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THE USE OF ELEVATORS FOR EVACUATION IN RESIDENTIAL BUILDINGS

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Abstract

This study focuses on the human factors associated with elevator use during evacuation in residential buildings. An online survey is conducted to explore seven factors that may influence people's choice of elevators in China and the United Kingdom, including floor height, waiting time for elevators, crowd density in front of elevators, mobility limitations, instructions, fire location concerning people's current location, and information about reliability of elevators during evacuation. Based on the results of online survey, a simulation with four scenarios in a fictitious 30-story residential building is performed to explore the evacuation process. Among the seven factors, the presence of people with mobility limitations is the primary factor that can influence people's choices in China and UK. The usage of the elevators for evacuation in residential buildings increases along with the floor height people are in. Over 90% of people are not willing to wait for elevators for evacuation longer than five minutes. People who are on the fire floor or adjacent floor have less willingness to use elevators. The instructions from a management team unfamiliar to evacuees are not associated with a high willingness to use elevators for evacuation. Information within the evacuation plan about the reliability of elevators for evacuation can increase people's willingness of using them. Considering total evacuation strategies, instructing people with mobility limitations to use elevators seems to be the priority as it can reduce the total evacuation time and the congestion in the staircase.

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摘要

本研究侧重于住宅建筑疏散过程中人类对于电梯疏散的观点。线上调查问卷探讨了可能影响中英两国人们选择电梯的七大因素，包括楼层高度、电梯等待时间、电梯前的人群密度、陪同人员的行动能力、疏散指令、居民当前的位置与火灾位置的远近，以及可靠的电梯疏散策略。基于线上问卷调查的结果，对一栋 30 层住宅楼中的四种场景进行了模拟，以探索更好的疏散策略。在这七个因素中，行动不便的人陪伴是影响人们选择的首要因素。住宅楼中疏散电梯的使用率随着楼层高度的增加而增加。超过 90%的居民不愿意等待电梯疏散时间超过五分钟。火灾楼层或相邻楼层的人使用电梯的意愿较低。比起可视标识和来自熟悉的管理团队的疏散指示，在不熟悉的管理团队的疏散指示下，更少的居民会选择使用电梯疏散。在疏散前了解居住建筑有包含电梯在内疏散计划可以提高居民使用电梯疏散的意愿。在疏散过程中，指导行动不便的人优先使用电梯，可以减少总疏散时间，减少楼梯间的拥挤。

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List of abbreviations

ISO	International Organization for Standardization
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
SFPE	Society of Fire Protection Engineers
WTC	World Trade Center

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1. Introduction

With increasing urbanization, more high-rise buildings are built for residential and commercial purposes. The maximum height among these skyscrapers reaches 825 meters, located in Dubai called Burj Khalifa. In addition, the tallest residential building in the world (85 percent of total floor is residential usage) has a height of 470 meters with 98 floors (Anthony, 2015). These high-rise buildings may contain a large number of occupants, thus making it extremely difficult for them to escape the building safely and rapidly in case of.

With regard to the safe evacuation, one more factor needs to be considered as well. An increase in the percentage of elderly people is happening in every country. An ageing population is a global phenomenon, especially in the Asian-pacific region, which is likely to see a rapid increase within these 30 years (Bjorn, 2021). By 2030, one in six people in this world will be over 60 years old, and this group of people is expected to rise to 1.4 billion at the end of 2030 and double in the years 2050, reaching 2.1 billion (United Nations, 2019). The ageing process is highly related to the ability of self-evaluation, confirmed by the rising number of fire-related death, underlining the vulnerability of older people. Therefore, this global issue is likely to further increase the challenges of performing evacuation from high-rise buildings (Bukvic, Gefenaite, Slaug, Schmidt, & Ronchi, 2020) especially in residential tall buildings, due to the growing proportion of older populations. Furthermore, older people show a higher prevalence of functional limitations, possibly associated with some chronic conditions such as cardiovascular diseases, strokes, diabetes, cancers, arthritis, osteoporosis, and obesity, which can influence the safe evacuation as well. The specific need for those older people and people with functional limitations should be taken into consideration for successful evacuation activities (Bukvic, Carlsson Gefenaite, Slaug, Schmidt, & Ronchi, 2020). This shift in population distribution offers a challenge in both policymaking and facility management: how to enhance the accessibility of facilities to ensure people age with dignity (Church & Marston, 2003).

The most common means of evacuation for people in multi-floor buildings is using stairs. In addition, the use of elevators for evacuation has been investigated for several years. A study by the National Institute of Standards and Technology in 2016 showed that 80% of participants knew little about other strategies of evacuation except for stairs (Bulter, Furman, Kuligowski, & Peacock, 2016). The Safety Code for Elevator and Escalator and building codes used in America (ASME A17.1-2019) require signage in every elevator lobby, indicating that occupants should take stairs rather than the elevators (Richard, 2010). In contrast, in this ageing and highly urbanized society, stairs may not offer equal opportunities to escape the buildings for all people. Occupants with functional limitations have more difficulties reaching a safe place during an evacuation through stairs (Bulter, Furman, Kuligowski, & Peacock, 2016).

As a result of this situation, an additional mean for inclusive evacuation is necessary to mitigate this risk for people with functional limitations in buildings in which defend-in-place strategies are not suitable (Ronchi, &Nilsson, 2014). Stairs are nowadays mostly considered the primary method to safely evacuate from buildings. Evacuation elevators are considered an alternative to conventional stairs for evacuation in recent decades (Turhanlar, He, & Stone, 2013). Elevators are a type of vertical transportation used primarily to relocate people between floors, especially used in high-rise buildings, and it is an extremely functional device for the buildings to help people with limitations as they allow them to move between different levels without incurring in physical strain.

The WTC evacuation in 2001 led to a large debate on the performance of evacuation by elevators. The investigation reports by NIST revealed this was an extremely successful evacuation paradigm when compared to the bombing events that happened in 1993 (Averill, Peacock, & Kuligowski, 2005). This evacuation process provided the availability of elevators for evacuation. Such a long travel distance of evacuation was considered a challenge, while only 12 percent of people in WTC failed to survive. Regardless of whether it was a successful evacuation or not, it provided a new awareness that evacuation by elevators or a combination of the use of stairs and elevators could become an alternative. Some people chose to use the elevators to escape even though they knew they should not utilize elevators during an emergency (Galea, Sharp, Lawrence, & Holden, 2008). With regard to the investigation report, those people using elevators to evacuate showed a positive attitude towards the use of elevators for evacuation, i.e., they considered it the quickest way or a safe route to escape. It also appears that people on higher floors had a higher likelihood of using the elevators as a means of egress (Fahy, & Proulx, 2005). This demonstrated that other means of egress can be used to reduce the total evacuation time and to improve the evacuation process so as to increase the evacuation efficiency (Ronchi, &Nilsson, 2014).

According to the discussion among different vertical transport evacuation means, Bukowski stated that the protected elevators will become the primary way of means of vertical travel in tall buildings since they can evacuate occupancies in up 50-story buildings within one hour, which was proved in Taipei 101 total evacuation case (Chien, & Wen, 2011).

In 2009, Guidance on the emergency use of lifts or escalators for evacuation and fire and rescue service operations (BD 2466) published by the Department of Communities and Local Government of the United Kingdom offers guidance on elevator use for emergency evacuation to designers, approvers, building operators, and managers. It points out four benefits of elevator evacuation, compared with stairs: 1) elevators may be the only options to evacuate for people with mobility limitations, 2) considering the fatigue of evacuation by stairs especially as buildings getting taller, less physical effort is expended through elevators, 3) combination of using both stairs and elevators can reduce the congestion in stairs, 4) total evacuation time can be reduced (Chapter 3, BD2466, 2009). BD 2499 only provided the guidance for the adoption of elevators and escalators, intending to improve the safety of buildings, without mentioning any requirement of the installation.

Before regulations allowed the use of occupant egress elevators, evacuation plans were developed for some of those high-rise buildings including elevators for people with mobility limitations. NIST investigated the evacuation strategies applied in several skyscrapers around the world, including a dedicated overview on the use of elevators focusing on the safety of occupants with mobility limitations. Burj Khalifa - completed in 2004 - was the first high-rise building to allow an evacuation procedure by combined use of elevators, stairs, and refuge areas. Evacuation strategies in Canary Wharf (opened in 1991) and Petronas Twin Towers priorly evacuated people with mobility limitations by using firefighter elevators (Kinateder, Omori, & Kuligowski, 2014).

1.1 Literature review

In the last decade, researchers studied the use of elevators in high-rise buildings from different aspects, including the reliability of using elevators, the optimal strategies through mathematics model and the simulation model, human behaviors during the evacuation, and elevators use in different fields through advanced technology.

The reliability of using elevators was analyzed by Turhanlar Daniel and He Yaping in 2013. Reliability is defined in SFPE handbook as the probability of an item functioning after a pre-defined time (Joglar, 2016). Data from 81 elevators in different high-rise buildings were collected for assessing the reliability and the probability distribution of elevator evacuation. The extensive data collection mitigated the limitation of classes and use. Based on the results of this study, compared with most fire protection systems, elevators are highly reliable as a component of an evacuation strategy. Nevertheless, elevators are expected to require more protection to avoid the effects of fires affecting their usage (Turhanlar, He, & Stone 2013). ISO 18870 details the requirement of using elevators for all types of buildings. It specified some key items that needed to be addressed in an elevator system, incorporating automatic recovery systems, remote elevator car surveillance, communication system. The features and particular tested scenarios for buildings should be defined by building designers and fire engineers for enabling the safe use of elevators, such as the size and number of elevators, protected equipment, the scheduling and operated modes of elevators, as well as evacuation strategies (ISO18870, 2014).

Due to the rapid development of computational models, several studies investigated the optimal total evacuation strategies for high-rise buildings through computer model tools. Research from Ronchi and Nilsson compared seven strategies in twin towers, containing sole use of stairs, occupant evacuation elevators, combined use of stairs, elevators and sky-bridges, analyzed through the Pathfinder model (Thunderhead Engineering, 2021) and STEPS model (Mott Macdonald Simulation Group, 2012). The results of total evacuation time appear that the lowest evacuation time is from the sole use of occupant evacuation elevators and the combined use of transfer floors and sky-bridges, which can prove that evacuation by elevators can significantly reduce the total evacuation time (Ronchi, & Nilsson, 2014). A study from Ning Ding and Hui Zhang studied an optimized evacuation strategy of using both stairs and elevators, which improved the efficiency by 41 percent compared with the conventional methods through stairs in the case study under consideration. Evacuation elevator, as a means of egress can mitigate the merging behaviors in stairwells (Ronchi, & Nilsson, 2014), preventing the decrease in the velocity of the pedestrian flow (Ding, Zhang, & Chen, 2017).

In these modeling studies, human behavioral factors have been identified as influencing the process of evacuation. During the 2001 evacuation of the World Trade Center, several people showed a positive attitude towards using elevators. However, some people in other cases showed a strong preference for stairs as their first choice, or they would only use the elevators if the stairs were unavailable (Heyes, 2009). The understanding of human behavior choices in the case of elevator evacuation allows designers to make more realistic assumptions when studying the application of those optimal strategies, and the understanding of the usage of both stairs and elevators can help them determine the egress capacity.

Based on the results of the survey conducted by Heyes, some factors showed a significant influence on the usage of elevators during an evacuation, including floor height and the waiting time for the elevators. Through statistical analysis of four different surveys towards different groups, Heyes derived an equation based on the results of one of the surveys, to show a linear relationship between floor level and usage of elevators in high-rise office buildings from the fifth floor to the sixtieth floor. It appears an upward trend in the usage of elevators with the increasing floor height. Another equation adds another correlated factor, waiting time for elevators, in the function of usage and floor level, to show how waiting time affects the percentage of people who choose to use elevators. The number of people who prepared to use elevators was found that it dropped when the waiting time was growing. Results from the online survey also showed that people would choose the evacuation way that was identical to their perceived fastest way. (Heyes, 2009).

Kinsey conducted an online survey for investigating people's choices related to the use of elevators and stairs by presenting several hypothetical situation questions. The floor height, waiting time for the elevators, and crowd density are the three main factors to determine people's choice of elevators as an evacuation method. Most people would not consider using elevators when evacuating despite they are informed the elevators are reliable for evacuation. It appears that when the evacuation system is designed for a building, much caution should be taken into account, and simple signages that can show the safety of elevators will not be sufficient to convince people to utilize the elevators. The cultural differences can also potentially influence the people's perspectives on elevator evacuation (Kinsey, Galea, & Lawrence, 2010). NIST mainly investigated the perspectives of people with mobility limitations. The interview results provided guidance on evacuation procedures for impaired people. It attached importance to including all impaired people in the planning and execution of evacuation, to rise the trust and reduce the anxiety about the fire evacuation. The different things should be done in different stages of an evacuation drill: education and consultation before the evacuation, enough information and attention during the evacuation process, and two-way feedback after the evacuation process (Butler, Furman, Kuligowski, Peacock, 2016).

On top of high-rise buildings, the use of evacuation elevators was studied in other domains. Mossberg et al created a virtual environment based on the 3D model of a metro station in Stockholm for investigating the usage of evacuation elevators in the metro station and the acceptable waiting time for them. This Virtual Reality experiment provided other possible methods to increase the usage of evacuation elevators: the percentage of people who choose to use evacuation elevators was slightly promoted by offering the evacuation route through the smartphones, while much more people would choose elevators when they are given both audible and visible signage of the instruction on evacuation by elevators and the arrival time for elevators. The results also indicate that a count-down timer for elevators can slightly increase the acceptable waiting time elevators (Mossberg, Nilsson, & Wahlqvist, 2021). Another experiment derived by Mossberg et al used eye-tracked equipment to collect information in an unannounced and non-repeat experiment done in a high-rise hotel. This real experiment was also with regard to studying the signage during an evacuation. The results indicate that people are more willing to use the elevators for evacuation through which they used to enter the hotel if they are told the elevators are reliable during a fire. The alarm and the green flashing light can raise people's awareness of noticing the instructed signage (Mossberg, Nilsson, & Andre´e, 2021).

1.2 Aim and objectives

1.2.1 Aim

Elevator evacuation has a great potential to reduce evacuation times and be the most effective as to enhance means of evacuation in high-rise buildings. The evacuation strategies including elevators are deemed to increase along with the widespread performance-based design (PBD) fire codes. PBD can help define the optimal evacuation strategies for buildings by proving the RSET is lower than the ASET of this building and enables comparison between designs and evacuation procedures. High-rise buildings can have designed with specific evacuation strategies for their specific use. In 2021, the London Plan (London Plan Guidance Sheet Policy D5, 2021) was published by the Great London Authority and required all building users to evacuate from a building safely and independently as much as possible. Robust emergency evacuation strategies and management solutions are required to be considered in the design. However, researchers have conducted many experiments and simulations for the identification of optimal evacuation strategies (Ronchi, &Nilsson, 2014). Limited empirical experimental data concerning human behaviors and universal strategies concerning their use for all buildings are available. Those affect the growth of elevator evacuation, especially for residential buildings.

Residential buildings may present several differences considering both design and occupancy characteristics compared to other building types (e.g., office or hotel buildings). Occupancy in residential buildings is more familiar with the environment, and it is not transient compared with those in office buildings and hotels. The total number of people in residential buildings will generally be much smaller than that of high-rise buildings. However, pre-evacuation times may be higher, due to given conditions, i.e., people may be asleep, or the presence is more likely to include people who have mobility limitations, or they have more bonds to the environment compared with the case of a transient space (Ronchi, &Nilsson, 2013).

Given these premises, the thesis aims to identify the human behavioral factors of using elevators for evacuation in residential buildings and analyze how these human factors influence the process of elevator evacuation in residential buildings. The analysis can provide useful data and inform recommendations on the design of evacuation strategies including the use of evacuation elevators in residential buildings.

1.2.2 Objectives

(1) To identify the human behavioral factors that may influence the evacuation process in residential buildings using elevators for evacuation through an online survey. This includes collecting the responses from the participants with different cultural backgrounds (in particular people from the UK and China), from various age groups.

(2) To conduct an evacuation simulation for identifying how those factors investigated in the online survey influence the evacuation process and identify advantages and pitfalls in using elevators for evacuation in residential buildings.

(3) To obtain information to improve total evacuation strategies by making use of elevators for evacuation, by using the results of the online survey and the simulation.

1.3 Scope & Delimitations

1.3.1 Scope

This study focuses on the human behavioral factors that can influence elevator evacuation in residential buildings. The factors that are analyzed in this study include the usage of the elevators in relation to the waiting time of elevators, floor height, crowd density in front of the elevators, the type of people they are accompanied by during an evacuation, the kings of instructions, and the reliable elevator evacuation strategies.

The methods are used for exploring the results of an online survey and a simulation. The participants of the online survey are mainly from the UK and China, recruited through a data collection website (the Prolific) and social media (Facebook, Weibo, et.al.). The timeframe for data collection is from 20th March to 2nd April. In total, 704 people responded to this online survey. The simulation is based on a 30-story hypothetical residential building. And the original floor plan is a fictitious building based on a commonly employed residential design recommended by Jensen Hughes. The layout is replicated for each floor plan, and the building design is not expected to influence the results Four evacuation scenarios are set in this simulation through Pathfinder for comparing the total evacuation time of different evacuation strategies. The data from the online survey and the simulation was handled through SPSS, Origin, and Excel.

1.3.2 Delimitation

This study only focuses on the evacuation of residential buildings. The subjects included in this online survey are mainly from China and the UK. The nationality of the author of this article facilitated the recruitment of the participants from China. In total, 138 participants are from China and 566 from the UK. Due to the limited data collection time and limited methods, the participants from China are much fewer than those from the UK.

The results of the comparison of the evacuation perspectives and behaviors in different cultural backgrounds are limited in these two countries. The subjects from these two countries are randomly recruited from the website and the social media, without balancing the number of people from each group.

The hypothetical building used in the simulation is 30-story which cannot represent all kinds of residential buildings. The total evacuation time obtained refers therefore only to this building. The chosen scenarios also can not represent all evacuation strategies and probable evacuation behaviors. In addition, the effect of a real fire and smoke are exclusive in the simulation. Only one evacuation model is applied in this simulation, which is Pathfinder. Pathfinder can provide a continuous spatial representation model.

2. Methodology

2.1 Online survey

Due to the lack of data and understanding concerning the evacuation elevator use in residential buildings, an online survey was conducted in order to collect the perspectives of people in this field by posing hypothetical scenarios. In 2022, with the current Covid19 pandemic condition, the online survey was deemed the best (and most feasible) way to collect such a large amount of data within a very limited period. This methodology can also reduce the difficulty of identifying suitable experimental locations and involve lower ethical concerns compared with experiments. In contrast, the results of behavioral intention online surveys should be evaluated taking into consideration the limitations concerning the validity of findings (i.e., linked to biases, etc.) (Rhoses, & Bowie, 2003).

This target questionnaire involved people from various cultural backgrounds, educational levels, and physical conditions. They are recruited from social media, Prolific, family and friends. In this pandemic condition, an online survey can help to collect a large amount of data from a diverse population within several days. Furthermore, this questionnaire was translated into two languages: English and Chinese, for comparing the different perceptions towards elevators based on different education and culture. This questionnaire was sent out from 20th to 30th March. Every response was tracked by recording their devices and time of completion to reduce the possibility of false and duplicate responses as much as possible.

2.1.1 Survey description

The concept of this survey is based on the one conducted by Kinsey in 2010 (Kinsey, Galea, & Lawrence, 2010). The survey consists of four parts and 33 questions.

The first two sections are created for comparing the usage of elevators in people's daily life or during an evacuation. A 30-story hypothetical residential building was provided for people and different scenarios were set. For the first section pertaining to the daily use of elevators, the information contains:

- Assume you are in a residential building (with 30 floors) with which you are familiar and in which you have lived for several years.
- This building contains both elevators and stairs.
- Assume you do not carry anything.

In this section, people were required to answer from which floor they would choose to use the elevators rather than stairs in different scenarios: 1) when they travel along, 2) when they are with people with mild mobility limitations, 3) when they are with people in a wheelchair.

In the section associated with elevator use in an evacuation, additional information was provided:

- There is a fire happening everyone in this building should be evacuated.

- This building contains both elevators and stairs. You can choose to use stairs or elevators to evacuate

The section focused on the factors that may influence the occupants' use of elevators in an evacuation process when a fire happens, containing the floor number they are on, waiting time for elevators, crowd density in front of the elevators, people's physical conditions who they are with, their current location in relation to the fire floor, instruction types on evacuation, and whether there is a reliable plan including elevators. Participants could choose the factors that influence their decision on elevator use during an evacuation, and then they would be asked further questions related to these factors they chose. Those further questions can determine the conditions that could influence their decision on elevator use (e.g., the differences between instructions of visible and audible signate and that from the management team of this building). What's more, the effect of past fire events on their answers was taken into account as well. Participants whose answers were affected by the past fire events were required to provide a brief description of them.

The following two sections mainly focus on their personal information, including the buildings they have lived in and the highest floor they have lived on, their occupation, and the level of functional limitation. These sections investigate the influence of the background and physical conditions on their choices.

2.1.2 Limitation of the survey

- Sampling issues: participants who are recruited through an online service website are relatively unknown- with little information available on them, therefore, people can easily respond in socially appropriate ways, and misrepresent their private details, which can reduce the accuracy of online survey results. In addition, the survey can only be completed by those who have an interest in this topic, and who were literate. The sampling bias results from the non-random samples (Chittaranjan, 2020).

- Scenario issues: this survey requires participants to provide their activities in real life based on the hypothetical situation. This highly requires the ability to predict their actual behaviors. The complication level magnifies the discrepancy of what they would do in a realistic evacuation in different circumstances (Wright, 2017).

- Time issue: This survey was disseminated within 10 days, conducted with a limited number of samples, and limited diversity of people.

- The online survey was conducted without supervision from the designer, which can lead to misunderstanding and misinterpretation (Kinsey, 2010).

2.2 Simulation

A simulation was conducted based on the findings of the online survey, to identify how some human behavioral factors influence the evacuation process. This study was carried out using the Pathfinder evacuation model, developed by Thunderhead Engineering, which is an agent-based egress and human movement simulator (Thornton, O'Konski, Hardeman, & Swenson, 2011). Some scenarios were set for comparing the total evacuation time. Three variables are set in this simulation: the distribution of occupants who choose to use elevators for evacuation, waiting time for elevators, and the instruction. Only total evacuation time is collected in this simulation. By comparing the results of different scenarios set in this simulation, some recommendations on the evacuation strategies can be provided to involve the application of the elevators in the residential buildings.

2.2.1 The geometric configuration of the hypothetical building

The 30-story hypothetical building that was set in the online survey was used in the simulation as well. The floor plan of the living floor was provided by Jensen Hughes from a project in London (see Figure 1). This hypothetical building contains 30 living floors replicated from the floor plan, and a ground floor only used for discharging people (see Figure 2). This ground floor did not contain any rooms, and only contains one lobby and five exits (see Figure 3). These exits are with unlimited flow rate to avoid the congestion in front of the doors. Once people reach the ground floor either through stairs or elevators, they only spend very few seconds getting out. In this simulation, only congestions in the staircase were focused on. As shown in Figure 1 and 3, one staircase and two elevators are placed on both sides of the lobby respectively.

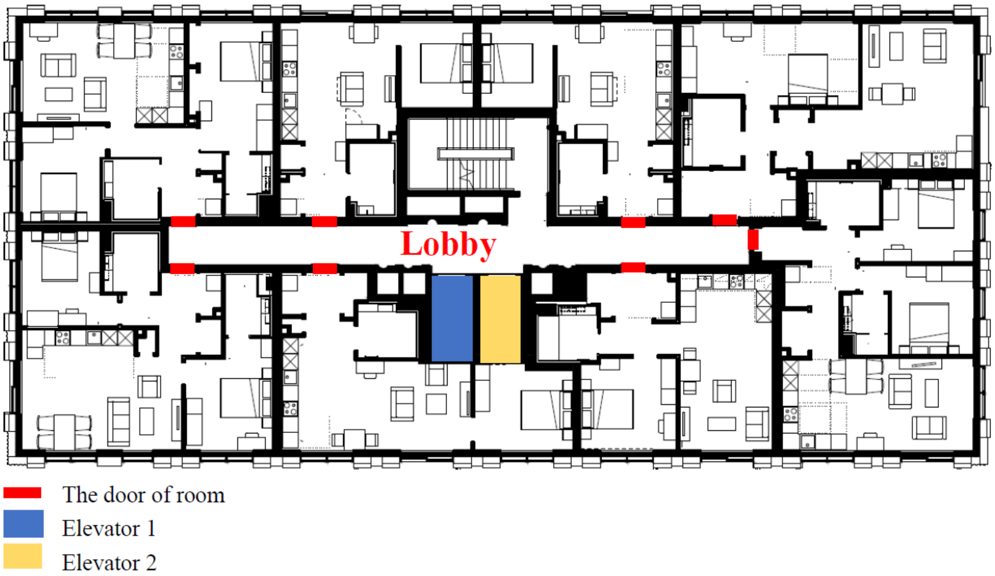


Figure 1. The original floor plan provided by Jensen Hughes

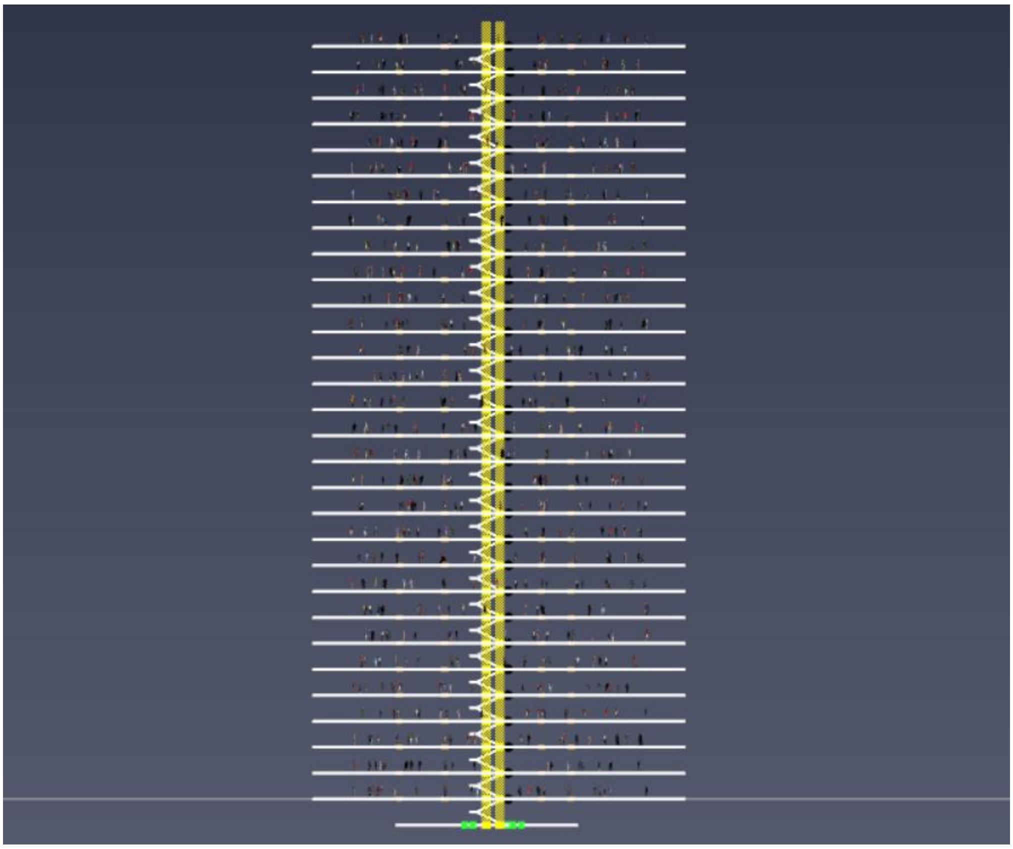


Figure 2. 30-story hypothetical building shown in Pathfinder

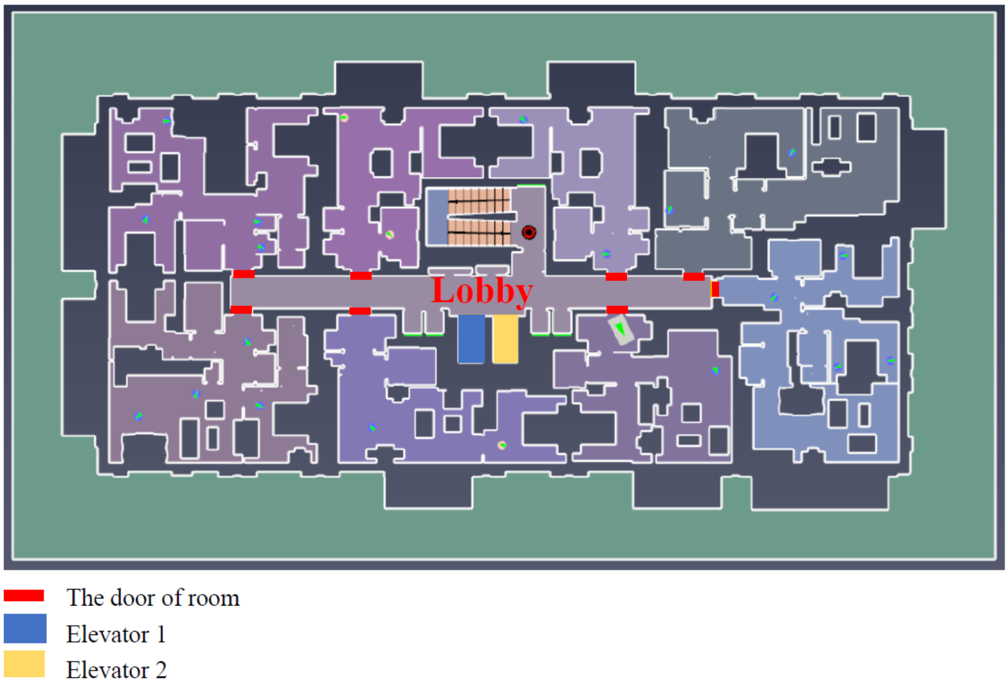


Figure 3. The imported floor plan in Pathfinder

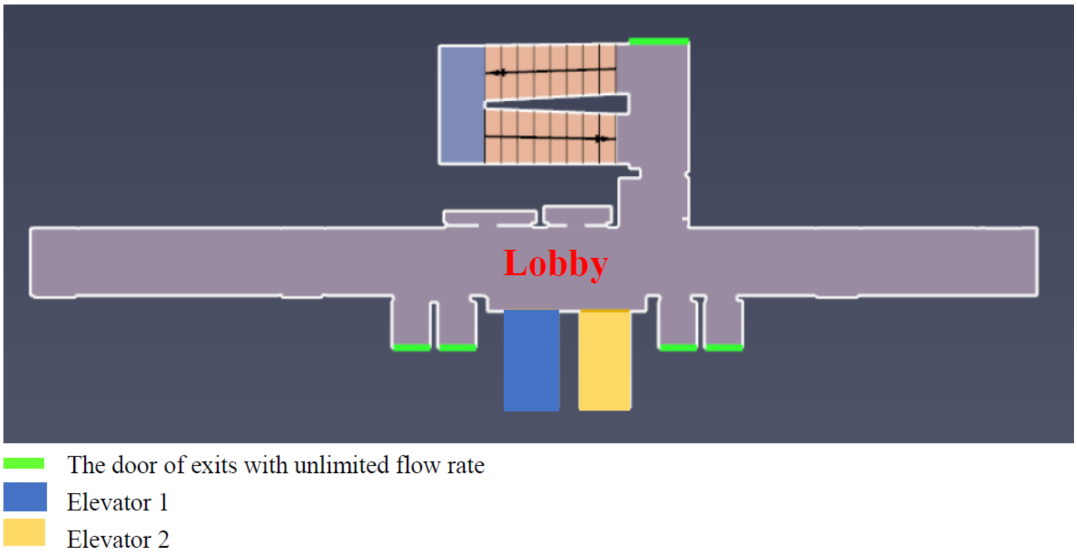


Figure 4. The ground floor built in Pathfinder

2.2.2 Agent information

Every floor has 7 rooms with 4 or 2 people on each floor, counted by the number of beds. In total, there are 660 people in this building. In this residential building, they are assumed to be familiar with this building. Their movements in this building are simulated by the Steering Model in the Pathfinder, which combined the steering mechanisms and collision handling to control the path followed by the occupants during an evacuation (Thunderhead Engineering, 2021). Their movement is assumed with influence by the smoke.

The occupants in this building are assumed to consist of three groups: adults, people with different levels of limitations, and people in wheelchairs, with the distribution of 90%, 9%, 1% respectively. The random distributions of occupants are quite conservative as they include many people with mobility limitation. This is for figuring out whether the elevator evacuation can benefit people with mobility limitations. Their walking speed is shown in table 1. A study conducted by Ronchi and Nilsson in 2014 provided input values for the speed of standard occupants and occupants with mobility limitations. The speed of wheelchairs is assumed constant from the study of the group of Sharon (Sonenblum, Springle, Richardo, & Lopez, 2012). The size of the wheelchair is set as the default size in Pathfinder.

Table 1. The characteristics of adults and people with mobility limitations

	Mean (m/s)	Standard deviation (m/s)	Range (m/s)	Shape	Height (m)
Adult	1.29	1	0.29-2.29	Cylinder	1.82
People with mobility limitations	0.8	0.37	0.1-0.67	Cylinder	1.82

Table 2. The characteristics of people in wheelchairs

	Speed (m/s)	Shape	Area (m2)	Corresponding occupant count

Wheelchair	0.48	polygon	1.0032	6

2.2.3 Pre-movement time

The pre-movement time is defined as the sum of recognition time and the response time of occupants, which can be influenced by the occupant's alertness and familiarity. Based on the category in PD 7974-6, people in this residential building can be assumed in two different conditions: 1) stay awake, and be familiar with this building, 2) stay asleep, and be familiar with this building. Assume that this building has an automatic alarm system and a well-trained management team, and the movement of people is not influenced by the smoke which is not the same as in reality. The pre-movement time of people in these two conditions can be defined as the constant values according to section H 1.7.1 and H 5.1 in PD 7974-6 (see table 3). The value of these pre-movement time is the lowest value in the PD7974-6. However, the objective of this simulation is for comparing the total evacuation time in different scenarios with the same pre-movement time. Therefore, the lowest value will not influence the comparison results. Nevertheless, this simulation is assumed in a residential building, families tend to discuss and evacuate together, in which they are likely to have the same pre-movement time. The use of distribution may lead to a less efficient evacuation, due to the fewer people starting their journey to take the elevators during an evacuation.

Table 3. Behavioral conditions and pre-movement time

Occupant alertness	Occupant familiarity	Pre-movement time (s)
Awake	Familiar	135
Asleep	Familiar	300

2.2.4 Elevator modelling

This building is facilitated with 2 elevators, running from the ground floor to the 30th floor. The elevators properties inputted in the simulation model were defined according to common practice and discussed together with Jensen Hughes, the company that supported this thesis project (see the table 4). This elevator is designed based on the existing codes.

Table 4. Elevator characteristics

Area (m^2)	2.4
Nominal load (pers)	10
Acceleration (m/s^2)	0.7
Open and close time (s)	7
Speed (m/s)	2

2.2.5 Scenarios

The occupants have two different behavioral conditions mentioned in section 4.2.3. Based on the two behavioral conditions, five scenarios are set for comparing the results under different usage of elevators on each floor and different waiting time for each condition. The general information of the four scenarios is shown in table 5. The 10 minutes waiting time are set based on the findings of the online survey of this study: over 95% of people would not wait elevators for evacuation for more than 10 minutes (see Figure 10 in the next section).

Table 5. The general description of the scenarios used in the simulation

Awake & Familiar	Asleep & Familiar	Waiting time (min)
Base case	Base case	10
Base case with unlimited waiting time	Base case with unlimited waiting time	Unlimited
People with mobility limitations in priority	People with mobility limitations in priority	10
Only use elevators for evacuation	Only use elevators for evacuation	Unlimited
Only use stairs for evacuation	Only use stairs for evacuation	-

Base case: This case is built to reproduce an evacuation scenario including elevators in real life. In this scenario, the usage of elevators on each floor was calculated by the equation that was derived from the results of the online survey (see equation 1), which is assumed representing the human behavior concerning elevator usage in residential buildings. A 10-minute waiting time for the elevators during an evacuation was assumed based on the results of the online survey. The occupants that are expected to use the stairs for evacuation are set to start the evacuation after the set pre-movement time and went downstairs through the staircase. Those who are expected to use elevators for evacuation first go to the lobby for waiting the elevators. After 10 minutes of waiting time, people who do not take the elevators will redirect their routes and go downstairs through the staircase. In this case, 1% of occupants who use wheelchairs always use elevators until they are evacuated from this building. In addition, each of these people is assisted by an adult to help them evacuate through elevators.

Base case with unlimited waiting time: This case is based on the Base case but with an unlimited waiting time. In this case, the usage of the elevators on each floor stays the same as the base case before 10 minutes. In contrast, people who are expected to use the elevator will not redirect their route and wait for the elevators until they take them, while the people who use wheelchairs stay the same as the base case.

Priority of people with mobility limitations: In this case, the percentage of using elevators for evacuation stays the same as the base case, while the people with mobility limitations will be instructed to use the elevators, and some adults will be instructed to use stairs first for balancing the usage of elevators. This setting makes sure that in the staircase, all people are adults with faster walking speeds. Those adults who are expected to use stairs start the evacuation after a certain pre-movement time and go downstairs through the staircase. The adults who use elevators for evacuation will redirect their routes to use stairs for evacuation. However, all people with mobility limitations will be instructed to wait for elevators until they are evacuated out of this building by elevators.

Only use elevators for evacuation: All occupants in this case use elevators for evacuation after the pre-movement time until they are evacuated out of the building.

Only use stairs for evacuation: All occupants in this case use stairs for evacuation after the pre-movement time until they are evacuated out of the building.

2.2.6 Convergence

The evacuation data has one kind of uncertainty, called behavioral uncertainty, which originated from the probabilistic nature of human behavior. Even the same evacuation route in the same building with the same group of people could give considerably different results. A convergence method to handle the evacuation data posed by Ronchi et.al. in 2014 is used in this study to reduce this kind of uncertainty. The variation of the results was examined for each run of each scenario until a predefined criterion was reached. Meeting a preset value for the percentage error between standard deviations (> 5%) of the result for successive runs is required (Ronchi, Reneke, & Peacock, 2014).

3. Results

The results of both the online survey and simulation are described in this section. The online survey is mainly for identifying the human behavioral factors that may influence the evacuation process by comparing the results of different factors and comparing among different groups. Moreover, the simulation is based on the results of the online survey. The results of the simulation are for identifying the better suggestions for the evacuation strategies.

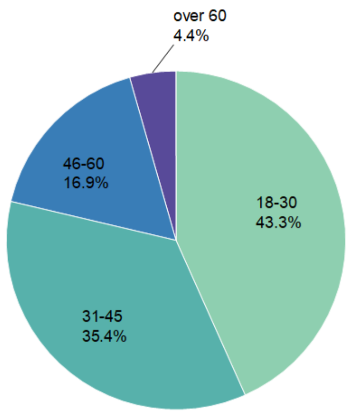
3.1 Online survey

3.1.1 Participants demographic

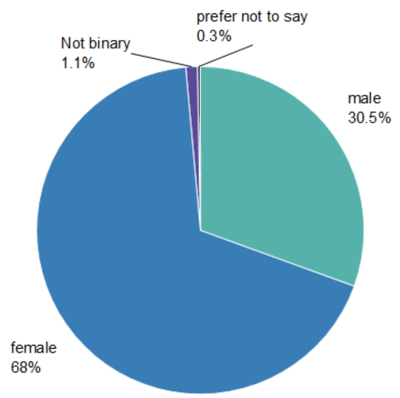
During the online survey, 704 participants completed this questionnaire in total, and all of them fully answered all the questions. The aggregated personal information they provided is shown in Figure 5.

The average age of all participants was 35.8, with the 18-30 age group accounting for 43.6 % of those who took part in this online survey. 68% of female respondents participated in this survey, which is more than twice as many as male respondents.

The countries in which participants lived longest were mostly the United Kingdom (68.2%), with 12.2% in China and 19.6% in other areas of the world. The participants from China are recruited from the Chinese social media (Weibo et.al,). The participants from the UK and other countries are mainly recruited from the website Prolific. Large samples were needed to be compared between different countries, while except for China and UK, samples from the other countries were less than 10 people respectively. Therefore, the samples from other countries (N=86) were included in the UK sample, since they were recruited from the British group on the recruitment website Prolific, so it was deemed reasonable to assume they were currently living in the UK.



Age



Gender

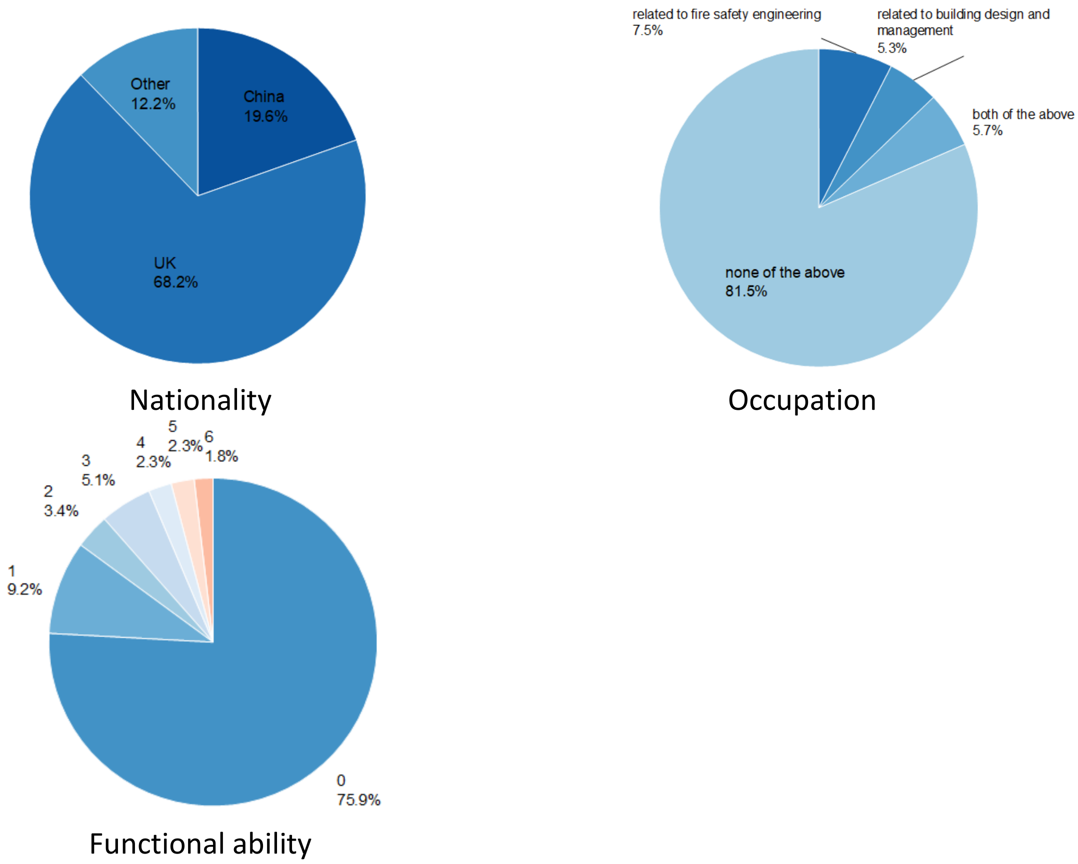


Figure 5. Participant demographic information

Less than 20% of participants were from either the fire safety profession or building design and management professions, the remaining 81.5% were from professions not related to these domains.

Participants described their functional ability through a six-level Likert scale question. 0 represents people declaring having no mobility limitations, while 6 represents extensive mobility limitations. Of all participants, 75.9% did not have any mobility limitations, and 24.1% of participants had different levels of limitation in mobility.

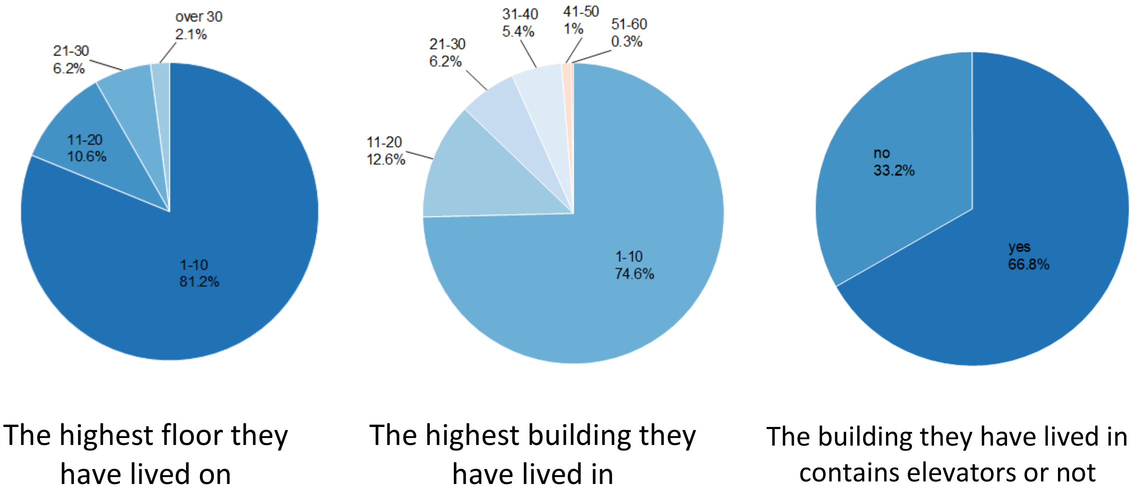


Figure 6. Residence information of participants

The buildings that participants have lived in and the height of floors they have lived on also can influence their perception of the elevator evacuation and whether they can conceptualize accurately their behaviors in a 30-story hypothetical building. The floors they resided on ranged in height from one to thirty, and the buildings in which they resided ranged in height from one to sixty stories. The majority of people (81.2%) have no experience living in a building above 10 stories and have never lived in a building higher than 10 floors (74.6%). Only 5.8% had lived in a building above 30 stories. 68% of participants confirmed the buildings they have lived in possessed elevators (see Figure 6).

3.1.2 Results of the online survey

- ***Daily use of elevators***

In the first part of the survey, the daily use of elevators under a hypothetical situation in a 30-story building was investigated. This included studying from which floor they would choose to use elevators if they travelled alone, or were accompanied by people with different levels of mobility limitations without time pressure (see Figure 3).

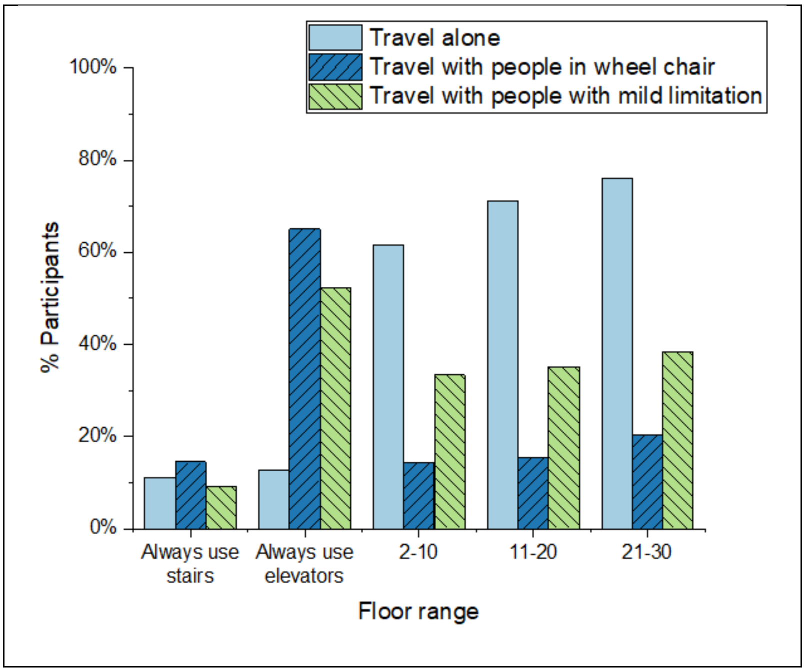


Figure 7. Proportion of participants who would use elevators in each floor range without time pressure

As expected, and as shown in Figure 7, as the floor number increased, the number of people who would use elevators to travel increased as well. While more than half of participants would want to use elevators all the time if they were accompanied by people with varying levels of mobility limitations, just 10% would prefer to use elevators all of the time if they went alone. Only approximately 10% would always use stairs in their daily life in these three situations.

Kruskal-Wallis H test was performed for testing the significant difference in the usage of elevators in these three scenarios. This non-parametric method was used for non-normal distribution paired answers with a 95% confidence interval. The results show there is a significant difference in elevator usage among the three scenarios (Kruskal-Wallis H= 374.548 $p<0.05$).

- ***Elevator use during an evacuation in a fire***

In the second part of this survey, evacuation behaviors were investigated when people faced a hypothetical fire in the same building as the one assumed for daily use. Participants could choose the different factors that may influence their choices on elevators during an evacuation: the floor height, waiting time of elevators, crowd density in front of the elevators, people they are with, instructions during the evacuation, and whether the evacuation strategy of this building included elevator evacuation. When they chose one or several of these factors, they would be asked questions related to the factors they chose. The distribution of choices of these seven factors is presented in Figure 8.

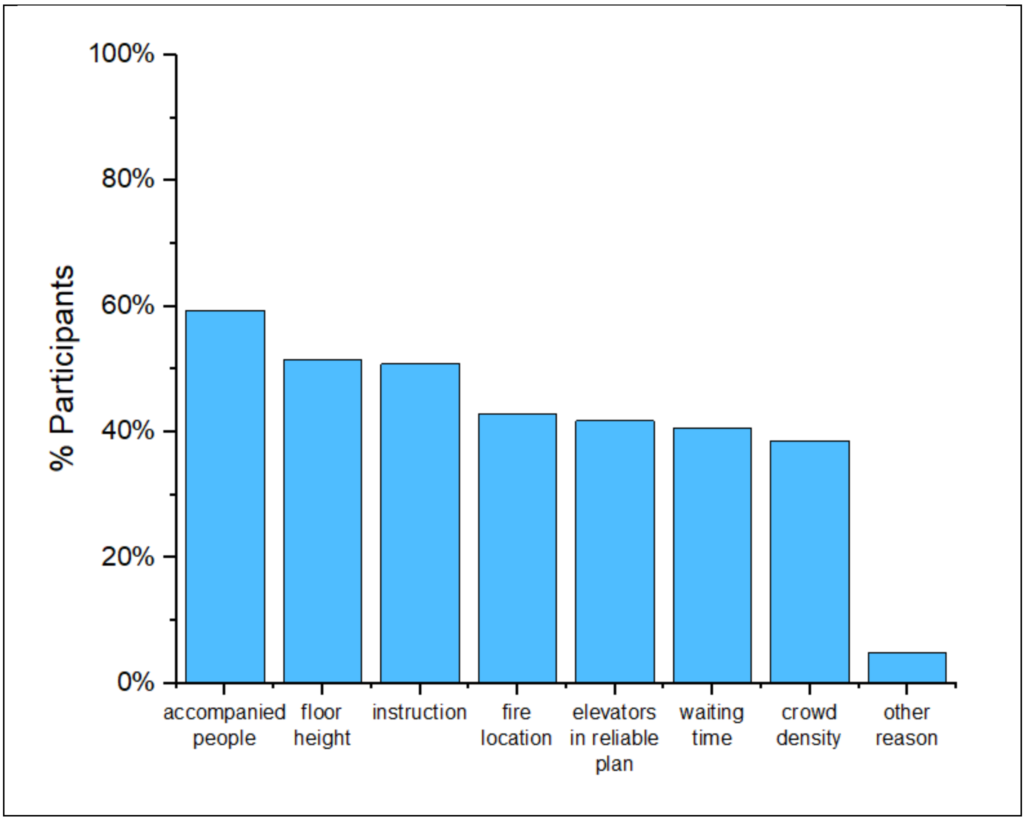


Figure 8. Proportion of participants for each factor that may influence their choice on using elevators for evacuation

Out of the 704 participants, approximately 60% answered that if they were accompanied by people with mobility limitations, this would affect their choice of using elevators for evacuation. The floor height they were located on and the instructions during the evacuation were slightly less important, as around a half of survey respondents answered this will affect their choices. Approximately 40% of participants cared about the other four factors respectively (crowd density, waiting time, reliable plan, and the fire location). This emphasizes the relevance of seven variables during the design of evacuation strategies. The people who chose “other” as an option could state additional factors. Most people who choose “other” stated they would never use elevators during a fire, and “how bad the fire is” was one factor mentioned several times as well.

Floor height

In order to know how the floor height can influence people’s choice, participants were asked from which floor they would use elevators for evacuation during a fire. Out of the 362 participants who chose the floor height as impacting their use of elevators in case of evacuation, 43% would consider using stairs all the time, and 6% would always use elevators to evacuate the building. The usage of elevators on the different floors is shown in Figure 9. Regression analysis can be used for obtaining an equation of elevator usage in evacuation correlated to the floor number. The participants who chose “always use elevators” were considered they would use elevators on any floor, which was added to the proportion of every floor when deriving the equation.

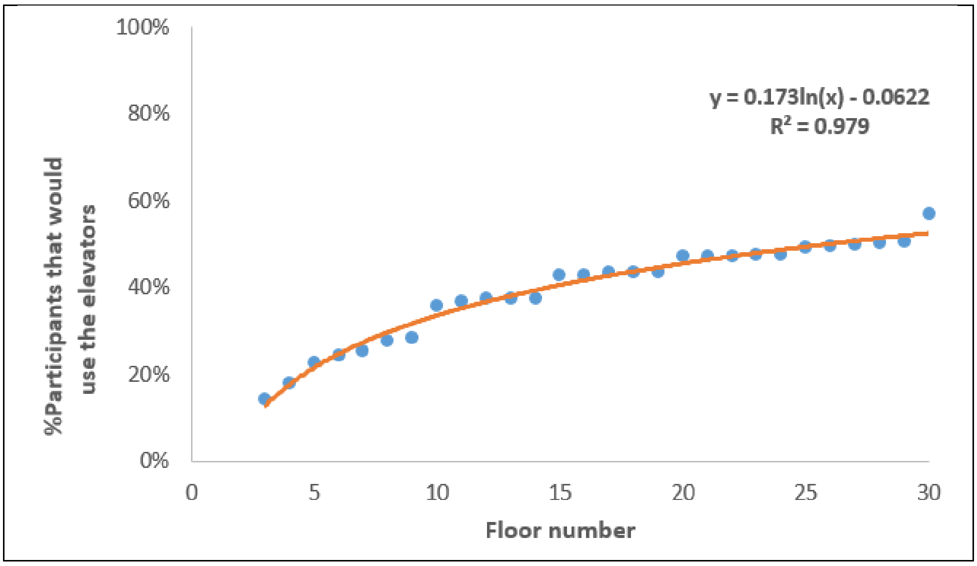


Figure 9. Proportion of participants who would use elevators for evacuation for each floor

The formula was defined through this curve.

$$Y = 0.173\ln(x) - 0.0622 \qquad for\ 3 \leq x \leq 30$$

Equation 1

Y=percentage of people who would use elevators for evacuation.

X= floor number.

The application range of this formula is limited from 3 to 30 floors.

The 362 participants were separated into four age groups every 15 years. The number of people in each group was shown in table 6.

Table 6. The distribution of different age groups who chose the factor of floor height

Age group	Number of people who chose this factor	The total number of people in each group	Percentage
18-30	195	305	63.93%
31-45	102	249	40.96%
46-60	46	119	38.66%
over 60	17	31	54.84%

As shown in Table 6, most people who are from the youngest group chose the floor height as the factor that may influence their choice during an evacuation, followed by the oldest group.

For identifying if age can influence the usage of elevators during an evacuation, the Kruskal-Wallis H test was performed in order to test whether the distribution of the number of people from each group who chose each layer has a significant difference. It only performed among the people who chose this factor.

The result showed that it is at the margin of statistical non-significance among different age groups in usage (Kruskal-Wallis H= 6.669 p=0.08), which means it failed to prove that age can influence the usage of elevators during an evacuation.

The number of people who chose the factors related to the experience of evacuation they had was shown in table 7.

Table 7. The distribution of people with different experiences on evacuation who chose the factor of floor height

Experience of evacuation	Number of people	The total number of people in each group	Percentage
In fire events	32	51	62.75%
In fire drill	179	362	49.45%
Both of the above	20	47	42.55%
None of the above	131	244	53.69%

The people who only had the evacuation experience in a real fire event cared about the floor height most, compared with the other groups.

The same test method is used for testing the probable differences in the choice of floor number from which they decided to use elevators for evacuation among people with different experiences on evacuation. It was performed among the people who chose this factor.

The result shows there is no statistically significant difference among people with varied evacuation experiences (Kruskal-Wallis H= 2.132 p=0.545), which means it failed to prove that the evacuation experiences can influence the usage of elevators during an evacuation.

Waiting time

286 participants in total choose the waiting time of elevators as the factor that can influence their choice of elevators during an evacuation. They were asked to provide the maximum time they would wait for an elevator during an evacuation regardless of the floor height. The distribution of their choices is present in Figure 10.

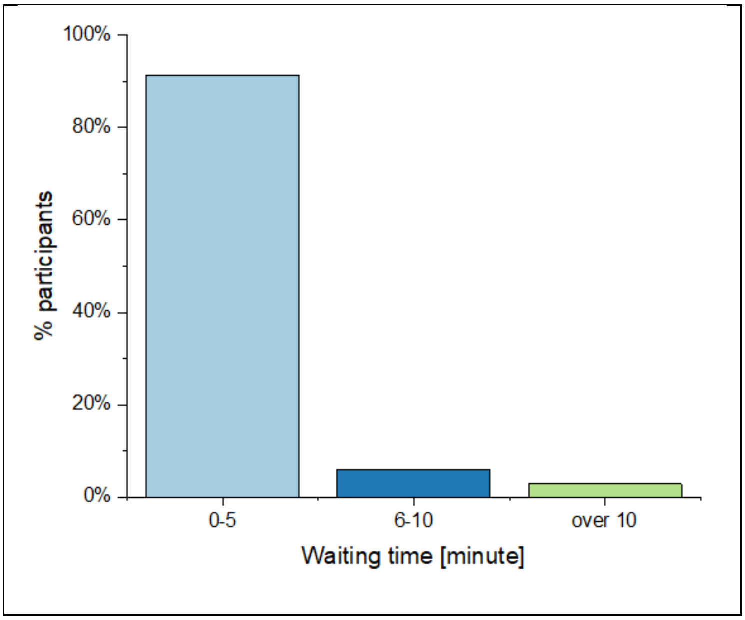


Figure 10. The proportion of participants in different waiting time

Of 268 participants in this part, over 90% would not wait for elevators more than five minutes when evacuating the building. Only 2 % would wait for the elevators for more than 10 minutes.

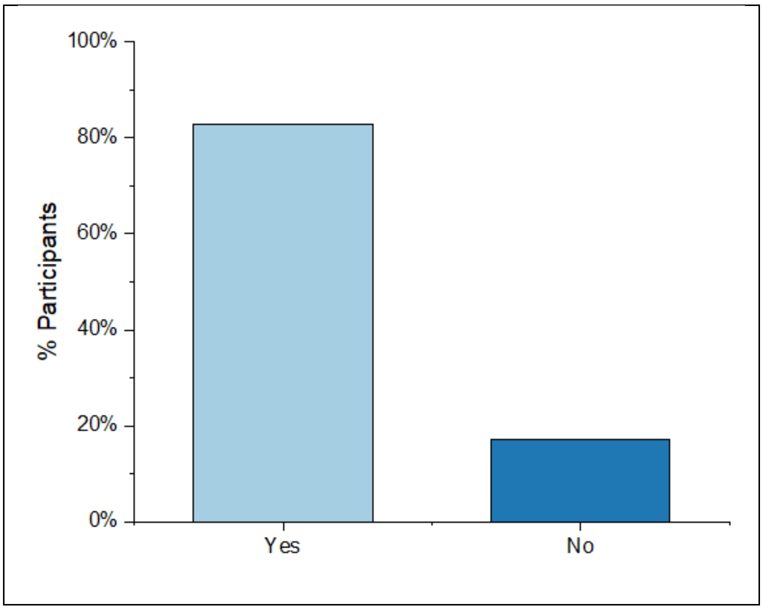


Figure 11. The proportion of participants who would change their choice when they knew the time-counter of the elevators

80% of participants of the total 268 claimed that they would change their choices on elevator use for evacuation when there was a time counter for the elevators as shown in Figure 11. A timer counter was set to let them know when they can take the elevators for evacuation.

This shows the significant importance of displaying the waiting time of elevators during an evacuation.

Crowd density

For identifying the effect of crowd density in front of the elevators during an evacuation, four pictures were displayed to represent four situations (see Figure 12). This option was selected by 272 participants who chose crowd density as an influential factor, and they could choose which one they could accept during an evacuation.

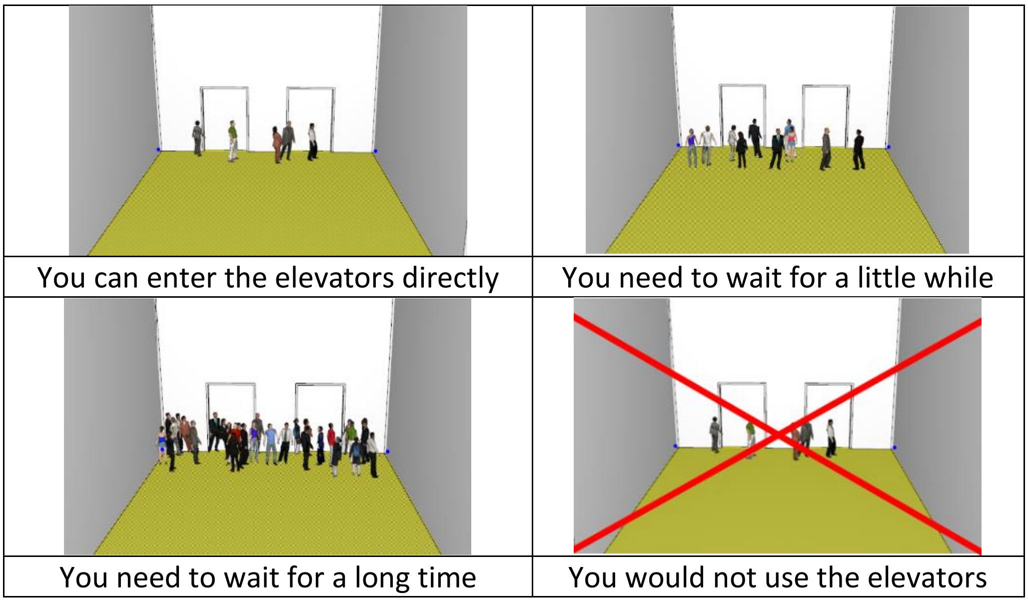


Figure 12. Four situations setting of crowd density in front of the elevators

The proportion of participants for the four situations is present in Figure 13.

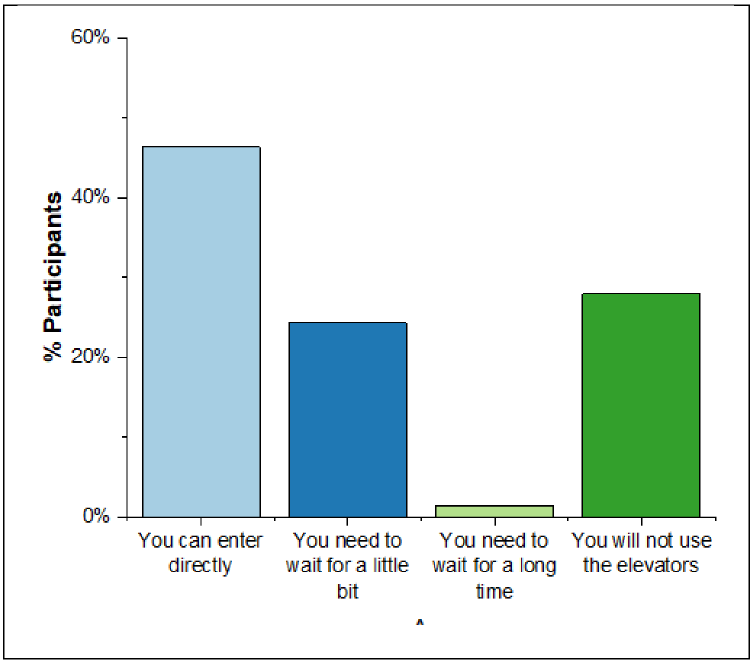


Figure 13. The proportion of participants for each crowd density situation

Most people (46%) would use elevators for evacuation if they could take the elevators directly. Less than 2% of participants would use elevators if they had to wait them for a long time. Of 28% of participants considered they would not use elevators.

Accompanied people

In this part, 418 participants who chose this factor were asked whether they would choose to use elevators in three different scenarios: 1) If they travel alone, 2) If they were accompanied by people in wheelchairs, 3) If they were accompanied by people with mild limitations. Their responses to these three conditions can be seen in Figure 14.

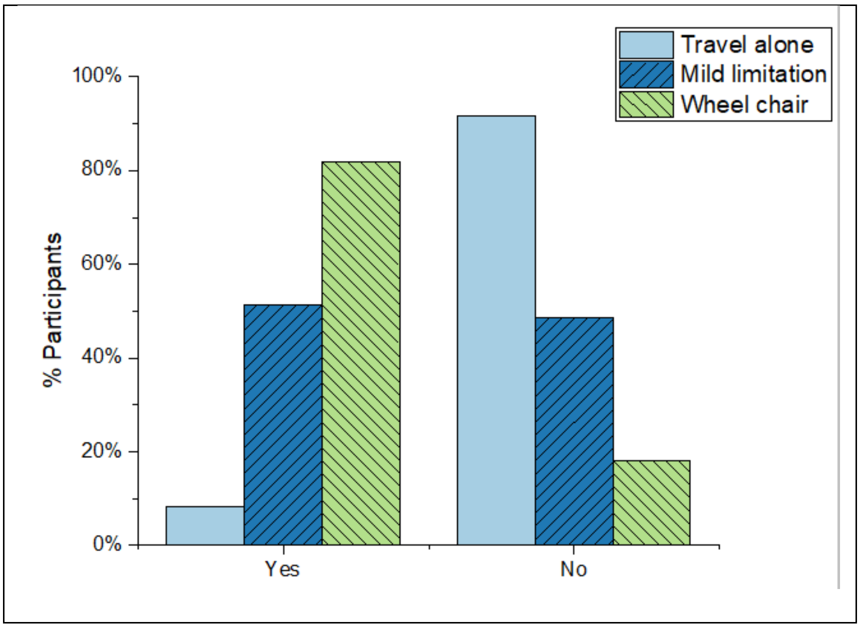


Figure 14. The proportion of participants for each type of people they were accompanied with

Over 90% of people would not use elevators when they evacuated alone, while 80% of participants would choose to use elevators for evacuation if they were accompanied by a person in a wheelchair. When it comes to people with mild mobility limitations, the number of people who stated they would use stairs and those who would use elevators to evacuate is roughly the same. The significant difference is found using a chi-square test ($\chi^2 = 456.856, p < 0.05$), which proved that the people they are with can greatly influence their choices of using elevators.

Fire location in relation to the current location of participants

301 participants chose the fire location as a factor influencing their choices to use elevators. They would be asked whether they would use elevators for evacuation either they were on the fire floor and adjacent floor, or they were farther from the fire floor. Their responses are presented in Figure 15.

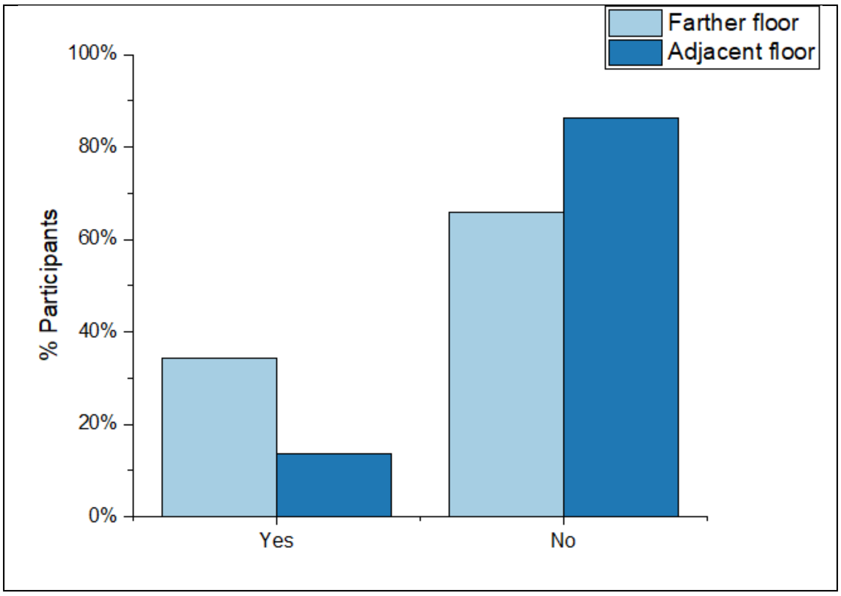


Figure 15. The proportion of participants for each fire location that claim that will use elevators

The number of people located on the farther floor who would use elevators (34%) is around twice than of those who were on the adjacent floor (14%). The significant difference is shown in the choices is tested with a chi-square test ($\chi^2 = 35.087, p < 0.05$).

Instruction during an evacuation

Three types of instructions were presented in this part to compare which one is the preferred method to instruct people to use elevators for evacuation. 358 participants who chose the instructions during an evacuation as an influential factor were required to present their choices for three types of instruction: 1) the audible or visible instruction, 2) the instruction from the people of the management team with who they are unfamiliar with, 3) the instruction from the people of the management team who they are familiar with (see Figure 16).

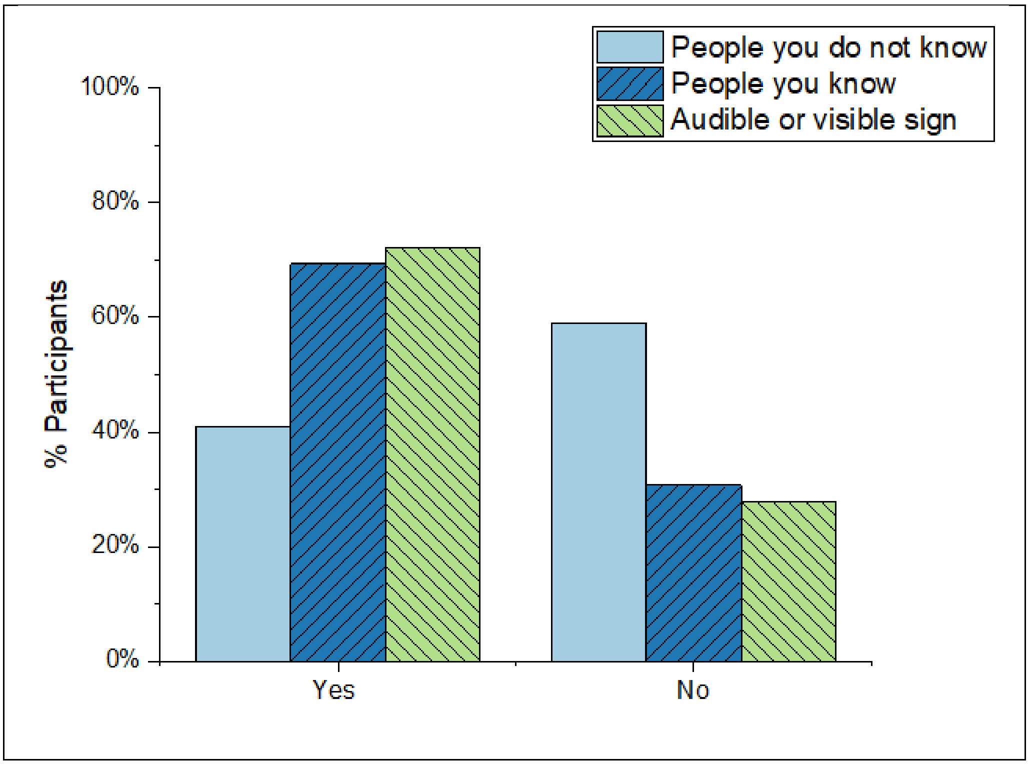


Figure 16. The proportion of participants for each type of instruction

The audible or visible signs and the instruction from people who people are familiar with can increase the usage of elevators during an evacuation. Around 70% of participants stating this factor is influential would consider utilizing the elevators when receiving these two kinds of instruction, compared to only 40% who are instructed by people they do not know. A chi-square test reveals a significant difference in the selections of these three types of instructions ($\chi^2 = 88.377, p < 0.05$).

The evacuation plan contains information that elevator evacuation is reliable

Most people stated they were educated that during a fire, taking elevators to evacuate the building is dangerous, and only stairs can be used. In this case, 294 participants answered the questions concerning if they would choose to use elevators despite it being contradictory to their knowledge (see Figure 17). This is assuming they were told it is reliable to perform an elevator evacuation.

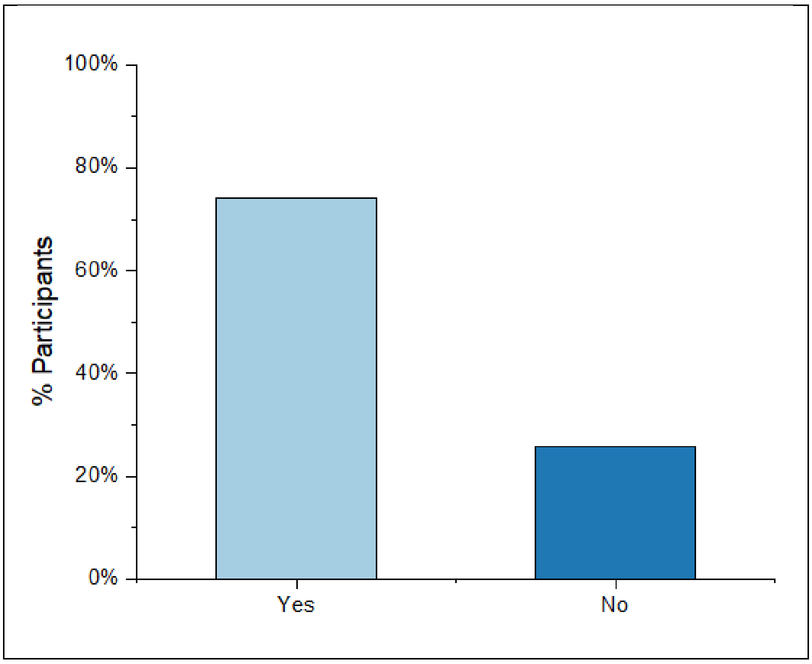


Figure 17. The proportion of participants for the reliable plan

If respondents are told that elevator evacuation is a reliable strategy, most people (74%) would choose to use the elevators for evacuation.

Impact of past fire events

In this survey, there was also a question about whether their answers to these questions were influenced by their previous experiences related to fire. The result is shown in Figure 18.

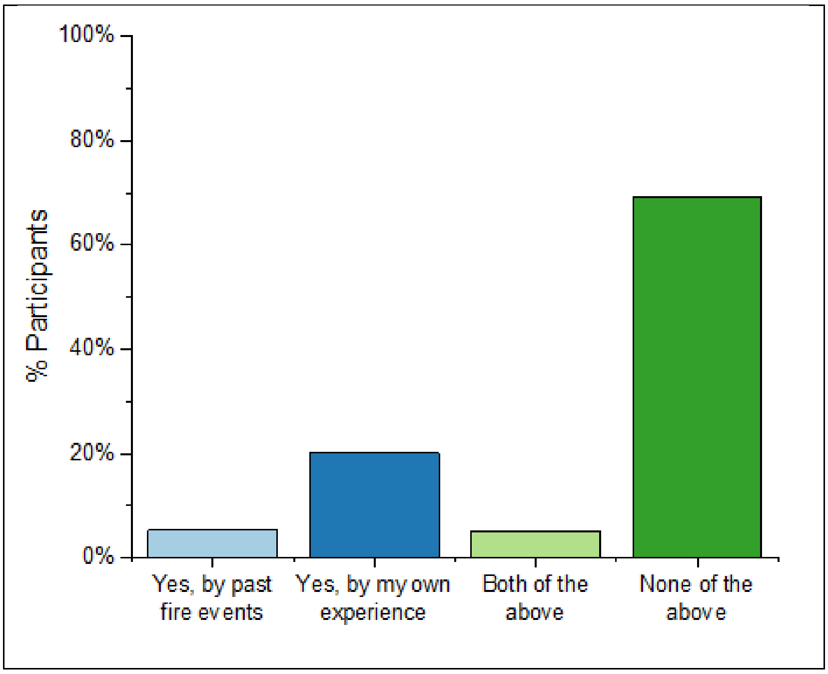


Figure 18. The proportion of participants whose answers were influenced by experiences

More than 70% of participants' answers were not influenced by experiences. Around 200 participants whose answers were influenced stated the reasons and the experiences they had.

The most mentioned events were the Grenfell tower fire (mentioned 31 times) and the 9/11 accident (mentioned 10 times). People who experienced real fire events also mentioned the time that they were trapped in elevators due to a power outage.

- ***Comparison of results between UK and China***

A comparison of survey results between the samples in the UK and China is carried out for identifying the differences in elevator use in case of evacuation considering different backgrounds. A total of 566 respondents from the UK were recruited from the UK group using the website Prolific, which is the reason why even though 86 of them stated the countries they had stayed for the longest time were not the UK, they were still included in the UK group. A total of 138 respondents from China were recruited using Chinese social media.

The comparison of results mainly focused on the choices of the seven factors that may influence their behaviors during an evacuation. For knowing how different their choices were, the chi-square test and Mann-Whitney U test were used for testing the difference in choices for the factors influencing the choices of these two groups.

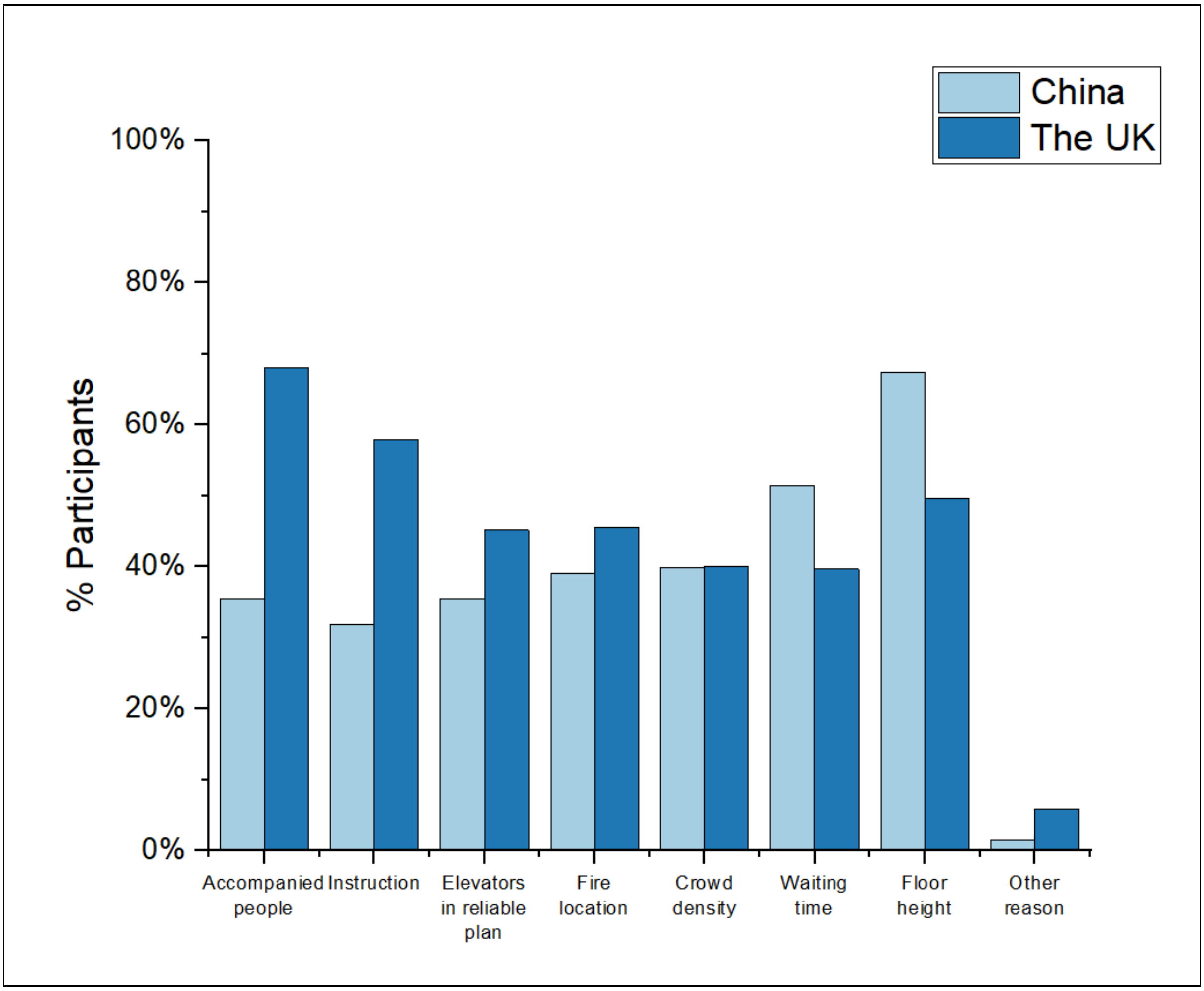


Figure 19. Comparison of the proportion of participants' choices among the seven factors

It appears that only the attitude towards the crowd density has the same percentage between these two groups in general (see Figure 19), the selections of the other elements exhibit varying levels of variation. The discrepancy is most evident in the influence of accompanying people, with the UK population being more influenced by the presence of people with functional limitations.

Floor height

For the floor height, Chinese participants who chose “always use stairs” accounted for 33%, slightly less than 46% of those in the UK. The usage of elevators on each floor of these two groups is shown in Figure 20. This figure also shows the usage of elevators of Chinese people for evacuation is consistently higher than of British people. The usage of elevators in both countries increases with the increasing floor number.

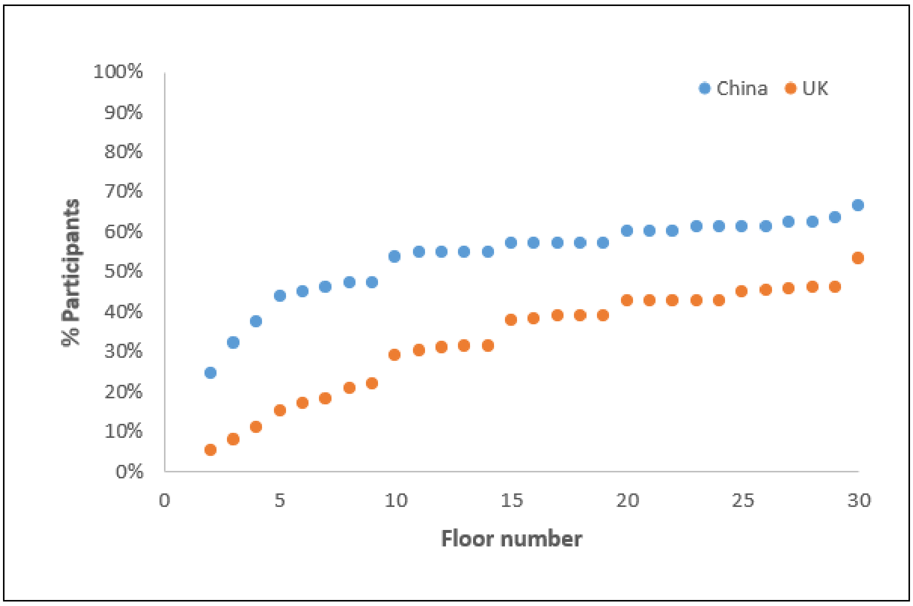
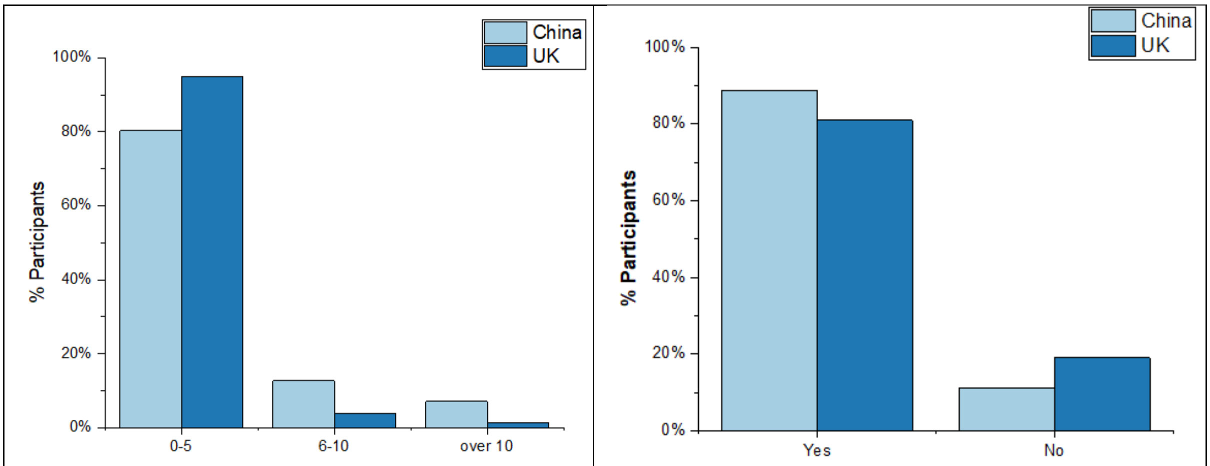


Figure 20. Comparison of the proportion of participants who considered using elevators on each floor between the UK and China



Waiting time in each floor range	When participants knew the time count of the elevator, did they change their choices?

Figure 21. Comparison of the proportion of participants in the waiting time part

As shown in Figure 21, Chinese participants tend to wait for the elevators for significantly longer time in general (p<0.05). The time-counter of the elevators marginally influence more in China than in the UK (10%), while no significant difference in this question between the two groups was found using a chi-square test ($\chi^2 = 2.28, p = 0.13$).

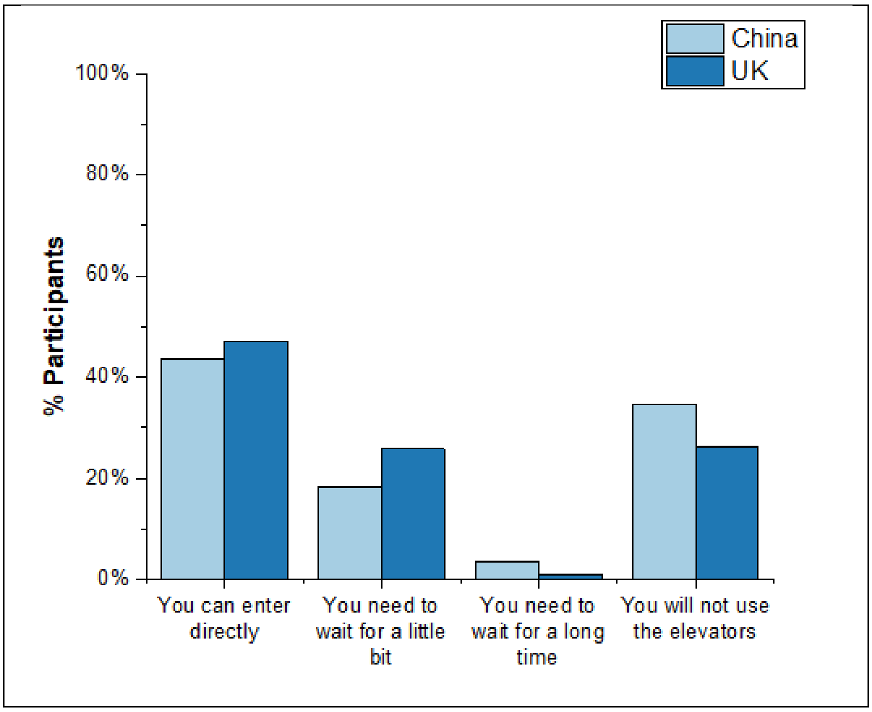
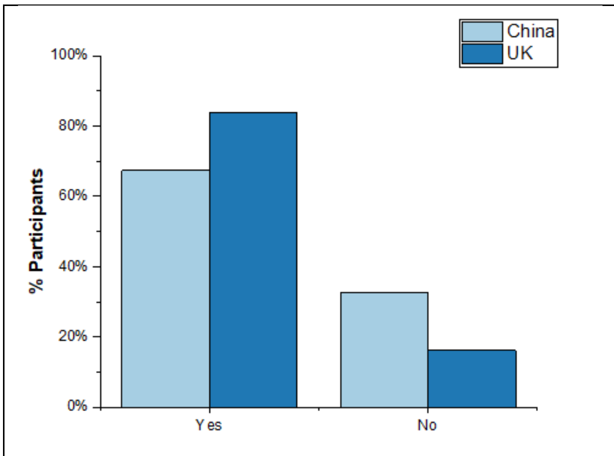
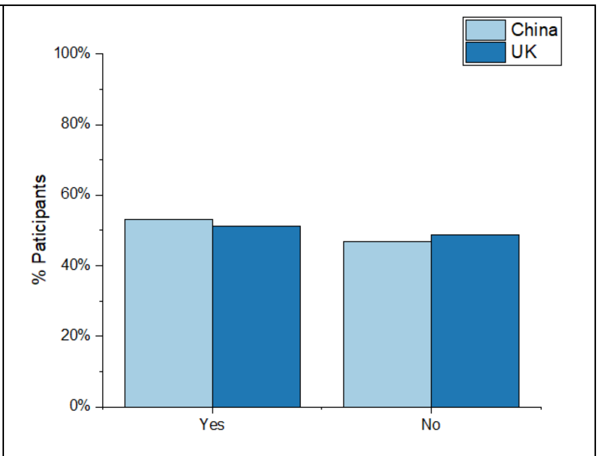
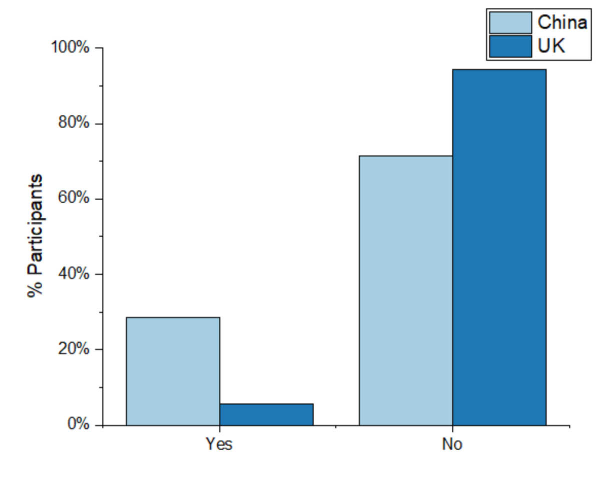


Figure 22. Comparison of the proportion of participants in the crowd density part

Figure 22 shows the slightly less tolerance for waiting in a crowd in China than in the UK, although no statistical differences were found ($\chi^2 = 4.434, p = 0.218$).

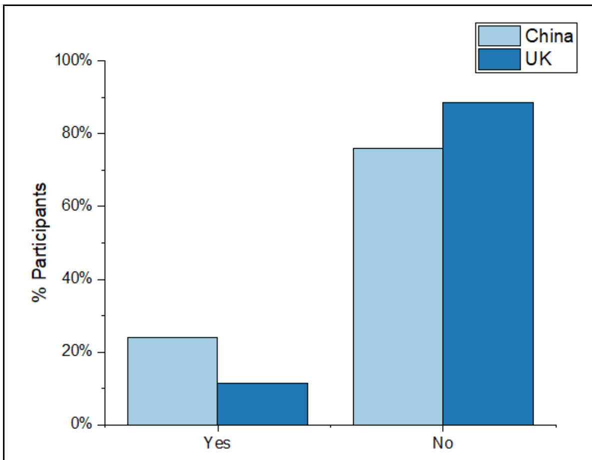
	
Accompanied by people in a wheelchair	Accompanied by people with mild limitations
$\chi^2 = 7.814, p < 0.05$	$\chi^2 = 0.059, p = 0.809$

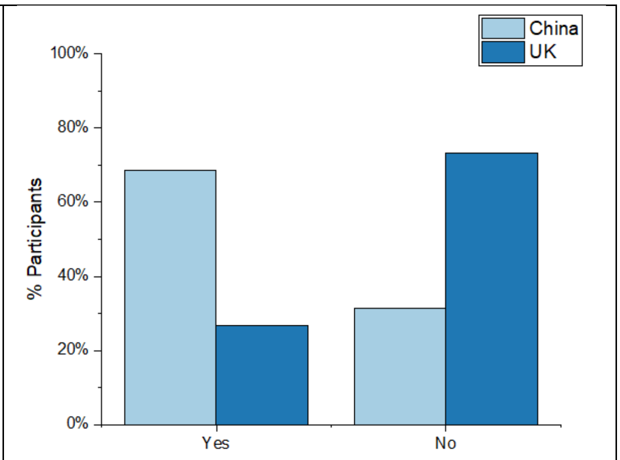


Travel alone	
$\chi^2 = 29.516\ p < 0.05$	

Figure 23. Comparison of the proportion of participants in the companied people part

As shown in Figure 23, significant differences were observed when people were accompanied by people in wheelchairs and when they travelled alone in the two groups. More people from the UK would use elevators with people in wheelchairs than people in China, while they would use elevators considerably less than Chinese participants when they travel alone.

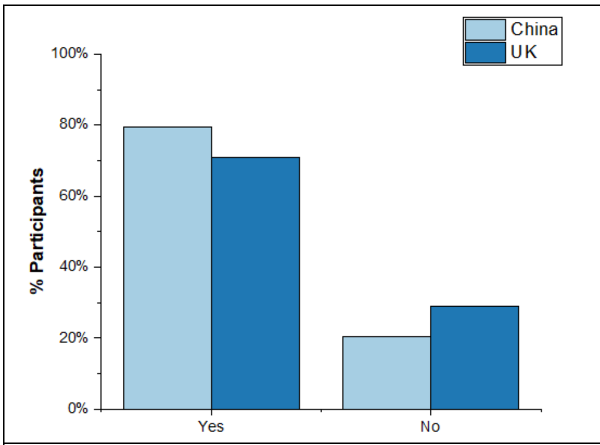




When participants were on the fire floor, or they were on an adjacent floor.	When people were on a floor farther from the fire floor
$\chi^2 = 6.11, p < 0.05$	$\chi^2 = 34.392, p < 0.05$

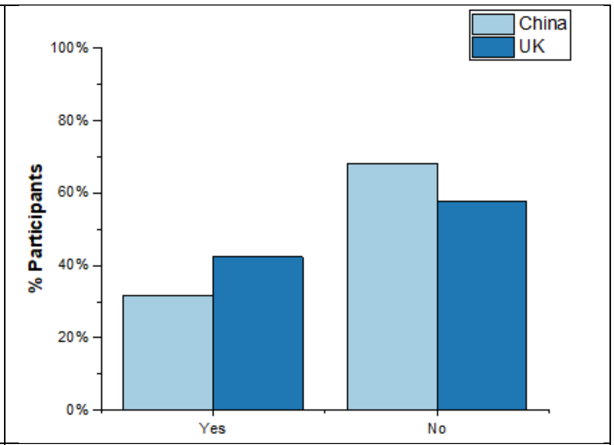
Figure 24.Comparison of the proportion of participants in the fire location part

As for the fire floor in relation to their current location, the statistical test results show significant differences in both scenarios (see Figure 24). Both Chinese people and British people are less willing to use elevators when they were on the fire floor, or they were on the adjacent floor, while the opposite trend is evident in another scenario. A significant number of Chinese people (69%) would use elevators when they were farther from the fire floor, compared to only around 30% of those in the UK.



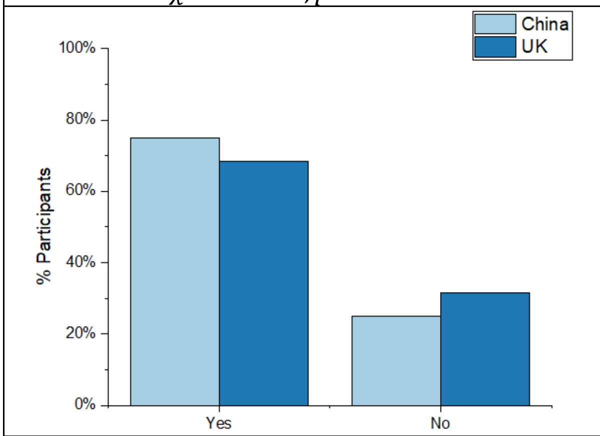
The audible or visible sign

$\chi^2 = 1.394, p = 0.238$



Instruction from people they do not know

$\chi^2 = 1.771, p = 0.183$



Instruction from people they know

$\chi^2 = 0.773, p < 0.379$

Figure 25.Comparison of the proportion of participants in the instruction part

No statistical difference was observed in three scenarios of instructions between the two groups as shown in Figure 25. The case of only instructions provided by people they do not know provides a higher proportion of people not using elevators in both samples.

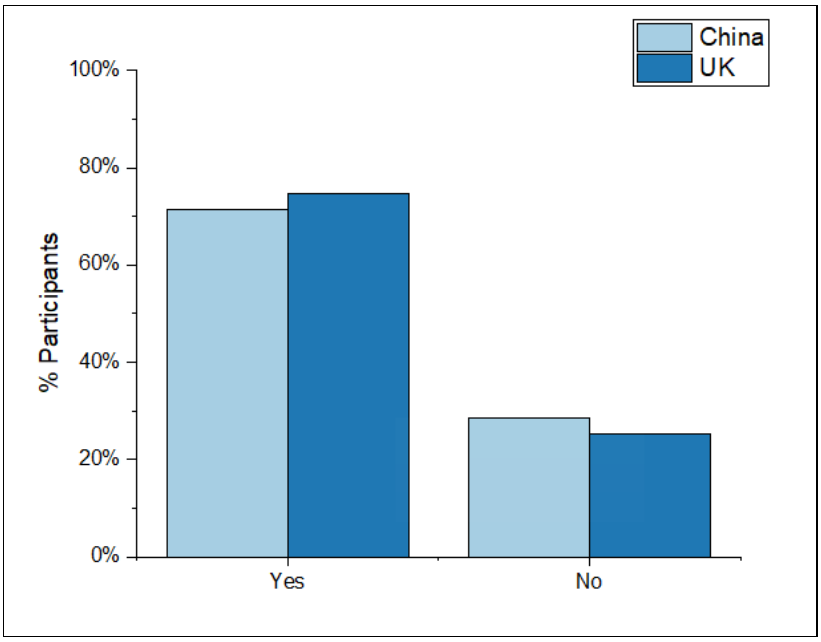


Figure 26. Comparison of the proportion of participants using elevators when told they are reliable for evacuation and considered in the evacuation strategies

As for the evacuation strategies of this building, both people in China and the UK shows the same positive attitude ($\chi^2 = 0.227, p = 0.634$) when they were told that the elevators were reliable to use in this building (see Figure 26).

3.2 Simulation

A simulation was conducted based on the results of the online survey. This was performed to test the impact of the survey results on evacuation times. Five scenarios were identified for two different situations of a fictitious residential building, and the usage of elevators for evacuation on each floor was set based on the equation 1 which was derived in aforementioned section. The usage of elevators on each floor calculated by the formula was implemented in the Pathfinder so that the number of people in each behavior is kept as an integer. In all scenarios, the people who used wheelchairs were set to use elevators all the time. These simulated people were accompanied by an adult to assist their movement, who always used elevators as well.

Except the scenarios "only use elevators for evacuation" and "only use stairs for evacuation", the usage of elevators in the other three scenarios was set for each floor before and after a given waiting time. People who chose to use the elevators would redirect their route through stairs after their waiting time expired. The waiting time was set to 10 minutes for the "base case" and the "people with mobility limitations in priority case", collected by the aforementioned section because 95% of participants in the online survey would not wait for elevators for more than ten minutes. The usage of the "Base case with unlimited time" stayed the same.

The usage of elevators in every scenario is shown in Table 8. To calculate the distribution of people who choose to use elevators for evacuation, first, some test results are conducted.

The test case was set for finding how many people can take the elevators within 10 minutes waiting time.

In the base case, agent who chose to use elevators for evacuation would redirect their route to use elevators after 10 minutes, if they can not enter the elevators. Therefore, in this simulation, only people who are on the floor from 26th to 30th can take the elevators within 10 minutes based on the test case results. Below the 25th floor, people would use stairs instead after 10 minutes, resulting in 0% of people using elevators.

In the base case with unlimited waiting time, people who use elevators for evacuation would wait for elevators regardless of time, until they can take elevators. Therefore, the distribution would not change.

In the people with mobility limitations in priority case, after 10 minutes, people below the 25th floor can not take elevators after 10 minutes as well. However, people with mobility limitations, people in wheelchair and their assistance would be instructed to use elevators, and the rest of adults would be instructed to use stairs for evacuation.

Table 8. The usage on each floor of each scenario before and after the waiting time

Floor number	The usage calculated by the formula Equation 1	Base case		Base case with unlimited waiting time		People with mobility limitations in priority case	
		Before 10 minutes	After 10 minutes	Before 10 minutes	After 10 minutes	Before 10 minutes	After 10 minutes
2	6%	5%	0	5%	5%	5%	5%
3	13%	9%	0	9%	9%	9%	9%
4	18%	14%	0	14%	14%	14%	9%
5	22%	14%	0	14%	14%	14%	0%
6	25%	22%	0	22%	22%	22%	9%
7	27%	22%	0	22%	22%	22%	13%
8	30%	22%	0	22%	22%	22%	9%
9	32%	32%	0	32%	32%	32%	9%
10	34%	32%	0	32%	32%	32%	18%
11	35%	32%	0	32%	32%	32%	9%
12	37%	36%	0	36%	36%	36%	9%
13	38%	36%	0	36%	36%	36%	18%
14	39%	36%	0	36%	36%	36%	9%
15	41%	40%	0	40%	40%	40%	9%
16	42%	40%	0	40%	40%	40%	9%
17	43%	40%	0	40%	40%	46%	9%
18	44%	46%	0	46%	46%	46%	9%
19	45%	46%	0	46%	46%	46%	18%
20	46%	46%	0	46%	46%	46%	13%
21	46%	46%	0	46%	46%	46%	13%
22	47%	46%	0	46%	46%	46%	18%
23	48%	50%	0	50%	50%	50%	0%
24	49%	50%	0	50%	50%	50%	0%
25	49%	50%	0	50%	50%	50%	18%
26	50%	50%	50%	50%	50%	50%	50%
27	51%	50%	50%	50%	50%	50%	50%
28	51%	50%	50%	50%	50%	50%	50%
29	52%	50%	50%	50%	50%	50%	50%
30	53%	54%	54%	54%	54%	54%	50%

Convergence was studied. After each scenario ran until the convergence was reached, the total evacuation time of each scenario is present in Table 9.

Table 9. The total evacuation time of each scenario

Scenario	Pre-movement time (s)	waiting time (s)	Total evacuation time-asleep (s)/(min)	Total evacuation time-awake (s)/(min)
Base case	300	600	2456(41min)	2287(38min)
Base case with unlimited waiting time	300	Unlimited	2909(48.5min)	2744(45.7min)
Only stairs for evacuation	300	Unlimited	2443(40.7min)	2290(38.2min)
Only elevators for evacuation	300	-	4722(78.7min)	4557(76min)
People with mobility limitations in priority	300	600	1982(33min)	1940(32min)

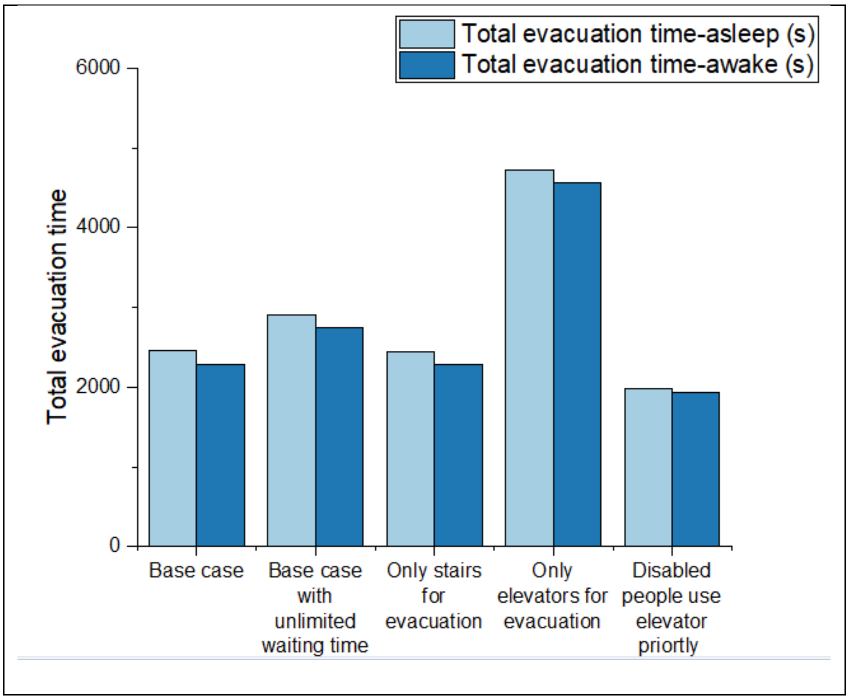


Figure 27. The total evacuation time in each scenario

The situation where all people were asleep can be seen as the worst case in the simulation, due to the longer pre-movement evacuation time than the other situation. For the situation where people were all asleep, in the base case and the base case with unlimited waiting time, the stairs and the elevators were not fully used. In the base case, the people who used elevators were fully evacuated within the 1400s (23 minutes), and then the rest of the people only used stairs for evacuation for the 1000s (17 minutes). In addition, in the base case with unlimited waiting time, the people who used stairs were fully evacuated before the people who used elevators. They took extra 500s (8 minutes) to evacuate the building only by the elevators. Both two cases were not the optimal one of elevator evacuation, due to the longer evacuation time compared with the case where people only used stairs.

The case of the shortest evacuation time is the case where people with mobility limitations were instructed to use elevators in priority with the same usage of elevators as the base case, and the wheelchair users who chose to use elevators would not change their direction during the whole process of the evacuation. There were no people with the lower speed in the staircase during the evacuation, reducing a lot of the congestion that happened in the two base cases. This suggests the instructions during the evacuation are greatly essential to reduce the total evacuation time and improve the process of evacuation.

In this example, the evacuation time by elevators may be overestimated since the elevators have been assuming travelling from the pick-up floor to the discharge floor directly, not traveling to other floors to pick up people to fill out the car. This means additional travel time was taken for more circulation, even though there was only one person in the elevators. This may be the reason why the case where people only used the elevators to evacuate the building took the longest evacuation time among all scenarios.

4. Discussion

The combination of the online survey and the simulation of the egress model has been utilized successfully for identifying the factors that influence human behavior in elevator use for evacuation, and how they affect the effectiveness of the evacuation. The statistical analysis of the survey responses and comparison between different groups can provide useful suggestions on the elevator evacuation strategies.

This study puts forward a new understanding of the use of elevators for evacuation. Most of the previous research related to the elevators for evacuation mainly focused on the office buildings, transportation infrastructures and hotels. Experimental data concerning the use of elevators for evacuation in residential buildings is lacking. This study focused on human behavior aspects linked to elevator usage in evacuation in residential buildings, comparing different factors that can influence human behaviors. Since it was based on a hypothetical residential building with a set of specific characteristics (e.g., 30 floors), it can not fully represent the real behaviors that they would have in real fire events and a wide variety of residential buildings. In other words, due to the diversity of the residential building type and different floor height, this hypothetical building cannot represent all of them. However, these results are still useful for the design of evacuation strategies in residential buildings which have similar characteristics to the hypothetical building under consideration.

The online survey was designed based on the study by Kinsey for high-rise buildings (Kinsey, 2010), while the characteristics of the population in residential buildings are slightly different than those in office high-rise buildings. In this study, the online survey is designed to investigate the human behaviors during an evacuation in residential buildings. People in residential buildings (as well as in hotels) have the possibility of staying asleep, which may lead to longer pre-movement time. At the same time, the lower population density in residential buildings compared to possibly those in office high-rise buildings results in elevators designed with less capacity, thus significantly affecting their ability to relocate people during an evacuation.

The survey results show the factors that may influence the usage of elevators for evacuation. In general, results show that the most important factor that needs to be considered in the evacuation design of residential buildings is the presence of people with functional limitations, instructions provided on elevator usage and the floor height. Differences between the UK and Chinese survey respondents were observed. For Chinese people, the floor height and the waiting time of elevators are more important during an evacuation, while for British people, the presence of people with functional limitations and the instructions obtained on elevator usage can have more influence. Therefore, cultural and educational factors might influence their perspectives of elevators for evacuation, and therefore this should be taken into account when designing an evacuation plan involving elevator usage. It is important to design an evacuation plan that accounts for people's perspectives on elevator usage. This study mainly focused on two populations (UK and China), and the people's perspectives of the elevators for evacuation need to be further studied for other cultural contexts.

Results on the usage of elevators during an evacuation have been used to derive an equation on elevator evacuation usage in relation to the floor height for residential buildings. The usage showed logarithmic growth as the floor height increases. This equation can be compared with the equations derived in previous research for other types of high-rise buildings, which are from Heyes (Heyes, 2009), Kinsey (Kinsey, 2010), and Jönsson (Jönsson, 2012). The application range and the equations are shown in table 10.

Table 10. Comparison of the equation of the usage of elevators for evacuation corresponding to the floor height derived in different research

Researcher	Equation	Application range	The applied building type
Heyes (2009)	Y=1.14X + 5.3	$5 \leq x \leq 60$	High-rise building
Kinsey (2010)	Y=0.3207ln(x) - 0.4403	$5 \leq x \leq 55$	High-rise building
Jönsson (2012)	Y=0.84x +1.05	$5 \leq x \leq 24$	High-rise building
This study	Y=0.173ln(x) -0.0622	$3 \leq x \leq 30$	Residential building

The comparison of the curve in the same application range ($5 \leq x \leq 24$) is shown in Figure 28.

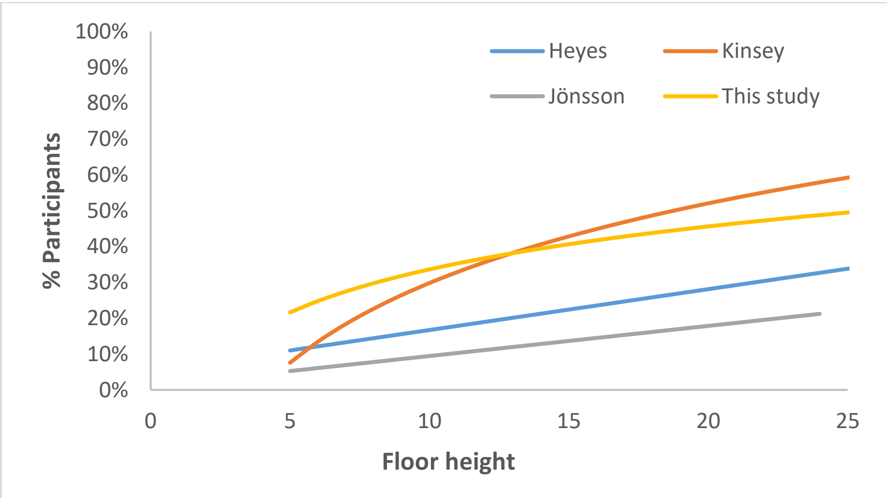


Figure 28. The comparison of the curve derived from aforementioned equations from 5th floor to 24th floor

Both equations from Heyes and Jönsson show a linear correlation, while the equations from Kinsey and this study showed a logarithmic correlation. The general usage of the elevators on each floor from this study is higher than those calculated by the equations from Heyes and Jönsson, which seems to indicate that online surveys may over-predict elevator usage. The usage in residential buildings shows a slower growth rate corresponding to the floor height, compared with Kinsey's curve. The reason why these two curves showed a similar logarithmic trend is possibly due to the similar methods of online survey used. The Fewer occupants in residential buildings would choose to use the elevators for evacuation above the 13th floor, compared with that in high-rise buildings.

The cross-comparison between different groups shows that the age and the experience of evacuation do not significantly influence people's choice of using elevators for evacuation, while different cultural background can affect it. Most people involved in this study stated that they are educated not to use elevators during an evacuation. More people in the UK shows a negative attitude towards elevator evacuation compared to the Chinese sample. This suggests that the evacuation strategies should be applied according to the local acceptance of elevator usage and the awareness of safety procedures during a fire event.

There are other factors that may influence the usage of the elevators for evacuation identified in this study. For the waiting time for the elevators for evacuation, Heyes stated that people would not wait for elevators for an infinite time. In the present study, it is concluded that 90% of people in residential buildings would not wait for elevators for evacuation for more than 5 minutes, compared to 15 minutes found by Kinsey. People in residential buildings tend to wait less time for elevators compared with people in high-rise buildings. It may be because they are also familiar with other routes to evacuate the building, compared with people in office buildings who used elevators more in their daily life. Redirection in the residential buildings that people know well is not easy to get lost. A time-counter has been identified as very useful to give people more information about the elevators, and it also can help the management team to instruct people to wait for a longer time if the strategies require (Mossberg, Nilsson, &Wahlqvist, 2021). This also can be seen in the results of the crowd density. Most people would use elevators for evacuation if they can enter it directly. Regardless of the risk of power outage, people would choose the fastest way for evacuation, which was also mentioned by Heyes. A significantly lower number of people claimed they would use elevators if they needed to wait them for a longer time (e.g., above 5 or 10 min), and there were many people in front of the elevators. The specific design of the capacity of the elevator on every floor according to the expected population density in elevator lobbies needs to be calculated before the evacuation strategies design. This is for ensuring people who are instructed to use the elevators can take the elevators directly or have a reduced waiting time for the elevators. This can reduce their risk perception associated with remaining in a threatened building while waiting for using the elevators during a fire. In addition, results show that people in China are willing to use elevators having more people in front of them in the elevator lobby. This may be linked to the higher average population density in each building in China.

The results of the fire location in relation to the current location of people show that people who are on the fire floor or the adjacent fire floor have less willingness to take the elevators. This means that evacuation strategies should not prioritize sending elevators to the fire floor or the adjacent floors, as people are less likely to use them there. However, the most urgent situation happens on the fire floor or the adjacent floor, so other specific plans for those floors should be studied rather than using elevators.

The results appear of high importance when it comes to the instructions during an evacuation, especially for the British sample. Among three kinds of instructions, only the instruction from people that are not familiar results in less usage compared with the other two ways. The occupants in residential buildings are rather stable compared with hotels or other spaces where there is a transient population. This means that it may be advisable to let the occupants know the people who are responsible for fire safety in residential buildings. It can help the management team to enhance the effectiveness of the instruction on evacuation.

As most people stated in this study, most of them are educated not to use the elevators during a fire. Therefore, taking elevators for evacuation is opposite to their general knowledge. In this study, people showed a positive attitude towards the use of evacuation plans including elevators when told those are reliable. If they know the evacuation plan is reliable beforehand, more people can accept to use elevators for evacuation. This is in contrast with the study by Kinsey for high-rise buildings (Kinsey, 2010), as most people in that study claimed they would not use the elevators even though they were told the elevators were safe for evacuation.

The people who survey respondents are accompanied during an evacuation is the most important factor, especially for the British sample. People would use stairs more when they are travelling alone, while most of them would use elevators when they were accompanied by people in a wheelchair. People who were with people with mild limitations also claimed an increased possibility of using the elevators. This means that when designing evacuation strategies, people with functional limitations should be considered with great emphasis, as the evacuation time would depend not only on their evacuation but also on the behavior of other building occupants along with them. The characterization of the population in residential buildings is necessary for adequate evacuation plans. This includes the space needed in elevators for accommodating people on a wheelchair.

In the simulation study, a set of limited total evacuation scenarios was investigated, compared with other research for optimal evacuation strategies in high-rise buildings. This study excludes egress components such as skybridges and refuge areas and focused only on stairs and elevators. This is in line with the typical floor plan and the structure of residential buildings, i.e., they are generally simpler than office/hotel high-rise buildings, as well as include a lower density of population. However, this simulation can help quantify the consequences of people's behavior as reported in the survey. The most effective way to reduce evacuation times is to instruct people with mobility limitations to use the elevators and have other occupants use elevators afterwards. People with mobility limitations will lead to a longer RSET in case of total evacuation, due to their lower travel speed which can make the congestion in the staircase The use of elevators for evacuation can reduce congestion in the staircases, which can greatly improve the efficiency of evacuation. This can also prove the importance of instructions. The instructions in the evacuation strategies should include the group of people who should be prioritized in using the elevators. Optimizing the usage of the elevators for those populations who would greatly benefit from them is an important point for an inclusive evacuation strategy.

5. Conclusions

This study focused on human behaviors in relation to elevator evacuation in residential buildings. According to the results of this study, the likelihood of people using elevators to evacuate buildings is related to seven factors at different level. It is shown that whether respondents are accompanied by people with mobility limitations is the primary factor that influences their choice of using elevators for evacuation. In addition, the floor height and the instruction types are also important factors.

Several conclusions are made based on the results of both the online survey and simulation:

- The usage of elevators increases with the floor height in residential buildings. It cannot be proved that this ascending trend is influenced by the age of participants, as well as their past experiences of evacuation and their cultural background. However, the difference in usage is shown in different countries (China vs UK).
- Most respondents claimed that they will not wait for elevators for more than 5 minutes, which is much less than research in previous studies for general high-rise buildings. Information from a count-down time of elevators can change their choice of using elevators. If participants can enter the elevators directly, their willingness of using elevators will be increased.
- The willingness of using the elevators for evacuation will decrease if people are located on the fire floor or the adjacent floor. More people will use elevators when they are far away from the fire floor, while the willingness varies in different countries (UK vs China).
- Fewer people will use elevators for evacuation if they are instructed by unfamiliar management team staff, compared with the visible and audible signages and the familiar management team staff.
- If people know the evacuation plan including elevators is reliable, the willingness of using them for evacuation will increase.
- Based on the results of the simulation, comparing other scenarios, letting all people with mobility limitations use elevators for evacuation leads to the shortest total evacuation time. In addition, this scenario also reduces the congestion in the staircase.

According to these results, some recommendations on the evacuation strategies design can be provided:

- Before designing evacuation strategies for a building, the number of occupants on each floor should be investigated to determine the capacity of elevators. In addition, the usage of elevators on each floor is recommended to be estimated. This is for confirming that people with mobility limitations and people who are willing to use elevators for evacuation can enter them as soon as possible.

- It is recommended to disseminate the evacuation plan to the occupants in a residential building and let them know the face of the staff of the management team who is responsible for fire safety.
- People who are on the fire floor have a very low willingness to use elevators for evacuation. It is recommended to set the elevators to the farther floor in priority. The people who are on the fire floor are better have other evacuation method.
- When designing a total evacuation strategy including elevators for a residential building, people with mobility limitations should be given priority. It is recommended to offer more instructions for those people to use elevators.

5.1 Future research

Due to the constraints of this online survey and the simulation scenarios, a broader range of research questions should be investigated in the future. Seven factors that can influence human behaviors are explored only between China and the UK. There is a need to explore more factors that are related to human behaviors in residential buildings during an evacuation. In addition, a broader range of people from different countries and regions can be involved in the research. The hypothetical building in this study can merely represent part of high residential buildings. More types of residential buildings and configurations can be investigated for broader use.

In this study, due to the model of Pathfinder, the recall system of the elevators can only discharge people on the exit floor, which will lengthen the waiting time for elevators of people on each floor. This can influence the usage of elevators in a real evacuation. Therefore, another model can be used to change the recall system for designing a better recall system of elevators for residential buildings. More scenarios can be set for detailing the evacuation strategies or including more evacuation methods, i.e., phased evacuation.

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8. Appendices

A1. Online survey

This section shows the summary of the questions in the online survey.

The questions related to the daily use of the elevators are present in A1.1. The questions related to the elevator use for evacuation are present in A1.2. The questions related to residence information are present in A1.3. The questions related to personal information are present in A1.4.

A1.1 Daily use of elevators

The aim of this part is to investigate your **daily use** of the elevators, different scenarios will be given in the following questions.

-Assume you are in a residential building (**with 30 floors**) with which you are familiar and in which you have lived for several years.

-This building contains both elevators and stairs.

-Assume you do not carry anything.

If you **travel alone**:

1. From which floor would you consider using elevators but not stairs to travel down **without** time pressure?
   Fill a number from 2-30 /or "0" represents "always use stairs", "1" represents "always use elevators",

   The first floor is regarded as the ground floor.

   _____ floor

If you **travel with a person/people in a wheelchair:**

1. From which floor would you consider using elevators but not stairs to travel down **without** time pressure? (Fill a number from 2 to 30)
   Fill a number from 2-30 /or "0" represents "always use stairs", "1" represents "always use elevators"

   The first floor is regarded as the ground floor.

   _____ floor

If you **travel with a person/people with mild mobility limitations** (e.g., minor problems in walking):

1. From which floor would you consider using elevators but not stairs to travel down **without** time pressure? (Fill a number from 2to 30)
   Fill a number from 2-30 /or "0" represents "always use stairs", "1" represents "always use elevators"

The first floor is regarded as the ground floor.

_____ floor

A1.2 Use elevators for evacuation

The aim of this part is to investigate your perspectives on **evacuation by elevators,** different scenarios will be given in the following questions.

-Assume you are in a residential building (**with 30 floors**) with which you are familiar and in which you have lived for several years.

-Assume you do not carry anything

-**There is a fire happening everyone in this building should be evacuated.**

-This building contains both elevators and stairs. **You can choose to use stairs or elevators to evacuate**.

1. What is/are the factor/factors that may influence your choice of evacuation way (through stairs or elevators) during a fire? (multi-choice)

A. The floor number you are on
B. waiting time for the elevators
C. Crowd density in front of the elevator
D. You are with people with mobility limitations or not
E. Your current location in relation to the fire floor
F. Instructions on evacuation
G. Reliable evacuation plan including elevators
H. Other reasons: ___________

-For answer A: The floor height:

1. From which floor would you consider using elevators but not stairs when evacuating in a fire?

   The first floor is regarded as the ground floor.

   -Fill a floor number from 2-30

   - Fill "0" represent "In any condition, I will use stairs"

   -Fill "1" represents "In any condition, I will use elevators"

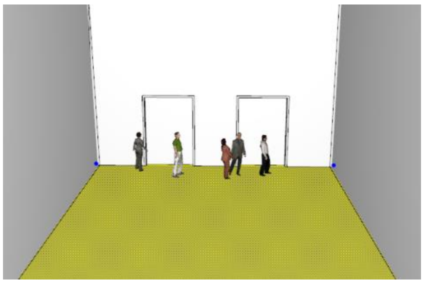
   _____ floor

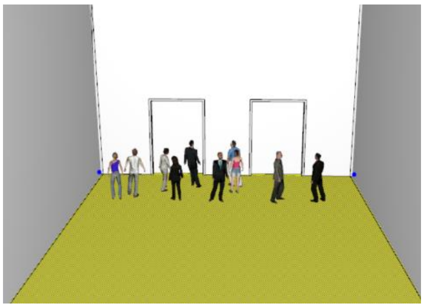
-For answer B: the waiting time:

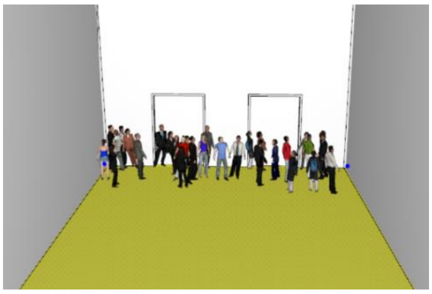
1. Regardless of the floor you are on, if you **don't know** how long you need to wait for the elevators, the maximum time you are willing to wait for them to evacuate the building. (minutes)____

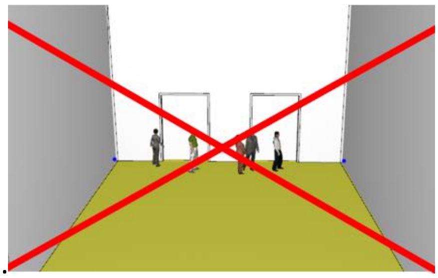
2. If you **know** how long you will wait for the elevators, would it affect your decision to wait for an elevator to evacuate?
    a. Yes
    b. No

-For answer C: crowd density of waiting for elevators

a.  You can enter it directly

b.  You need to wait for a little while

c.  You need to wait for a long time

d.  You will not use elevators

choose the figure with the maximum number of people you can wait for when evacuating by an elevator?

-For answer D: people you are accompanied by

1. If you are **with people/a person in a wheelchair**, would you choose an elevator for evacuating the building?

   a. Yes
   b. No
2. If you are **with people/a person with mild mobility limitations** (e.g., minor problems in walking), would you choose an elevator for evacuating the building?
   a. Yes
   b. No
3. If you are **alone**, would you choose an elevator for evacuating the building?
   a. Yes
   b. No

-For answer E: the floor on fire or not

1. If you **are on** the floor where the fire happens or on one of the adjacent floors above or below, would you use an elevator for evacuating the building?
   a. Yes
   b. No
2. If you **are not on** the floor where the fire happens or on one of the adjacent floors above or below, would you use an elevator for evacuating the building?
   a. Yes
   b. No

-For answer F: the instructions on evacuation procedures

1. If there is **audible/visible signage** instructing you to evacuate by elevators, would you use an elevator for evacuating the building?
   a. Yes
   b. No
3. If a person from the management team of this building that **you don't know** instructs you to evacuate by elevators, would you use an elevator for evacuating the building?
   a. Yes
   b. No
4. If a person from the management of this building that **you know** instructs you to evacuate by elevators, would you use an elevator for evacuating the building?
   a. Yes
   b. No

-For answer G:

1. If you know the evacuation plan can include elevators to evacuate safely, would you use them for evacuation?
   a. Yes
   b. No

2. Are your answers influenced by past fire events?
   a. Yes, by my own experience of fire events
   b. Yes, by the fire events I heard from other places
   c. Both of above

d. No influence by past fire events

3. If yes, please give a brief description of one fire event that affected your perception of elevator evacuation.

A1.3 Residence information

1. What is the type of building you have lived in during your life? (multi-choice)
    a. Multi-story house
    b. Single-story house
    c. Apartment
    d. Other types

2. How many floors does the highest building you have lived in have? ______

3. what is the highest floor you have lived on? _____

4. Have you lived in a building with elevators?
    a. Yes
    b. No

5. If yes, did any of the buildings you lived in have elevators that can be used during a fire?
    a. Yes
    b. No
    c. I don't know

6. Do you own or rent the current place you live in?
    a. Own
    b. Rent

7. Have you experienced an evacuation in a real fire event?
    a. Yes, in a real fire event
    b. Yes, in a fire drill
    c. Both of the above
    d. I have never experienced an evacuation

Please give a brief description of an evacuation event that influence you the most.

A1.4 Personal information

1. What is your age?

2. What is your gender? _____
    a. Male
    b. Female
    c. Not binary
    d. Prefer not to say

3. In which country have you lived the longest during your life?
4. Is either your occupation or education related to fire safety, building design, or building management? _____
    a. Related to fire safety,
    b. Related building design, building management
    c. Both of the above
    d. None of the above

5. Grade your functional limitation: Mobility limitation

   Description:

   Temporary Impairment is not included in this grade.

   Zero represents no limitation,

   Six represents the extensive impaired "You need to be cared for by others in your own place".

	☐	☐	☐	☐	☐	☐	☐	
No limitation	0	1	2	3	4	5	6	Extensive limitation