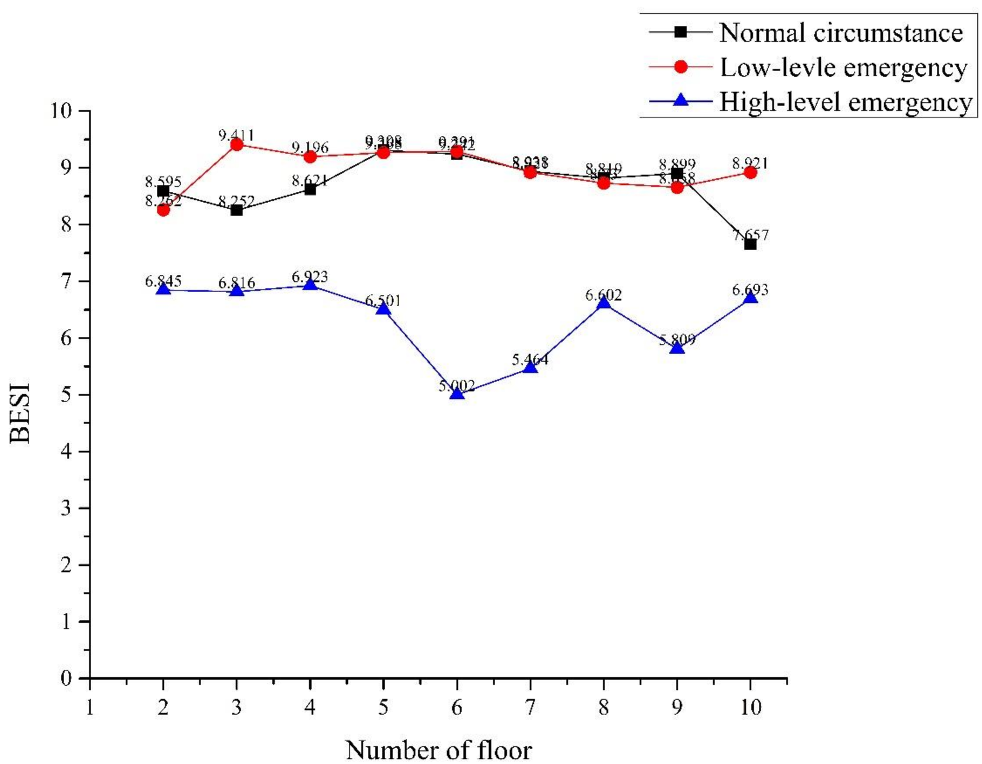


Figure 12 The sub-scores of BESI for the elderly on different floors

5. Discussion

5.1 Performances of the building egress safety of the elderly

This study mainly focuses on the building performance in the egress safety of the elderly. From the original simulation and BESI results, kinds of effects can be explored and analyzed deeply.

(1) Diverse circumstances with different urgent levels

By comparing the building egress safety indices in Figure 11, the building performance changes with the circumstances. The building egress would be much safer to the elderly under normal circumstance and low-level emergency than under high-level emergency. More specifically, under high-level emergency, the building performance in the domain of non-simulation is the highest, while the building performance in the domain of simulation is the lowest. What's unexpected is that the elderly obtain a bit better safety under low-level emergency than normal circumstance.

Based on analyses of detailed scores of BESI, egress plans, egress behavior, and significances of indicators under diverse circumstances are considered as main reasons for various egress safety of the elderly. When high-level emergency occurs, leaving the building as early as possible is very important, since the later egress, the more dangerous they are. Unlike the egress plans under normal and low-level circumstances, the elderly on the fifth or higher floors have to egress via the stairs, rather than the elevator. The simulation results show over 50% of the elderly on these floors egress building late, and on most floors, this proportion of the elderly is much higher than other residents. Meanwhile, owing to the later egress, the elderly have to bear high density and flow rate in the stairs of second to fourth floors, which cause great danger as well. Fortunately, the residential building has equipped segregation facilities and other auxiliary facilities that can significantly reduce the risks of emergencies.

Furthermore, the building performanceunder low-emergency is slightly better than normal circumstance. In daily life, the elderly leave by taking the elevator, and their egress safety is mainly reflected by the egress duration, density, and flow rate of the elevators. However, other residents living on lower floors take relatively fixed and short time to egress by the stairs, while the egress duration of the elderly living on lower floors is more uncertain; other residents living on higher floors choose to share the elevator with the elderly, leading to higher density in the elevator room. On the contrary, when low-level emergency happens, egress duration, earlier egress, density, and flow rate are essential to the elderly's safety during the process of egress within a limited time. The egress plan reserves the elevator for the elderly to ensure their convenience of egress, more population of other residents have to egress by the stairs. Compared with normal circumstance, there are significant improvements in egress duration and density from other residents' egress to the elderly's egress. Moreover, unlike the normal circumstance, earlier escape is much more essential to low-level emergency. The ratio of the elderly, who belong to the later half of all residents egressing building successfully, increases the egress danger. In summary, the egress plan for low-level emergency makes the egress of the elderly even slightly safer than normal egress in daily life.

(2) Absolute performances of building egress safety

Besides the information retrieved from the BESIs, more information can also be explored from the simulation results in detail. The absolute performances means only the building egress safety for the elderly are focused, without the comparison with ordinary residents. According to the evaluation indicators of building egress safety for the elderly, the absolute performances include the averaged egress duration of the elderly, the proportion of later egress of the elderly, the density, and the flow rate of key points in the egress paths of the elderly.

Firstly, the averaged egress duration of the elderly is quite dissimilar under different circumstances as shown in Fuigure 7. Normally, due to the randomness of residents' egress, the total egress duration of the elderly fluctuates between 100 seconds to 200 seconds. The low-level emergency reduces the uncertainty of the total duration that the elderly spend on their egress and makes their egress more quickly. The range of the egress duration is between 60 seconds to 150 seconds. However, the elderly have to suffer from taking the stairs and the congestion under the high-level emergency, so the range of their egress duration is larger, and the average egress duration of the elderly on each floor increases with the number of floors. Secondly, the later egress is one of the most critical indicators to decide the survival from high-level emergencies. The living floor is higher, the proportion of later egress of the elderly is larger, even up to 100 percentage on the top three floors.

Besides, the high density and flow rate in the elevator room and the stairs imply the crowded spaces that would hinder the elderly from egressing safely. According to the egress plan, only the density and the flow rate on the egress way of the elderly are considered in the absolute performances. In daily life, the elevator rooms under the fifth floor are low-density the majority of the time, and high-density only a few of the time. The low-level emergency raises the percentage of medium-density, and the percentage of high-density is still a little. Since the elevator cannot operate under high-level emergency, the proportion of high-density in the stairs increases dramatically, especially in the stairs under the sixth floor where the density is low for only less than half of the time. Owing to a certain amount of residents in the residential building, the flow rate of the elevator room is usually low enough for safe egress most of the time under normal and low-level circumstances. Even during high-level emergency, only the flow rate in the ground floor stairs temporarily reaches the high level.

(3) Relative performances of building egress safety

The relative performances refer to the differences in building egress safety between aged and ordinary residents. Since this evaluation targets the elderly, the relative performances can reflect whether the residential building is friendly to the elderly's egress especially. Two types of relative performances are evaluated: one is the increment of egress duration, and the other one is the increment proportion of the later egress.

According to Table 6, scores of the increment of egress duration under three circumstances are between 9 and 10, indicating that the increment of egress duration of the elderly is not much, and changes slightly with circumstances. Compared with the egress duration of ordinary residents, the increment of the elderly in daily life is the most, while that under low-level emergency is the least. To be specific, lines with circle dots on behalf of the elderly and lines with square dots on behalf of ordinary residents in Figure 7 are compared. In daily life, since the elderly on the second and third floor still need to wait for the elevator, they would take a longer duration to egress from the building than ordinary residents on the same floor. When low-level emergency occurs, the elevators are reserved for the elderly, and their walking distances are quite short. So, there is a minor increment of total egress duration from ordinary residents to the elderly, except those who live on the second floor. When high-level emergency happens, the lower physical capability leads the elderly to spend more time on going downstairs in the crowd of residents. However, due to slower reaction to the emergency conditions, the elderly usually depart from their homes later, making them avoid part of the congestion with other residents on the stairs and save time in the egress process.

Even though the later egress can help to avoid congestion, it can also put residents in danger. The later egress refers to residents egress later than half of all residents on the same floor, and the increment is the increased proportion of the elderly with later egress, compared with ordinary residents with later egress. As mentioned above, the later egress is meaningless to safety unless emergencies occur, so only the increment under low-level and high-level circumstances are considered in relative building performances. In terms of scores of the increment of the proportion of later egress in Table 6, the increment under high-level emergency is much larger than that under low-level emergency, implying that increasing urgent level leads the elderly to egress late more significantly than ordinary residents on the same floor. From the comparison of lines with circle dots and square dots in Figure 8, under low-level emergency, the proportion of the elderly belonging to the later half egress is lower than the proportion of ordinary residents on the most floors; but under high-level emergency, this proportion of the elderly become much higher on all floors. The high urgency causes the rapid reaction of residents to current circumstances. Unfortunately, the elderly generally react and move slower than others. Even though the elderly can avoid some congestion and fall dangers in the crowd, the significant increment of the proportion of later egress still indicates less possibility for the elderly to survive than ordinary residents.

(4) The effect of non-simulation indicators

Last but not least, the effects of building facilities and egress drills cannot be ignored when assessing the building egress safety of the elderly under diverse circumstances. Even though the performances of building facilities and egress drills are fixed, their contributions to building egress safety would change with circumstances. In daily life, the elderly utilize the exit signs to guide their path to egress building, no matter whether separation facilities and egress drills exist. Nevertheless, separation facilities and egress drills are more critical to egress safety. Once emergencies happen, the periodical experience of egress drill makes residents familiar with egress paths, saving time to consider and decide; and the separation facilities can reduce diffusion speed of hazardous contents, offering more safe time to egress building.

5.2 Practical implications

The evaluation approach of building egress safety for the elderly developed in this study, containing the ABEM-enabled simulation, a series of indicators, BESI and its thresholds, can benefit stakeholders to achieve diverse functions. There are several ways for developers of residential buildings and potential the elderly to take advantage of this evaluation approach.

As people age, people have to consider the place where they choose to age. The elderly generally prefer to stay at their homes, move to live with children or relatives, or move to professional institutions, such as nursing homes and retirement homes (Golant, 2015). Due to the high expense of professional institutions and the primary moral principles to take care of aging family members (Li et al., 2017), especially in Asia, only a minority of the elderly choose the professional institutions and the majority of the elderly would keep living at homes of themselves, children, or relatives. Before they make decisions, the elderly should consider the safety of their future residences. As one kind of building safety, the building egress safety has not raised much attention during the decision-making, it might be because lacking a convenient way to judge the egress safety in advance. The BESI score can be used as a reference for the elderly, to help them choose safer residences for later lives. In terms of its thresholds, unacceptable, acceptable or good BESIs reveal whether this building is safe enough during egress of the elderly, the detailed scores of BESI show the shortcomings from each domain. Furthermore, the simulation results can also provide the building performances on different floors if needed.

As mentioned above, the building egress safety should be paid more attention to, even in the phrase of design. In terms of the planned number of residents, assumptive circumstances and current design schemes, the initial building egress safety can be conducted to identify insufficiencies of design schemes in the egress of the elderly. It is quite a valuable opportunity to improve building egress safety for the elderly by optimizing the building design. For instance, if the BESI is not high due to the large ratio of high density in the elevator room during the egress process, the designer should consider enlarging the area of the elevator room or adding one more elevator room. Furthermore, this evaluation benefits not only the residential building design, but also other types of buildings where a large proportion of occupants are aged people, like senior homes, nursing homes, or public housing.

Once the residential building is in use, the managers can collect the actual building condition, current residents, egress plans, and other actual information. Due to the dynamic building information during the operation, the evaluation of building egress safety can be conducted regularly to obtain more accurate evaluations and identify egress problems in time. Based on the results of regular evaluations, the manager can improve the egress safety for the elderly timely. For example, according to the results of the case study, it is possible for the elderly under low-level emergency to have similar or safer egress than in their daily lives. The appropriate egress plan is able to enhance the safety of the elderly with lower urgency. However, it is hard to significantly reduce dangers in the egress process of the elderly only by the egress plan when high-level emergencies happen. We can find the building performs worse in the earlier egress of the elderly under high-level emergencies, which is very critical to building egress safety under emergencies. Targeting the reduction of the later egress of the elderly, more specific supports should be set for the elderly with the concern about the diversity of declining capabilities of the elderly. Regarding the elderly with poor hearing, indoor signal lights should be installed in residential units to notice the elderly the emergency conditions. The egress maps with lightings are necessary to present current egress plans. The brightness of exit signs should be improved to make the egress paths more easily to be noticed, and continuous direction signs with different colors can be placed on the wall or the floor to direct different residents. Considering the worse visibility under some emergencies and the elderly with poor eyesight, high-quality acoustic alarm system is essential to inform the elderly about the emergency condition through the sound. Most basically, egress plans and paths should be announced by the repetitive broadcast. As the buildings become larger, different alarms are suggested in different areas of buildings, such as the alarm-at-one system being replaced by the priority alarm system in Korea (Jeong, 2021). A well-designed acoustic system can help people direct the right ways, even in low-visible conditions. Meanwhile, the exit signs and continuous direction signs with high brightness are also effective in this condition.

Moreover, the periodical egress drill not only can improve the building egress safety directly, but also can work with the ABEM-enabled simulation to achieve better effects. Obviously, the periodical egress drill makes residents familiar with the newest visual signals, acoustic signals, and egress plans for different circumstances. As a result, residents can rapidly judge the current circumstances and choose the right ways to egress from buildings. Meanwhile, the periodical egress drill can be used as the supplement to the ABEM-enabled simulation. The records of actual egress drills provide the firsthand and newest data of residential egress process, which is the most accurate evidence to adjust the existing ABEM. Since the conduction of egress simulation would be more convenient than egress drill, revised ABEM simulation can be conducted frequently to obtain the up-to-date BESIs for the elderly more accurately with the help of actual drills.

5.3 Challenges and limitations of ABEM and BESI

The ABEM and BESI are proposed to simulate the egress process and measure the safety degree of this egress process for the elderly. There are challenges we have to overcome in this study and limitations that are waiting to remedy in the following research.

Regarding the ABEM, it is critical to clearly distinguish different residents and circumstances further to uncover the differences in their egress behavior and safety. Therefore, the two kinds of agents are developed to represent the elderly and ordinary residents in the ABEM. Furthermore, the egress behavior and the agent parameters are set to make a distinction between three circumstances with different urgent-levels. Besides, the main challenge to developing the BESI is to reveal the friendliness of the building to the elderly in the aspect of egress safety. The traditional measurements of building safety usually set some age-related indicators to assess building performance. This way is useful, but susceptible to the choice of indicators. In order to assess building egress safety more efficiently for the elderly, the relative indicators are proposed based on the differences of building egress between the elderly and ordinary residents. The better performances of these relative indicators mean fewer differences between the elderly and ordinary residents, further manifesting that the building is more friendly to the elderly. Moreover, the weights of the relative indicators change with different urgent-levels to reflect the changing significances of the friendliness of building in the BESI.

Even main challenges have been overcame, limitations still exist in this study. At first, the ABEM only distinguish the elderly from other ordinary residents. Since this study mainly focuses on egress safety especially for the elderly, it is effective for this study to regard all other residents as a whole, instead of further dividing other residents into more detailed groups, like male, female, young and mid-aged. Similarly, potential circumstances are classified into three urgent-level circumstances. This classification is not very detailed, but can reflect the dissimilar egress processes. In the following research, it is worth focusing on not only the elderly and optimizing approaches of classification of residents and circumstances for more perfect simulation.

Moreover, the simulation is conducted based on the assumption that all residents stay at home, which is an extreme status of each circumstance. So, the BESI based on the simulation results under the extreme status is a minimum value among all possible values in reality, that reveals the worst building performance of egress safety under each circumstance. Since residents' actual occupancy generally varies with the time periods, it is valuable to explore the change rules of BESI within the day in our further research. Besides the time period, the scale of residents, the distribution of the elderly in the building, and the building scale are also indicators that would influence the egress behavior and BESI of the elderly. Therefore, uniform thresholds of BESI may not be very suitable for every type of building. Actual building conditions should be considered to set proper thresholds of BESI for different buildings to guarantee the egress safety of the elderly.

6. Conclusions

As the deepening of the aging of society, the proportion of the elderly increases in urban residential buildings. The building egress safety for the elderly and its changes with diverse circumstances should not be neglected, especially in mid-rise or high-rise buildings of high-density cities. This study contributes to proposing an ABEM-enabled evaluation approach of building egress safety especially for the elderly, considering the different urgent-level circumstances in the evaluation, and adopting both absolute and relative indicators to quantify the building performance as BESIs according to simulation results. The evaluation approach provides concise and effective references for the elderly to make decisions about their aging places, and also for developers and managers to reduce egress risks and facilitate safer residential buildings for the elderly.

Appendix

Table A.1 The Criteria of LOS (Singh and Jain, 2011)

LOS	Space (ft^2/ped.)	Flow Rate (Ped./min/ft)	Speed (ft/sec)	V/C Ratio
A	>60	≤5	>4.25	≤0.21
B	>40-60	>5-7	>4.17-4.25	>0.21-0.31
C	>24-40	>7-10	>4.00-4.17	>0.31-0.44
D	>15-24	>10-15	>3.75-4.00	>0.44-0.65
E	>8-15	>15-23	>2.50-3.75	>0.65-1.00
F	≥8	Variable	≤2.50	Variable

Declaration of interests

None.

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