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ABEM-based Simulation of Building Egression Safety for the Elderly Under Different Circumstances: Enlightenments of Healthy Residential Buildings for the Elderly

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Abstract. People generally spend 90% of their time indoors. Owing to the increasing proportion of the elderly, how to develop healthy residential buildings, especially for the elderly, has raised more concerns. Even though many researchers have studied the healthy performance within the home environment of the elderly, there is little research focusing on the safety of indoor public spaces in mid-rise or high-rise residential buildings that are quite common in high-density cities. Dissimilar to other ordinary residents, the elderly would take changing and greater dangers during the egression under normal and urgent circumstances. Therefore, this study aims to explore building egression safety for the elderly under diverse circumstances. The agent-based egression models (ABEMs) are developed to simulate the egression process, and absolute values and relative values of simulation results are proposed to explore the egression safety for the elderly. One ten-story residential building is adopted as the case of simulation. The findings reveal how building egression safety for the elderly changes with different circumstances. This study offers an effective tool to ensure building egression safety. In practice, the ABEM-based simulation and indicators of building egression safety would benefit several stakeholders, by helping the designers and developers to improve their design schemes for better egression safety in the design stage, assisting the developers and property managers in updating egression plans and facilities based on the new occupancy status in the operation stage, helping potential old home buyers to make decisions, and finally facilitating the development of healthy residential buildings.

Keywords. Egression, the elderly, healthy building, agent-based model, emergency

1. Introduction

People spend 90% of their time indoors. Current modes of working and living have been changed dramatically, especially in the post-pandemic era when working from home and aging in place have become more common. It reminds us that buildings should be flexibly adapted to different circumstances without compromising occupants' wellbeing. So the healthy performance of the building began to attract more attention than before.

Population aging has been regarded as a global issue universally. According to the United Nations [1], the percentage of the elderly over 65 years old reached 9% in 2019, and this percentage is predicted to increase to 12% in 2030 and 16% in 2050. Owing to the declining mobility and functional impairment, the elderly have to stay at home most of the time, and the quality of life of the elderly mainly relies on the living environment [2-3], making them more sensitive to the healthy performance of residential buildings. Countries and regions should support the later lives of increasing old residents in the future, so the development of healthy residential buildings for the elderly has raised many concerns. How to provide a healthy living environment for the elderly should be considered seriously by governments and developers.

Especially in high-density cities, residents usually live in mid-rise or high-rise buildings, where more indoor health and safety risks would appear. As a typical high-density city, Hong Kong faces a more severe aging issue [4]. Hong Kong Housing Society predicts that residents over 60 years old will account for 45% of all residents in 2026 [5]. Most residents of Hong Kong live in the units of mid-rise or high-rise residential buildings, where the indoor spaces and environment are more complex than single-family house, townhouse, or villa. For the elderly, buildings are very likely to be incentives to their chronic diseases [6], epidemic diseases [6-7], injuries [8], mental diseases [9], and other unhealthy states. Consequently, it is pretty essential to pay attention to developing healthy residential buildings for the elderly in high-density cities.

Besides indoor spaces of residential units, the common mid-rise or high-rise residential buildings also contain public indoor spaces, like the corridor, the elevator, the stairs, the entrance hall, and other public spaces. Since residents usually stay at home most of the time, much research about healthy performances of buildings focus more on the healthy performances of residential units. But, the elderly are also likely to bear unhealthy environments in public spaces when they egress the building, whether in daily life or under different types of emergencies. However, previous research seldom focuses on building safety of the elderly in public indoor spaces, and also lacks exploring the changing building performances with different urgent levels of circumstances.

In order to analyze the safety of building public spaces for the elderly, this study develops agent-based egression models (ABEMs) to simulate the elderly' egression process. In order to judge whether the building public spaces are friendly and healthy to the elderly, this study concerns more about the differences of safety performance between the elderly and general residents, and proposes absolute and relative indicators to assess the simulation results. Finally, how safety performances vary with different residents and different circumstances can be analyzed.

2. Literature Review

2.1. Healthy building

The healthy building should be safe and free of environmental and health threats. Several versions of its evaluation standards have been developed, such as WELL certification of health-safety rating [10], World Health Organization (WHO) housing and health guideline [11], and Chinese evaluating standard for healthy housing [12].

The standards and guidelines mentioned above are designed for all kinds of buildings, rather than for residential buildings. Before retirement, people have to work in office buildings for several hours every working day. Many studies have been conducted to explore the office buildings' impacts on occupants' health and effective approaches to improving the healthy performance of office buildings. For instance, the enhancement of indoor air quality brings positive impacts on occupants' health and wellbeing [13-14]. Some studies have analyzed the main building factors affecting residential physical health and mental health [15-16]. Especially due to the COVID-19 spread, building healthy performance is considered to be quite critical to prevent residents from being infected during pandemics [9, 17-18].

After retirement, the time that residents spend within their residential buildings would increase immediately. The assessment and guidelines for healthy residential buildings have been provided to enhance residential wellbeing, such as healthy assessment system [7] and development method of healthy buildings [19]. The healthy performance of residential building is generally evaluated by static data manually. The traditional evaluations are time-consuming and not enough since the building conditions and indoor circumstances are most likely to be dynamic.

However, the elderly would be more sensitive and fragile to healthy conditions of buildings than other residents. But, the current development of healthy residential buildings mainly relies on a limited number of official standards and guidelines, which lack efficient strategies for old occupants and are not enough to promote healthy residential buildings for the elderly in high-density cities. Previous researchers have studied certain building factors and healthy domains of aged residents, like indoor air quality, indoor facility management, fall risks, and quality of life [8, 20-21]. It should be noted that previous studies are short of systematic analysis, evaluations, and a smart total solution to promote healthy residential buildings for aged residents. Previous approaches were proposed to reduce risks of the elderly at home, but neglected potential risks of aged residents in other indoor building spaces. This research aims to develop healthy residential buildings especially for aged residents via smart approaches in high-density cities, targeting to offer a healthy, safe and smart living environment for aged residents.

2.2. Building egression and evacuation

In daily life, residents egress from buildings based on designed egression routes and building circulation [22]. The quality of egression routes should be considered in the phase of building design. Researchers have proposed “indoor walkability” to evaluate the normal egression routes [23-24]. Moreover, owing to the severe dangers under emergencies, more researchers paid more attention to residential safety during urgent egression, also called evacuations. Many factors have been proved to be critical to the safety of egression when emergencies occur, such as exit signage [25-26] alternative routes [27], building floor planning [28], and other building elements.

Even though the main research objective of relevant research is the building egression and evacuation of the general occupants, several researchers have noticed that different occupants may suffer different risks during their egression, and have distinguished diverse types of occupants in previous research. As a specific group of residents, the elderly have raised concerns [29]. Besides, in their daily lives, the elderly is considered to encounter more difficulties and dangers under emergencies [30] Owing to their declining ability of movement and decision-making, the elderly usually spend a longer duration to egress building [31] and sometimes require essential assistance to help them choose the correct egression routes [32]. Furthermore, few researchers have pointed out that evacuation behavior is also impacted by the urgent degree of emergencies [33]. Therefore, the building egression of the elderly must be quite changeable with urgent degrees of emergencies as well. However, the changing building egression safety of the elderly under different circumstances seldom raised the attention of researchers previously.

3. Research Methodology

This study aims to identify the building egression safety for the elderly under different urgent degrees of emergencies by simulations of ABEMs. The completed research methodology is proposed to fulfill this objective, as shown in Figure 1. The research methodology can be divided into five steps, elaborated as follows.

3.1. Step 1: Determining critical indicators of egression safety for the elderly

At the beginning of this study, setting appropriate indicators to assess results of ABEM-based simulation is required to reflect the egression safety quantitatively. Through the literature review, the critical indicators of simulation widely used in previous studies are adopted to reveal the egression safety, such as the entire egression time [34] and safety margin [35]. Furthermore, new increment indicators are proposed to reflect the egression safety of the elderly, which is quite dissimilar to ordinary residents. The increment in egression time and percentage of the later half egression from general residents to the elderly can reveal the difficulties that the elderly suffer during the process of egression. All indicators and their descriptions are summarized in Table 1.

Table 1. The critical indicators of building egression safety for the elderly

Type	Indicator	Description
Absolute indicator	Average egression time	The average whole duration that the elderly spend on the egression.
	Percentage of the later egression	The percentage of the elderly whose sequence of successful egression is in the later 50%.
Relative indicator	Increment of average egression time	The increment of average egression time from ordinary residents to the elderly.
	Percentage increment of the later egression	The increment of percentage of the later egression from ordinary residents to the elderly.

3.2. Step 2: Setting the scenarios of different emergencies

In order to compare the changing building egression safety under different circumstances, these circumstances must be defined in advance. Three kinds of circumstances are set for the ABEM-based simulation, including the normal circumstance, semi-urgent circumstance, and high-urgent circumstance.

The normal circumstance means the building operates in the normal condition without any emergencies or anomalies, and all residents can move freely within the building under this circumstance. The semi-urgent circumstance refers to some emergencies that would not affect the building condition and cause harm to occupants immediately and heavily, but residents need to leave the building within a certain time to avoid unnecessary harm on residents. The high-urgent circumstance is the most severe, and its harm would impact on building and residents immediately and heavily. Under this high-urgent circumstance, like earthquake, fire, or explosion, all residents should egress the building as soon as possible to save lives and reduce physical injuries [31].

In addition, different residents on different floors would egress buildings in different ways. For instance, residents living on the higher floor would like to take the elevators, while residents on the lower floor would prefer to take the stairs. Furthermore, the urgent-level of emergencies would also impact the egression behavior of residents. Therefore, according to the actual conditions of residential buildings, the egression plan for different circumstances should be determined for the convenience of egression simulation.

3.3. Step 3: Developing the ABEMs for scenarios

Anylogic is adopted as the software of agent-based simulation [36]. The ABEMs consist of two main parts: the physical model, and the other one is the logic model. The physical modeling is to build digital building model in the software according to the basic information of the residential building. The field investigation of residential buildings is required to collect the basic building information of the built environment and residential egression habits, which are references for basic settings of ABEM-based simulation.

The logic modeling is to develop the egression logic for all residents according to basic characteristics of residential actual egression behavior. Following the logic model helps to simulate the actual egression process in the software as much as possible. The process modeling library, pedestrian library, agent palette, statechart, and java code are applied to build the egression logic model under different circumstances. However, the detailed egression logic models would vary with different residential buildings and circumstances, and there is no standard logic model which can be applied in different cases. Since residents generally egress building through either the elevators or the stairs, basic parts of the logic model for taking the elevator and the stairs are provided in the research methodology, as shown in Figure 2.

3.4. Step 4: Conducting the ABEM-based simulations

After modeling the physical environment and egression logic under the circumstances, the ABEM-based simulation can be conducted in the software. In order to generate enough simulation data and also avoid generating lots of useless data, we set the standard simulation time for each circumstance: the ABEM-based simulation lasts 30 minutes under normal circumstance, and the ABEM-based simulation should be stopped once all residents egress building successfully under urgent circumstances.

Only useful simulation data should be exported from the software by setting events, variables, datasets, and java codes, including the agent ID, category of agent, departure floor, departure time, and finish time. Based on Java codes, events are executed to assign values to particular variables and store all assigned values in datasets, then datasets are written into excel files when the simulation is finished.

3.5. Step 5: Data analysis of building safety for the elderly under different emergencies

An amount of simulation data are generated during the conduction of ABEM-based simulations. Since not all data is helpful to identify the building egression safety for the elderly, only the data related to critical indicators mentioned in step 1 need to be retrieved from the software. Based on the original data, the value of critical indicators can be calculated. The comparative analyses of absolute values and relative values are conducted to find out the egression safety for the elderly under different emergencies.

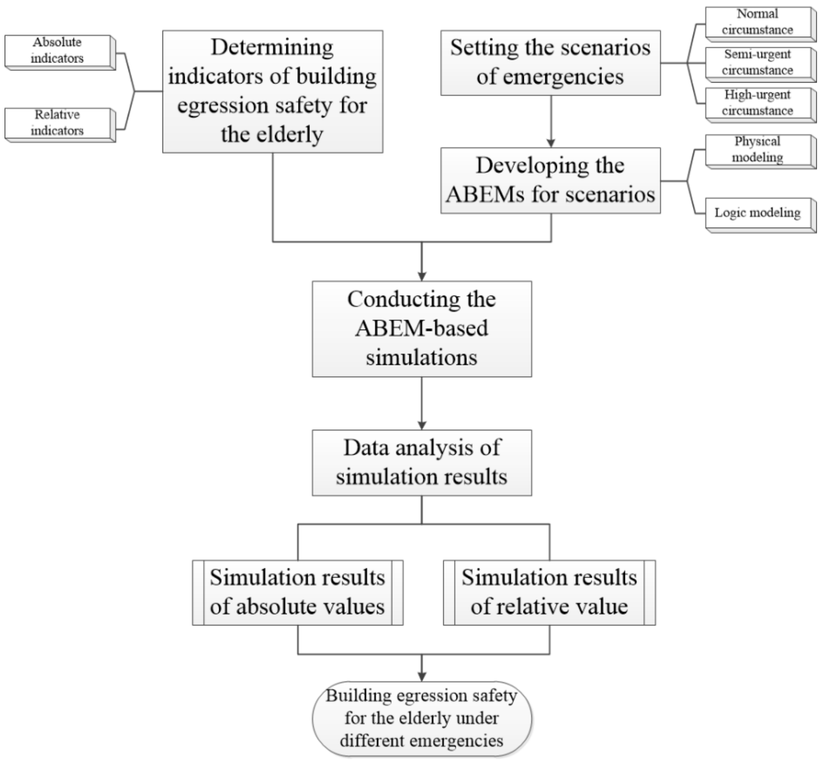


Figure 1. The flow chart of the proposed research methodology (source: developed by authors)

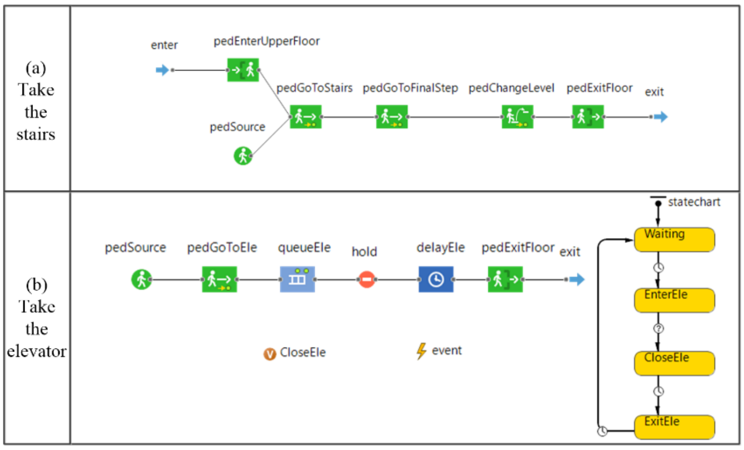


Figure 2. Critical parts of egression logic models (source: developed by authors)

4. Case study and findings

4.1. Study case

A common mid-rise residential building is chosen as the case of ABEM-based simulation. This residential building has ten floors, and four apartments on each floor except the ground floor. Two stairs and two elevators are equipped in this building. According to the field investigation of this residential building, the corridors, lobbies, stairs and entrances meet the building standards, with flat floors, wide enough, no obstacle and other essential settings, but without particular barrier-free facilities for the elderly. The egression plans for this case is supposed as follows: in normal circumstance, all elderly and other residents living on the fifth floor or above rely on the elevators, while other residents living on the fourth floor or below can egress by the stairs; when semi-urgent emergencies happen, the elevators are reserved for the elderly, and all other residents need to egress by the stairs, no matter which floor they live; when high-urgent emergencies, it is unsafe to use the elevator generally, so all residents have to egress by using the stairs.

4.2. Results

Based on the research methodology, the ABEMs are built based on the detailed information of this case. Since there is no evidence to show seasonal influence on the egression behavior of the elderly, the period of ABEM-enabled simulation is not set at a particular day. The detailed simulation data of ABEMs are exported from the software. The values of critical indicators can be calculated by processing these original simulation data, as illustrated in Figures 3 and 4. Figure 3 shows the average egression time (a) and its increments (b) of the elderly of each floor in three circumstances, and Figure 4 shows the percentage of the later half egression (a) and its increments (b) of the elderly of each floor in three circumstances.

There is a significant increment of egression time of the elderly from the normal and semi-urgent circumstance to high-urgent circumstance. Due to high randomness under normal circumstance, the average egression time of the elderly under semi-urgent or high-urgent circumstances shows more causal relations to their living floors. Compared with other residents, the increment of egression time of the elderly is not significant under high-urgent circumstance, perhaps because high-density and congestion restrict the speed of other residents. But, the egression time of the elderly under the semi-urgent circumstance has a significant negative increment on the higher floors, since other residents living on the higher floor have to spend longer time walking down the stairs.

Besides the total egression time, the sequence of successful egression is essential to the egression safety as well. Since comparing the later egression makes no sense under normal circumstance, only the later egression under semi-urgent and high-urgent circumstances are considered in the comparison analysis. It is obvious that the elderly living on every floor is likely to be the one who egresses later than half of all residents under the high-urgent circumstance, and this possibility of the later egression of the elderly significantly increases with the floor level they live on. Differently, the elderly egress building more quickly, but the possibility gyrates up with the floor level under the semi-urgent circumstance. Furthermore, the percentage of the later egression of the elderly shows significant increment comparing with other residents under the high-urgent circumstance, indicating that other residents on the lower floors leave the building much earlier than the elderly on the same floors. However, under the semi-urgent circumstance, the percentage of later egression of the elderly is similar or lower that other residents, which means the elderly is less likely to egress late when semi-urgence occurs.

4.3. Implications

This study offers a practical approach to developing healthy buildings. The absolute indicators present the egression safety of the elderly directly. The longer egression time and the later egression mean more dangers would happen to the elderly during their egression [8]. Furthermore, the main contribution to current egression safety evaluation is to integrated absolutive and relative indicators to reveal the building demerits that hinder safe egression of the elderly. The relative indicators are the different performances of above absolute indicators between the elderly and other residents. The value of the relative indicator is higher, the building is more unfriendly to the elderly's egression. Moreover, the building safety would be various with different emergencies as well [33]. By comparing the changing values of indicators under different circumstances, we can explore how different urgent levels impact the building performance of egression safety.

The ABEM can be regarded as an effective tool to make the egression plan and improve the building egression safety, especially for the elderly. In the phase of planning and design, designers can simulate the egression process by ABEM to ensure building safety, then make targeted improvements on the building design based on the simulation results. Even after the construction phase, the ABEM can be conducted regularly based on updated occupancy and building conditions, to revise the egression plans and maintenance scheme.

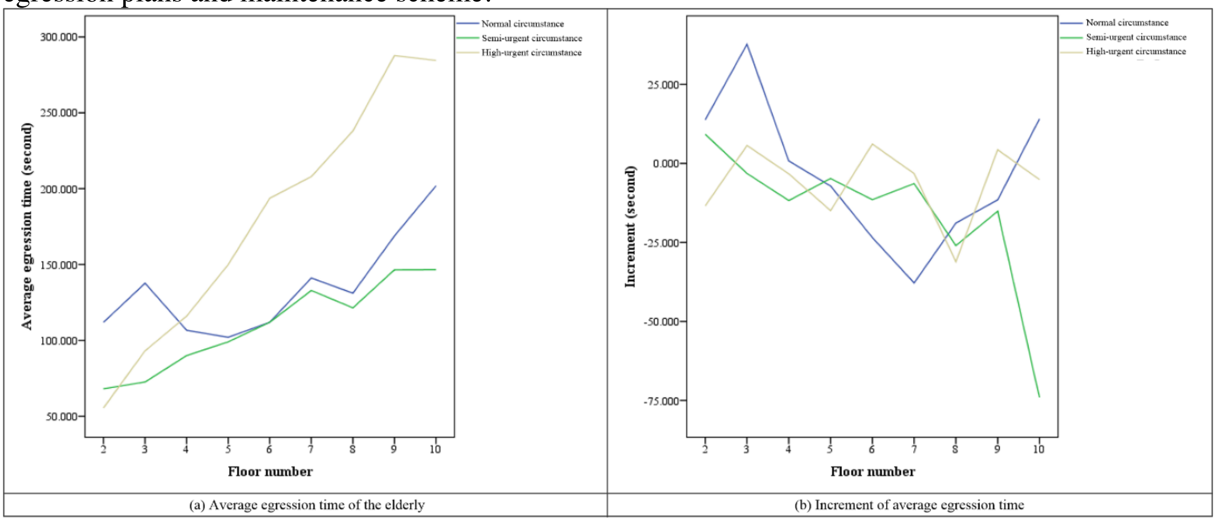
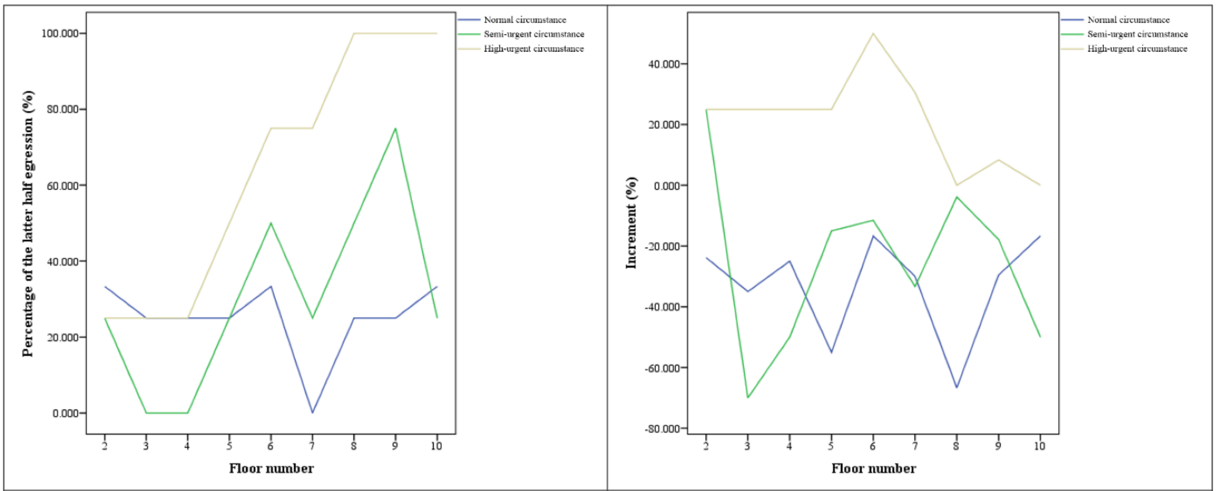


Figure 3. The average egression time of the elderly & its increment comparing with other residents (source: developed by authors)



(a) Percentage of the latter half egression of the elderly | (b) Percentage increment of the latter half egression

Figure 4. The percentage of the latter half egression of the elderly & its increment comparing with other residents (source: developed by authors)

5. Conclusions and Further Research

Through the literature review, it was found that previous research about healthy buildings paid little attention to healthy and safe performance of indoor public spaces for the elderly, and seldom distinguished the different population groups and different circumstances to evaluate the building performances. This study proposed a way to judge the building egression safety for the elderly under different circumstances by ABEM-based simulations. The simulation results help to reveal whether the building is safe enough for the elderly's egression, no matter under which circumstance. This method is quite effective for the elderly before they make choices of moving homes, and also benefits property developers to upgrade the healthy buildings, particularly for the old residents.

However, this study adopts only two absolute indicators and two relative indicators that cannot fully reflect the building egression safety, lacking a completed evaluation method. On the basis of this study, a completed methodology will be developed to simulate the residential eregssion processes, comprehensively evaluate the building egression safety for the elderly, and deeply explore actual unsafety that the elderly would meet during their egression under different circumstances.

6. Acknowledgement

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References

[1] United Nations 2019 World Population Ageing 2019 In P.D. Department of Economic and Social Affairs (ed.)
[2] Stephens C, Szabo A, Allen J and Alpass F 2019 Livable Environments and the Quality of Life of Older People: An Ecological Perspective *Gerontologist* **59** 675-685
[3] Zhang F, Li D and Chan A P C 2020 Diverse contributions of multiple mediators to the impact of perceived neighborhood environment on the overall quality of life of community-dwelling seniors: A cross-sectional study in Nanjing, China *Habitat International* **104** 102253
[4] Jayantha W, Qian Q ang Yi C 2018 Applicability of 'Aging in Place' in redeveloped public rental housing estates in Hong Kong *Cities* **83** 140-151
[5] Hong Kong Housing Society 2019 *Ageing-in-Place Scheme Booklet* (Hong Kong)

[6] Frank L and Wali B 2021 Treating two pandemics for the price of one: Chronic and infectious disease impacts of the built and natural environment *Sustainable Cities and Society* **73** 103089
[7] Gong X, Liu J, Wu L, Bu Z and Zhu Z 2021 Development of a Healthy Assessment System For Residential Building Epidemic Prevention *Building and Environment* **202** 108038
[8] Du X, Chen Y, Bouferguene A. and Al-Hussein M 2020 An agent-based simulation framework for analysing fall risk among older adults in the evacuation procedures *Safety Science* **129** 104790
[9] Akbari P, Yazdanfar S, Hosseini S and Norouzian-Maleki S 2021 Housing and mental health during outbreak of COVID-19 *Journal of Building Engineering* **43** 102919
[10] International WELL Building Institute 2021 *WELL Building Standard V2*
[11] World Health Organization 2018 *WHO Housing and Health Guidelines* (Geneva)
[12] China Association for Engineering Construction Standardization 2017 *Evaluating standard for healthy housing T/CECS462-2017* (Beijing)
[13] Lee J, Wargocki P, Chan Y, Chen L and Tham K 2020 How does indoor environmental quality in green refurbished office buildings compare with the one in new certified buildings? *Building and Environment* **171** 106677
[14] Wu P, Fang Z, Luo H, Zheng Z, Zhu K, Yang Y and Zhou X 2021 Comparative analysis of indoor air quality in green office buildings of varying star levels based on the grey method *Building and Environment* **195** 107690
[15] Mao P, Qi J, Tan Y and Li J 2017 An examination of factors affecting healthy building: An empirical study in east China *Journal of Cleaner Production* **162** 1266-1274
[16] Suzuki N, Nakayama Y, Nakaoka H, Takaguchi K, Tsumura K, Hanazato M, Hayashi T and Mori C 2021 Risk factors for the onset of sick building syndrome: A cross-sectional survey of housing and health in Japan *Building and Environment* **202** 107976
[17] Awada M, Becerik-Gerber B, Hoque S, O'neill Z, Pedrielli G, Wen J and Wu T 2021 Ten questions concerning occupant health in buildings during normal operations and extreme events including the COVID-19 pandemic *Building and Environment* **188** 107480
[18] Yip T, Huang Y and Liang C 2021 Built environment and the metropolitan pandemic: Analysis of the COVID-19 spread in Hong Kong *Building and Environment* **188** 107471
[19] Bluyssen P 2010 Towards new methods and ways to create healthy and comfortable buildings *Building and Environment* **45** 808-818
[20] Fan G, Xie J, Yoshino H, Yanagi U, Hasegawa K, Wang C, Zhang X and Liu J 2017 Investigation of indoor thermal environment in the homes with elderly people during heating season in Beijing, China *Building and Environment* **126** 288-303
[21] Leung M, Famakin I and Kwok T 2017 Relationships between indoor facilities management components and elderly people's quality of life: A study of private domestic buildings *Habitat International* **66** 13-23
[22] Fu M, Liu R and Hon Carol K 2021 Walkability evaluation of building circulation based on user preference *Engineering Construction and Architectural Management* **28** 2904-2924
[23] Shin J and Lee J 2019 Indoor Walkability Index: BIM-enabled approach to Quantifying building circulation *Automation in Construction* **106** 102845
[24] Lee J, Shin J and Lee Y 2020b Circulation analysis of design alternatives for elderly housing unit allocation using building information modelling-enabled indoor walkability index *Indoor and Built Environment* **29** 355-371
[25] Fu L, Cao S, Song W and Fang J 2019 The influence of emergency signage on building evacuation behavior: An experimental study *Fire and Materials* **43** 22-33
[26] Fu M and Liu R 2020 BIM-based automated determination of exit sign direction for intelligent building sign systems *Automation in Construction* **120** 103353
[27] Rendón Rozo K, Arellana J, Santander-Mercado A and Jubiz-Diaz M 2019 Modelling building emergency evacuation plans considering the dynamic behaviour of pedestrians using agent-

based simulation *Safety Science* **113** 276-284

[28] Qu L, Wang Y and Cao Y 2019 Fire safety in high-rise buildings under elderly housing *IOP Conference Series: Earth and Environmental Science* **238** 012055

[29] Du X, Chen Y, Bouferguene A and Al-Hussein M 2018 Multi-agent Based Simulation of Elderly Egress Process and Fall Accident in Senior Apartment Buildings *2018 Winter Simulation Conference (WSC)* 929-940

[30] Li J, Wang J, Jin B, Wang Y, Zhi Y and Wang Z 2020 Evacuation of Nursing Home Based on Massmotion: Effect of the Distribution of Dependent Elderly *KSCE Journal of Civil Engineering* **24** 1330-1337

[31] Lui G and Tong L 2010 Survey on total fire safety in residential care homes for elderly persons in Hong Kong *WIT Transactions on Information Communication Technologies* **43** 171-182

[32] Rahouti A, Lovreglio R, Gwynne S, Jackson P, Datoussaïd S and Hunt A 2020 Human behaviour during a healthcare facility evacuation drills: Investigation of pre-evacuation and travel phases *Safety Science* **129** 104754

[33] Haghani M, Sarvi M and Shahhoseini Z 2020 Evacuation behaviour of crowds under high and low levels of urgency: Experiments of reaction time, exit choice and exit-choice adaptation *Safety Science* **126** 104679

[34] Shen T 2006 Building egress analysis *Journal of fire sciences* **24(1)** 7-25

[35] Marzouk M and Mohamed B 2019 Integrated agent-based simulation and multi-criteria decision making approach for buildings evacuation evaluation *Safety Science* **112** 57-65

[36] Busogi M, Shin D, Ryu H, Oh Y and Kim N 2017 Weighted affordance-based agent modeling and simulation in emergency evacuation *Safety Science* **96** 209-227