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Phased evacuation: Is it suitable for multi-purpose residential buildings?

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Disclaimer

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摘要

这项研究调查了多功能住宅建筑中分阶段疏散策略的全球采用及其适用性，将11个国家的33个规范的审查与基于仿真的分析结合，并涵盖了30种分阶段疏散场景。审查结果显示，全球范围内对分阶段疏散的重视程度存在差异，特别是在欧洲的英国显示出了更加强烈的重视程度。在建模与模拟研究中，所有场景都设置了四种不同的占用者类型，其中包括10%的功能障碍占用者，这增强了研究的包容性与真实性。多因素方差评估（MVA）被用来解决疏散模拟中的固有不确定性。为了选择合适的疏散模拟器，对Evacuationz和Pathfinder进行比较分析，结果显示二者的一致性，Evacuationz具有更快的模拟时间。分阶段部分疏散场景总体上显示出比分阶段全部疏散场景更短的总疏散时间。尽管在第一阶段纳入了最拥挤楼层的疏散可以减少总疏散时间，但这会延迟火灾楼层的清场。没有一种标准化的分阶段疏散策略可以普遍适用于所有多功能住宅建筑。因此，可能希望使用分阶段疏散策略的项目利益相关者应利用精心设计的分析方法，以各自案例为基础理解疏散动态并证明他们的决策。这可以通过疏散模型来实现。然而，两个已确定的关键方面可以被考虑：1）在启动模拟研究之前，需要仔细选择模拟工具并解决其中的不确定性；2）避免在第一阶段与火灾楼层一起疏散上层楼层或最拥挤的楼层，以防止对火灾楼层疏散造成延迟。此外,未来的研究应聚焦于以下方面：1）探索与实际实践相一致的最佳疏散间隔，2）引入新的场景，逃生选项的冗余性得到测试，例如：一个楼梯间被烟雾填满，以及3）研究对相关法规框架的任何修正和新版本所产生的影响。

关键词：分阶段疏散，疏散模拟，Pathfinder，Evacuationz，多功能住宅楼

List of Abbreviations

BIM	Building Information Modelling
EPC	Euclidean Projection Coefficient
ERD	Euclidean Relative Difference
ICC	International Code Council
ISO	International Organization for Standardization
MVA	Multifactor Variance Assessment
NFPA	The National Fire Protection Association, United States of America
NIST	National Institute of Standards and Technology, United States of America
OECD	Organization for Economic Cooperation and Development
OEEs	Occupant Evacuation Elevators
SC	Secant Cosine
SFPE	Society of Fire Protection Engineers

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1. Introduction

1.1. Background

It is predicted that the population worldwide in cities will almost double in 2050, making urbanization as one of the most influential trends of the twenty first century. (UN-Habitat, 2017). By 2020, urbanization had been integrated into the national policy frameworks and institutional structures of more than 150 nations (OECD et al., 2021). Following the trend of urbanization, Generalova et al. (2018) stated that strategically planned muti-purpose buildings have the potential to enhance urban economies and environmental circumstances, all the while promoting a high quality of life. A multi-purpose building is a building designed to accommodate two or more functions, with each function allocated a specific amount of floor area, while usage and facility management are interconnected, establishing a relationship among all the utilized areas (Chi et al., 2011). Furthermore, Culaba et al. (2020) highlighted that one of the notable trends in the construction industry involves the rise of muti-purpose residential buildings, which integrate diverse functions within a single structure. A multi-purpose residential building includes various combinations such as assembly spaces, hotel rooms, as well as retail units combined separately with residential flats (Culaba et al., 2020; Azian et al., 2023). The advantage of this type of building is convenient as it can provide occupants with various living activities, facilitated by its wide range of units within one single building (Narvaez & Penn, 2016).

However, different occupant types and occupant loads across various sections within the multi-purpose residential building might lead to challenges regarding the adopted evacuation strategy and their ability to execute such strategy. For example, some occupants might be sleeping, while others are awake. This can also lead to different values of pre-evacuation times. The difference between pre-evacuation times may cause congestion on stairs for a simultaneous evacuation strategy.

1.2. Evacuation Strategy

An evacuation strategy is also known as the evacuation philosophy or egress strategy. It helps occupants evacuate from an unsafe place of a structure to a secure location where their health is ensured, or to remain in a protected place during emergencies (Lay, 2007; Bukowski & Tubbs, 2016; Home Office, 2022). Ronchi et al. (2022) described the term evacuation as related to movement during an emergency scenario, while egress is used to refer to the movement of occupants when they leave the structure. Furthermore, Groner (2016) has also suggested that the term "occupant movement" should replace the "evacuation strategy", because occupants may be advised to either relocate to a different position within the same building or stay in their current location. However, only the term "evacuation strategy" is used in the following sections to avoid the semantic confusion.

There are several types of evacuation strategies elaborated by various researchers and organizations. Lay (2007) mentioned two fundamental evacuation strategies, which are phased evacuation and simultaneous evacuation. Ronchi and Nilsson (2013) highlighted there are four main types of evacuation strategies, including defend-in-place and delayed evacuation in addition to the two strategies mentioned above. Home Office (2022) summarized there are six widely accepted evacuation strategies, namely, phased evacuation, simultaneous evacuation, stay put, partial evacuation, delayed evacuation, and defend-in-place (also referred as 'stay-in-place'). The delayed evacuation and the defend-in-place are deemed as two primary variants of the partial evacuation (Home Office, 2022). To clarify their similarities and differences among evacuation strategies from various research works, how they guide affected occupants and unaffected occupants to react to fire emergencies in buildings are summarized in the Table 1 below. The refuge area mentioned in the table is the designated area for holding occupants in buildings, offering advantages such as reducing smoke exposure, aiding evacuation for people with functional limitations, and facilitating firefighting, although challenges from human behavior and cost-effectiveness may affect their effectiveness (Ronchi & Nilsson, 2013).

Table 1. Summary of various evacuation strategies, as intended in the present work only

		Affected Occupants	**Unaffected Occupants**
Total Evacuation	**Simultaneous Evacuation**	Evacuate (All Occupants)	Evacuate (All Occupants)
	Phased Evacuation	Evacuate (Occupants in the vicinity of fire)	Remain in place for later evacuation or instructions /Stay (Others)
Partial Evacuation	**Defend-in-Place**	Evacuate (Minimize evacuating occupants)	Not to evacuate until instructed (Others)
	Delayed Evacuation	Wait to be rescued in refuge areas (Occupants who need help to evacuate)	Remain in place, then evacuate (Others)
	Stay Put	Evacuate (Occupants directly affected)	Remain in homes (Occupants not directly affected)

It is crucial to select a suitable evacuation strategy for a specific type of building. Establishing an evacuation strategy constitutes a key step in ensuring a satisfied level of fire safety (Aleksandrov et al., 2019). The interrelation between evacuation strategies and building safety design is also evident, as Tubbs and Meacham (2009) affirmed that the safety design of structures is greatly impacted by the specific evacuation strategy selected. In the Sub-Clause 4.2.1 Occupant Protection of National Fire Protection Association (NFPA) 101 Life Safety Code, there is a statement: "*A structure shall be designed, constructed, and maintained to protect occupants who are not intimate with the initial fire development for the time needed to evacuate, relocate, or defend in place.*" (NFPA, 2023a), which highlights the proposed evacuation strategy needs to satisfy an appropriate level of safety of the occupants.

Furthermore, various international evidence prove phased evacuation is a safer choice than simultaneous evacuation in the residential buildings when effective passive fire protection system is operating efficiently (Home Office, 2022), i.e., fire rated compartmentation, well-maintained pressurized stairwells, etc.

1.3. Phased Evacuation

As briefly mentioned above, the foundation idea of phased evacuation is that the compartmentation and other fire safety systems can contribute to put limitations on rapid fire growth rate between adjacent floors (Lay, 2007). Many compelling benefits of implementing phased evacuation in buildings were discussed. Ronchi and Nilsson (2013) highlighted a set of benefits of adopting the phased evacuation, i.e., to reduce the overcrowding in the evacuation routes and minimize waiting times in front of the evacuation components. In addition, implementing phased evacuation strategy in residential buildings can minimize queuing times for occupants during the evacuation process, predominately through reducing the possibility of congestions in staircases (Wood, 2007; Kulkarni & Agashe, 2016). While the benefits of adopting a phased evacuation strategy in fire safety design have been discussed, there has been limited simulation or experimental validation of the benefits of phased evacuation in multi-purpose residential buildings. Previous studies have primarily focused on general high-rise residential buildings (Koo et al., 2013; Gravit et al., 2018; Home Office, 2022), commercial office buildings (Lay, 2007), high-rise elderly housing (Fang et al., 2023), and high-rise office buildings (Kadokura et al., 2015; Zhai, 2019), which reveal necessity of exploring the suitability of phased evacuation for multi-purpose residential buildings.

Currently, there is no uniform procedure defined for phased evacuation, including who should evacuate in the first phase, what an appropriate phase interval is, and how many floors should be evacuated at a time in subsequent phases. The evacuation action for occupants will preferentially take place on the floor where the fire occurs and the floors above it, while in some cases, it may also include the floors below it (Hartmann, 2005; Lay, 2007; Ronchi & Nilsson, 2013). Additionally, Groner (2016) provided a brief definition of the phased evacuation of the entire building, i.e., all occupants are required to leave the building, but the evacuation is carried out in different phases based on vulnerability of occupants during the emergency scenario. According to this definition, there is no explicit mention of evacuating the residents of the fire-affected floors and adjacent floors first. It only implies that the evacuation should be based on the vulnerability of occupants. The definition of phased evacuation is examined in the subsequent review for codes and standards. Additionally, it is well noted that some researchers and organizations tend to use “phased evacuation” and “staged evacuation” interchangeably or treat these two terms synonymously, e.g., Hosseini et al. (2021), NFPA 101 Life Safety Code (NFPA, 2023a). To avoid semantic ambiguity, only “phased evacuation” is employed in this research.

1.4. Occupants on Evacuation Components

When occupants start evacuation following a specific evacuation strategy, they need to pass through various evacuation components. The evacuation components in buildings include staircases, occupant evacuation elevators (OEEs), and additional evacuation components, i.e., refugee floors, sky-bridges, escalators, as well as several alternative evacuation systems (Wood, 2007; Ronchi & Nilsson, 2013; Bukowski & Tubbs, 2016; Zhang, 2017; Hutomo & Tambunan, 2020). Among these evacuation components, the utilization of alternative evacuation systems is infrequent and rare (Ding et al., 2021). Ronchi and Nilsson (2013) have mentioned evacuation on stairs is one of the most traditional evacuation components. To date, stairs are still regarded as one of the primary evacuation components (Fang et al., 2023), and in certain cases, they might be the only available vertical evacuation component (Huo et al., 2016). However, occupants who have functional limitations, might encounter challenges in using staircases for evacuation (Spearpoint & MacLennan, 2012; Koo et al., 2013; Bukowski

& Tubbs, 2016; Ding et al., 2021; Hostetter & Naser, 2022). Sometimes, elevators have the potential to be utilized as an effective evacuation component. For instance, during the 2001 World Trade Centre evacuation, a proportion of survivors were able to successfully evacuate with elevators, although they were not originally designed for this purpose (Bukowski & Tubbs, 2016). During vertical evacuation on stair, occupants' characteristics often differ from those in horizontal evacuation scenarios (Ding et al., 2021). Some researchers have analysed some easily measurable aspects, e.g., unimpeded walking speed (Kuligowski et al., 2015b), while others have concentrated on crowd dynamics, e.g., merging behaviour (Gwynne & Boyce, 2016). Additionally, the ability of occupants with functional limitations to use staircases are reviewed, as not all residential buildings were equipped with elevators, e.g., the building model described in Section 1.6.

It is worth to note that downstair walking speed and unimpeded walking speed often exhibit different ranges. The downstair walking speed limited by the discrete nature of the steps and the landing between two consecutive stairs, which requires occupants to make lateral turns on landings with a slower pace than they step downstairs (Ding et al., 2021). Meanwhile, the presence of longer evacuation distances and higher building floors may result in a decrease in the speed of evacuation with staircases (Peacock et al., 2012; Peacock et al., 2017). However, Ronchi et al. (2014a) mentioned that the determination of downstair walking speeds is generally influenced by the assumed travel path, and inconsistencies can arise when different hypothetical paths are employed. Gwynne and Boyce (2016) summarized research which studied walking speed on staircases in the Fifth Edition of the SFPE Handbook. A collection of data from their summaries and suitable data from other experiments, pertaining to the downstair walking speed of occupants is summarized in the Table 2. Although they are not applied in subsequent simulation settings, understanding the dynamics of occupants descending stairs in real-life scenarios can facilitate better understanding of the underlying logic of the employed evacuation model. Proulx & Bénichou (2010) performed evacuation experiments with various illumination conditions, which showed that downstair walking speed ranged from 0.40 m/s to 0.66 m/s. Hoskins (2011) analysed data from various type of buildings, downstair walking speed typically falls within the range between 0.44 m/s to 0.72 m/s. Ma et al. (2012) organized the evacuation experiment of young, middle-aged, and elderly people with a mean speed as 0.28m/s at Shanghai World Financial Center. Choi et al., (2013) investigated downstair walking speed of 0.83 m/s for male and 0.74 m/s for female in a 50 floors long evacuation. The NIST Engineering Laboratory has gathered data of downstair walking speed during fire drill evacuations, which indicated downstair walking speed range from 0.1 m/s to 1.7 m/s (Kuligowski et al., 2015b; Peacock et al., 2017). Furthermore, a very recent experiment consisting of 18 different occupants' groups aligned with the occupants' characteristics in multi-purpose residential buildings. The results of the experiment reveals a 1.18 m/s – 1.49 m/s downstair walking speed range (Wei et al., 2023). This range significantly surpasses the findings of other data sets.

Table 2. Downstair Walking Speed under Different Conditions

Source	**Downstair Walking Speed (m/s)**	**Occupants Characters**	**Number of Floors**	**Notes**
Proulx & Bénichou (2010)	0.40 – 0.66	Age: 18 – 65	13 floors	Canadian data; various illumination conditions
Hoskins (2011)	0.44 ± 0.15 0.48 ± 0.20 0.59 ± 0.23 0.61 ± 0.12 0.72 ± 025	-	30 floors 18 floors 10 floors 62 floors 24 floors	United States Data; Evacuation Drills
Ma et al. (2012)	0.59 – 0.62	Age: 21 - 62	< 20 floors	Chinese Data
Choi et al. (2013)	0.83 0.74	Male Female Average age:23.4	50 floors	South Korean Data, Long Evacuation
Kuligowski et al. (2015b); Peacock et al. (2017)	0.44 ± 0.19 (0.10 ± 0.008 – 1.7 ± 0.13)	-	6 floors – 62 floors (Different in 14 buildings)	United States Data; Evacuation Drills in 14 buildings
Wei et al. (2023)	1.18 – 1.49	Adult College Students	18 floors	Chinese Data; 18 different evacuation groups; Much Higher speed than others

In addition, considering the presence of occupants with functional limitations in residential buildings, it is necessary to review their movement characteristics on stairs. They may have difficulties traverse on staircases when they need to evacuate (Bukvic et al, 2021; Hostetter & Naser, 2022), as they usually need assistances from other occupants or use one of walking aids (Ding et al., 2021). Kuligowski et al. (2013) observed the walking speed of occupants with functional limitations on stairs, which ranged from 0.11m/s to 0.29m/s. In another study, Kuligowski et al. (2015a) further summarized an average downstair walking speed of 0.31m/s ± 0.16m/s. Compared the finding with Table 2, it reveals occupants with functional limitations tended to move at much slower on stairs. In addition, when they need assistance in evacuation, auxiliary evacuation devices are often required, e.g., hand-carried stair descent devices (Lavender et al., 2014), sled-type stair descent devices (Lavender et al., 2015), and track-type staircase descent devices (Mehta et al., 2015), etc. The use of aid devices and personnel (usually firefighters or trained staffs) are expected to slow down walking speed of other occupants on staircases (Averill et al., 2005). The use of OEEs would shorten the time takes for every occupant to evacuate outside, especially benefiting those who have functional limitations (Kinateder et al., 2014). Previous phased evacuation simulations for occupants with functional limitations has shown that elevators contribute to a more effective evacuation, because it can avoid bottleneck on staircase landings and shorten the total evacuation time (Koo et al., 2013). Reneke et al. (2013) investigated that evacuation can speed up by approximately 16% to 25%, while the higher the floor, the greater the impact. It has already been applied in real-life cases, e.g., Shanghai World Financial Center employs emergency elevators to evacuate occupants with functional limitations when fire occurs (Katz & Robertson, 2008), while Taipei 101 Financial Center allows occupants with functional limitations below the fire-occurring floor to evacuate with specific elevators and others are required to use staircases (Chien & Wen, 2011). Furthermore, there will be the extra benefit for utilizing elevator only to evacuate occupants with functional limitations in the phased evacuation. If all occupants be evacuated simultaneously on elevators, total evacuation time might be dramatically prolonged because of the limited capacities of OEEs, which also lead to potential congestion and longer waiting times in front of OEEs (Harding et al., 2010; Heyes & Spearpoint, 2012; Ronchi & Nilsson, 2013). Instead, using OEEs to evacuate occupants with functional limitation in phases might mitigate these negative impacts.

Furthermore, downstair walking speed of occupants on stair landing are expected to be influenced by merging flows (Ding et al., 2021). Occupant merging flow on stairs is defined as the confluence of the occupants' flow from upstairs and the other occupants' flow from each floor of the multi-story structure (Sano et al., 2017). A demonstration of merging flow is shown in Figure 1. There is a key character called merging ratio in a merging flow scenario, which is also referred as configuration ratio (Zeng et al., 2018). It represents the proportion of individuals entering a landing from the floor to those entering from the staircase (Sano et al., 2017), which enables designing the architecture with flexible sizes of doors and landings to control the occupant flow into the stairs (Sano et al., 2018). Several researchers have determined the likely ratio, which approximation of 50:50 (sometimes also referred as '1:1') appears to be a reasonable estimate (Pauls, 2004; Purser & Gwynne, 2007; Boyce et al., 2012; Zheng et al., 2019).

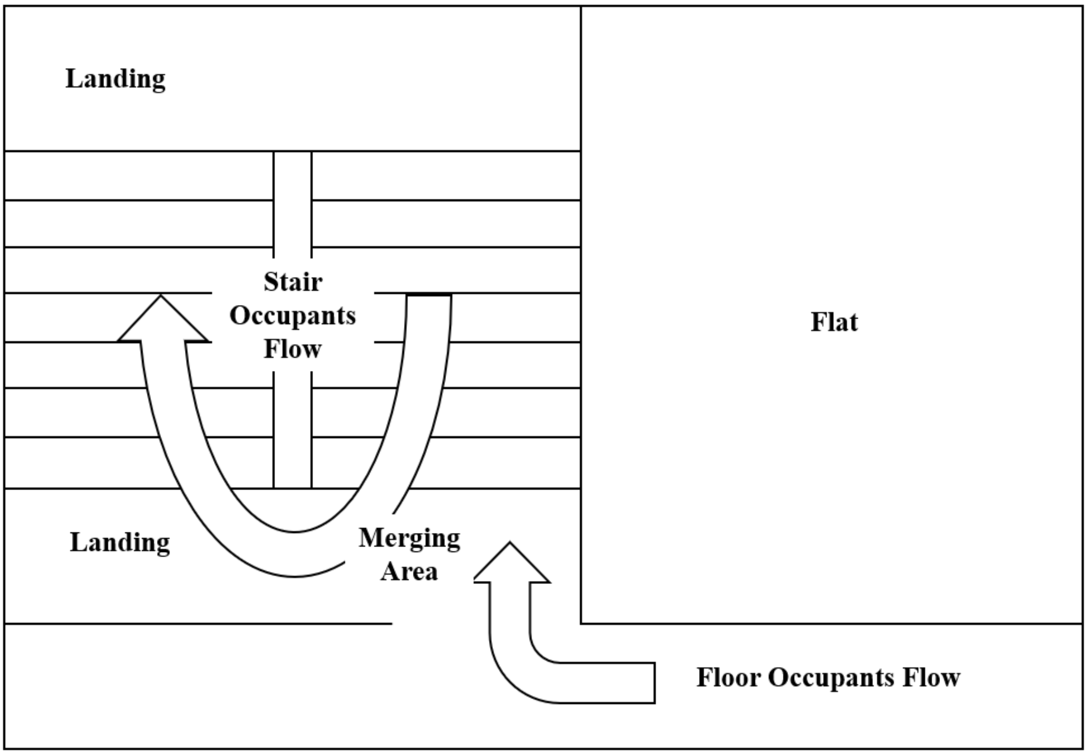


Figure 1. A schematic representation of a staircase-landing merging flow

The merging flow is facilitated when the door is initially open, while closing the door initially results in a 30% decrease in downstair walking speed, and merging is simpler when the crowd density is lower (Takeichi et al., 2005). Kadokura et al. (2015) examined the flow and congestion patterns in staircases during phased evacuation in a 25-story office building. They observed that congestion occurred due to the merging flows from both floor area and upper floors. This provides valuable insight for analysing the relationship between floor clearance time and total evacuation time. Huo et al. (2016) conducted an experiment to indicate when occupants converge and merge at stair landings, walking speed of occupants from upstairs are obviously reduced, and the staircase landings can become a bottleneck. In addition, a series of experiments were conducted to examine the impact of illumination, merging ratio. and availability of handrails (Zeng et al., 2017; Zeng et al., 2018). Their findings indicated that the occupants' walking speed initially decrease and then stabilize as they enter the merging area over time. The available handrails were found to reduce the time spent at landings or interfaces, while the merging flow is influenced by illumination and initial merging ratio. Ding et al. (2013) explored that positioning the door on the opposite side of the landing from the stair is the most suitable location. This setup improves the efficiency of evacuation on upper floors while restricting evacuation on lower floors. Zhu et al.

(2020) also discovered that the most optimal door location should be adjacent to the upward staircase. This is consistent with findings of Ding et al. (2013).

1.5. Evacuation Modelling

This research employs evacuation modelling to investigate various phased evacuation scenarios. It is necessary to familiarize oneself with the modelling tools to be used before starting the simulation. Evacuation modelling is a simulation approach in performance-based design, which means that evacuation simulators can be used to assess the level of life safety in any type of buildings (Kuligowski & Peacock, 2005; Ronchi & Nilsson, 2016). There are three approaches to study a specific evacuation in a performance-based design (Kuligowski, 2016). The first one is empirical approach which involves comparing the given building to data gathered from a similar building for analysis, while the second is manual engineering approach based on calculation methods, i.e., Predtechenski & Milinski (1978) method, Gwynne and Rosenbaum (2016) SFPE method, etc. The third approach is computer evacuation modelling, which includes a broad range of methods and complexity levels, spanning from basic representations of uniform occupant movement to advanced simulations of agents navigating in three-dimensional nodes, grid, or continuous space (Kuligowski, 2016).

There are several key factors should be incorporated into an evacuation model, i.e., occupant behaviour, building layout configuration, building environmental factors, and implemented evacuation procedures in building, where the occupant behaviour is often regarded as the most important one (Gwynne et al., 1998). Three modelling methods are categorised based on presence of occupant behaviour, namely, movement models, partial behaviour models, and behavioural models (Kuligowski, 2016). They are categorised based on how much behavioural components are incorporated. For the behavioural models, occupants (agents) can perform operations according to presets, and not only move toward the specified exit. However, it is significant to note that while some theories regarding occupant movement during evacuations are integrated into models, there is currently no generalized theory that explains all occupant behaviours in fire incidents (Gwynne & Kuligowski, 2016). Many existing evacuation models lack the capability to assign actions and behavioural itineraries due to limited data available (Kuligowski, 2016). In other words, even if there are behavioural modules in the model, they tend to be simplified. As for the building layout configuration, there are four basic representations of them. Originally, geometries of evacuation models were mostly based on the coarse network and then the fine network (Gwynne et al., 1999; Kuligowski & Peacock, 2005), and over time, continuous space models have gradually become more popular (Kuligowski et al., 2010). For coarse network, the representation of the geometry is achieved by utilizing network comprising nodes and arcs that are interconnected. While fine network models depict a well-structured geometry by employing either a grid composed of cells or a network consisting of nodes interconnected by arcs (Ronchi & Nilsson, 2016). As for continuous space models, geometry is designed through continuous space that includes individual agents. These microscopic-level agents possess coordinates indicating their occupants' sizes, positions, and shapes, which can move about unrestrictedly, relatively emulating real-world behaviour (Ronchi & Nilsson, 2016). Various evacuation models are incorporated one of these occupant behaviours and geometrical configurations.

Many researchers reviewed, categorized, and evaluated over 70 computer evacuation models over past dozens of years (Gwynne et al., 1999; Kuligowski & Peacock, 2005; Kuligowski et al., 2010; Kuligowski, 2016; Lovreglio et al., 2020). It is crucial to select the appropriate simulation tool prior to initiating the research based on their input features simulation capabilities (Kuligowski, 2003; Forell et al., 2013), while check their availability for research purposes. Employing two different modelling tools can facilitate the discernment of natural variations between the models regarding their predictions for evacuation times (Ronchi & Nilsson, 2014). There are two models have distinct occupant behaviours and geometrical configurations from each other, i.e., Pathfinder and Evacuationz. Both Evacuationz and Pathfinder are incorporated with behavioural module (Kuligowski, 2016). However, the Evacuationz is categorised as behavioural model, while the Pathfinder is regarded as a partial behavioural model. For building geometries configuration, Evacuationz adopts coarse network, meanwhile the Pathfinder is on the basis of continuous space. These two models are presented in subsequent paragraphs, to especially explore their potential benefits and limitations for this simulation on phased evacuation in multi-purpose residential buildings.

The Evacuationz is a probabilistic Monte Carlo-driven evacuation model which employs coarse network to represent geometries, while occupants are represented as entities with their distinct behavioural characteristics (Spearpoint, 2009). It has been validated for a set of evacuation components (Teo, 2001; Tsai, 2007; Spearpoint, 2009), and various building types, i.e., a single-storey industrial building (Ko, 2003), a lecture theatre (Ko, 2003; Xiang, 2006), a single-storey recreational building (Spearpoint, 2012), high-rise buildings (Tsai, 2007; Spearpoint, 2009; Heyes & Spearpoint, 2012), a mega high-rise multi-purpose building (Spearpoint & Glasgow, 2017), and a series of high-rise residential building floorplates (Spearpoint et al., 2024a; Spearpoint et al., 2024b). Evacuationz can simulate complex building geometries while spending a relatively short time (Spearpoint, 2009). Thompson et al. (2015) used to raise concerns about the validity of data used in existing evacuation models which might not reflect the changing occupants' profiles. While Heyes and Spearpoint (2012) already demonstrated that Evacuationz is a model capable to consider several occupant variables, especially older and obese occupants who may have functional limitations. However, they also highlighted several limitations of Evacuationz, i.e., an elevator component is not incorporated into the model, it does not consider the possibility of resting or reduced movement due to fear of falls or fatigue, nor does it incorporate the effects of occupants' body size given its coarse network modelling approach (Heyes & Spearpoint, 2012).

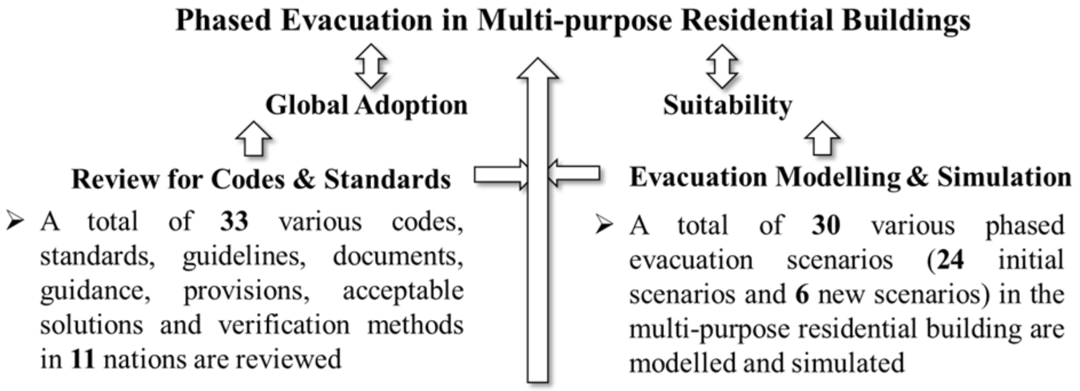
Pathfinder is an evacuation simulator developed by Thunderhead Engineering (2009), which is based on a continuous spatial representation (Ronchi & Nilsson, 2014). Pathfinder is a commercial simulator widely used for evacuation modelling (Lovreglio et al., 2020), which has large community of research and application users worldwide. Researchers have previously employed it to assess the most suitable evacuation strategy in high-rise buildings (Ronchi & Nilsson, 2014), while others utilized it to investigate a new phased evacuation algorithm (Gravit et al., 2018). More currently, some researchers applied Pathfinder simulation against experimental results (Ivanov & Chow, 2023), whereas another group of researchers used Pathfinder and an add-in prototype to implement and test a proposed two-way integration framework for Building Information Modelling (BIM) and fire evacuation models (Yakhou et al., 2023). Compared with Evacuationz, Pathfinder can display a three-dimensional evacuation process, which allow users intuitively see the distribution and movement trend of occupants at various times. In addition, a BIM file can be directly imported into Pathfinder for evacuation modelling. This is significant because it is becoming increasingly popular for project key stakeholders to adopt the project BIM model to enhance collaboration among each other (Gaur & Tawalare, 2022), including fire engineers.

2. Research Objectives & Methodology

As discussed in Section 1.3, there are various definitions or evacuation procedure suggestions for phased evacuation in the world today. However, there are often differences in the definitions of phased evacuation procedures across different regions. The importance placed on phased evacuation varies among different regions as well, showing a trend of differentiation. Additionally, no dedicated research has been found on phased evacuation strategies for multi-purpose residential building including assembly spaces, with the majority of research focusing on office buildings (Zhai, 2019), elderly housing (Fang et al., 2023), etc. This research proposes to explore the current state of phased evacuation adoption, and the potential suitability of phased evacuation strategy within the context of multi-purpose residential buildings, i.e., a residential building with assembly spaces in this research. By analysing a series of scenarios and variables, it aims to determine a detailed understanding of the suitability of phased strategy in diverse real-life scenarios.

To fulfil the aim, there are two key objectives initiated. And Figure 2 demonstrates the research aim and objectives.

i. First, to complete a review of current codes and standards in various regions around the world. This aims at finding out if phased evacuation is discussed and how. If they incorporate phased evacuation, there is a summary of under what circumstances it can be employed, and requirements for its implementation.
ii. Subsequently, to find out and justify if phased evacuation strategy is suitable for multi-purpose residential buildings. 30 various scenarios designed under different conditions are analysed, focusing primarily on total evacuation time and floor clearance time, particularly the clearance time of the fire floor.



- A total of **33** various codes, standards, guidelines, documents, guidance, provisions, acceptable solutions and verification methods in **11** nations are reviewed
- A total of **30** various phased evacuation scenarios (**24** initial scenarios and **6** new scenarios) in the multi-purpose residential building are modelled and simulated

Figure 2. Demonstration figure of research aim & objectives

In other words, this research adopts a hybrid methodology, which including both a review for codes and standards and a software simulation approach. In research, these two methods are complementary. A codes review can inform the conceptual framework and design of the evacuation simulation study, providing a foundation of knowledge and identifying gaps that the simulation can address. The codes review is a research method that falls under the category of secondary research. It involves the summary, and analysis of current fire engineering design related codes, standards, guidelines, documents, guidance, provisions, acceptable solutions and verification methods (Hereinafter referred to as “codes and standards”) to gain insights into the current state of knowledge. In this research, the main focus of the codes review is to explore current fire safety design codes in various countries and regions, and to use results as the base for further settings of evacuation modelling scenarios in multi-purpose residential buildings. The evacuation simulation involves the use of computer-based evacuation models, i.e., Pathfinder and Evacuationz, to simulate various evacuation scenarios.

3. Review for Codes and Standards

3.1. Review Procedure

The codes review for phased evacuation includes current codes from a wide range of countries and regions, which also includes international codes and several fire safety engineering books. Within this stage, the consideration for selection of countries and regions is on the basis of their economic influence and population size. The initial selection of reviewing scope is shown in the Table 3. In Western Europe, the United Kingdom of Great Britain and Northern Ireland, Federal Republic of Germany and Republic of Ireland are initially selected, with England and Scotland being singled out for respective review due to their separate codes within the United Kingdom. In Northen Europe, the Kingdom of Sweden is chosen. Meanwhile, in Southern Europe, the Italian Republic is chosen for screening. In Asia, the initial selection is more focused on the economically vibrant East Asian area. While in America and Oceania, five countries are chosen in the initial scope for screening.

Table 3. Initial scope for screening

Europe	Asia	America	Oceania
United Kingdom of Great Britain and Northern Ireland	People's Republic of China	United States of America	Commonwealth of Australia
England	Hong Kong Special Administrative Region of the People's Republic of China		
Scotland			
Federal Republic of Germany	Japan	Canada	New Zealand
Republic of Ireland	Republic of Korea	Federative Republic of Brazil	
Italian Republic	Republic of Singapore		
Kingdom of Sweden			

The second procedure is to identify, collect, and screen the current fire engineering design related codes, standards, guidelines, documents, acceptable solutions and verification methods from those countries and regions. This process is according to the following criteria:

i. If there are fire engineering design related codes and standards.
ii. If they are available to public.
iii. If they are written in English.

iv. If they have an official English version in addition to their local language version, or an unofficial English translation whose quality can be confirmed through cross-referencing with translation aids and native speakers.

v. If they are the most current versions within their applied region, i.e., the latest version before January 31st, 2024, when the thesis is in progress.

The procedure is driven by these specific criteria aimed at ensuring thoroughness efficiency and timesaving. The first and second criteria are considered together to exclude countries and regions without fire design codes, or such codes and standards cannot be acquired. The third and fourth criteria focused on review barriers raised by language. Many non-English speaking countries in the world do not have official English version of their national or regional codes and standards, and searching for their current codes is also hard because of the existing language barriers. The final criteria is about ensuring that the latest version regarding these codes and standards is included in this review to enhance comprehensiveness. If the current codes and standards cannot be easily acquired, external support for finding the latest version will be proposed. The procedure of selection and exclusion is illustrated in Figure 3.

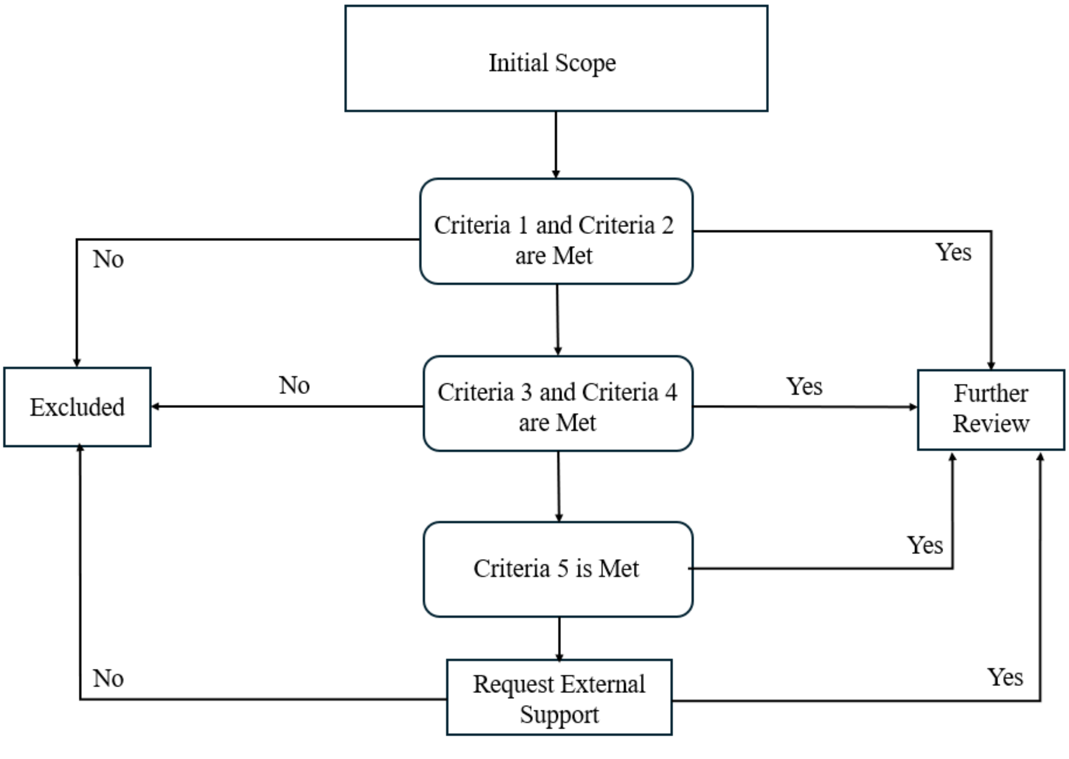


Figure 3. Review scope screening procedure flowchart

After this procedure, the scope for review is narrowing down, as shown in the Table 4. In addition, the international documents and the books have been added to the final review scope to explore whether definitions or recommendations for phased evacuation are mentioned in the literature.

Table 4. Final scope for reviewing

Europe	Asia	America	Oceania	Others
United Kingdom of Great Britain and Northern Ireland	People’s Republic of China	United States of America	Commonwealth of Australia	International Documents
England	Hong Kong Special Administrative Region of the People's Republic of China			
Scotland				
Republic of Ireland	Republic of Singapore	Canada	New Zealand	Books
Italian Republic				
Kingdom of Sweden				

Within this scope, a total of 33 codes and standards were selected for review in the final scope, comprising 10 from Europe, 3 from Asia, 3 from North America, 11 from Oceania, and 5 from others. From the review in Section 1, it becomes evident that various terms in evacuation studies are likely interchanged, e.g., "evacuation" and "egress," or "phased evacuation" and "staged evacuation," posing a challenge for reviewing. Therefore, this research conducted multiple rounds of keyword searches and respective document reviews. In keyword searches of codes with official English versions, keywords including "partial evacuation," "delayed evacuation," "phased evacuation," "staged evacuation," "evacuation strategy," "evacuation," and "egress" are used in seven separate searches. This approach aims to avoid incomplete reviews caused by terminology confusion. In Italian code reviews, keywords "Esodo per fasi" and "Esodo" are employed, while in Chinese codes, keywords "疏散策略", “安全疏散与避难设施” and "分阶段疏散" are used. After keyword searches, obtained information is reviewed in context and then recorded in the Appendix 1. Following the completion of the first round of keyword-based reviews, the second round examines sections of codes containing "means of escape" Any oversights not covered in the first round is supplemented into the Appendix 1 for final review.

3.2. Review Results

After completing the review of 33 codes and standards, all results have been tabulated in Appendix 1 of this thesis. This sub-section demonstrates the significant findings therein. Overall, phased evacuation-based means of escape design has not yet become a prevalent approach in international fire safety engineering design. It is worth to noting that the review not only contains codes and standards, but also involves documents, guidelines, guidance, provisions, acceptable solutions and verification methods. There are 11 codes and standards reviewed worldwide, which has highest quantity among all categories. The least reviewed category is provision, with the only provision reviewed from Sweden. This classification is shown in Figure 4. It is worth noting that this research also reviewed two international documents, namely the International Fire Code (ICC, 2021b), and ISO 13943:2023 Fire safety — Vocabulary (ISO, 2023), as well as three prestigious books within the fire engineering field, i.e., SFPE Handbook of Fire Protection Engineering Fifth Edition (SFPE, 2016), SFPE Guide to Human Behavior in Fire Second Edition (SFPE, 2019), and Fire Safety for Very Tall Buildings Engineering Guide Second Edition (SFPE & ICC, 2022).

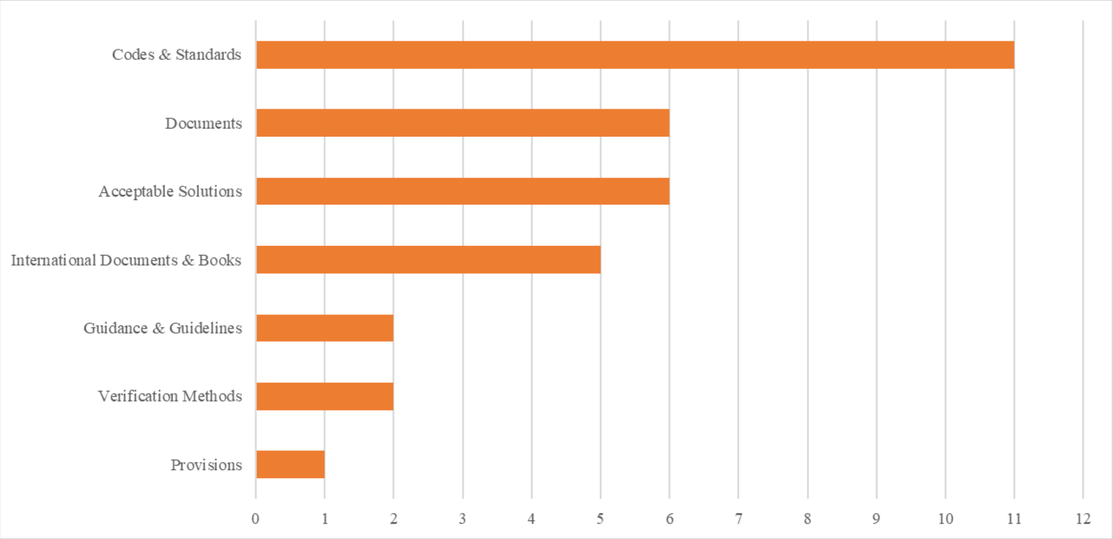


Figure 4. Review Scope by Category

Among the 33 codes and standards reviewed, only 5 provided a recommendation allowing fire engineers to design means of escape based on the assumption of a phased evacuation. This proportion is only around 15%, and all are concentrated in codes and standards from Europe. Additionally, several reviewed codes only provides a definition of phased evacuation, accounting for 18% of the total. The remaining 67% of codes and standards reviewed does not include any content related to phased evacuation, whether in terms of definition or phased evacuation-based design. This summary is demonstrated in the Figure 5.

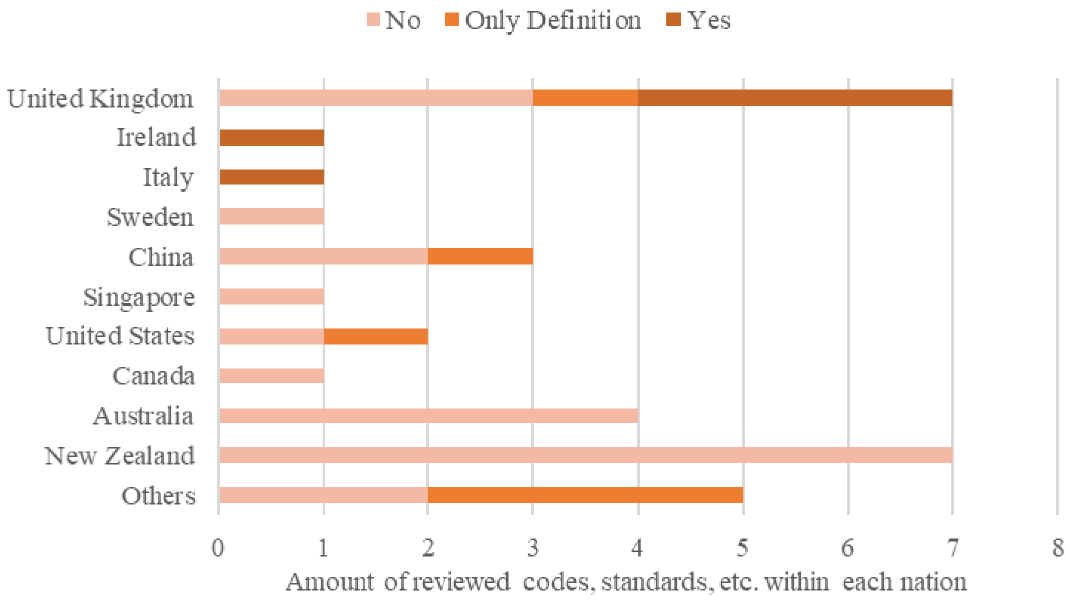


Figure 5. Whether reviewed scope includes phased evacuation based design

The difference and similarity across the definitions from the review are summarized in Table 5. It is evident that Europe places a greater emphasis on phased evacuation. Meanwhile, the United Kingdom leads within Europe with the highest number and most detailed guidance on phased evacuation across various their various codes and standards. It is worth noting that within these codes and standards from Europe, the phased evacuation-based design only provides guidance for aggregate stair width, with no specific guidance provided for exit width, travel distance, or other design aspects related to means of escape. Within these, BS 9999 and the Building Standards Technical Handbook provide the most comprehensive and detailed overview of phased evacuation, while the phased evacuation definition from Approved Document B closely mirroring that of BS 9999. As for PD 7974, its similarity to BS 9999 persists, with the difference being that PD 7974 stands as the only code offering a tentative recommendation for phase interval, i.e., 1 to 2 minutes between each phase. Among other codes defining phased evacuation, none provide even vague guidance on the phase interval. However, it is noteworthy that PD 7974 fails to state how this recommended phase interval is derived.

There are another two codes from Europe includes phased evacuation-based design, i.e., Technical Guidance Document B - Fire Safety from Ireland, and Technical Standards for Fire Prevention (Norme tecniche di prevenzione incendi) from Italy. Their definitions are relatively more ambiguous compared to those provided by codes and standards from the United Kingdom. The Technical Guidance Document B defines the first phase in the same manner as the Building Standards Technical Handbook. However, the subsequent evacuation phase remains ambiguous, only suggesting that it should occur on a sequential basis. The Technical Standards for Fire Prevention defines the first phase of evacuation should be the compartment where fire starts, and the subsequent evacuation involves occupants in other compartments. In contrast to other definitions emphasizing vertical evacuation, the Italian standard places a greater emphasis on horizontal evacuation.

Table 5. Summarized phased evacuation procedures

Evacuation Procedure	First Phase	Phase Interval	Subsequent Evacuation
BS 9999	Occupants on fire floor and all occupants with functional limitations	Not Applicable	Two floors at a time
Approved Document B			
PD 7974		1-2 minutes	
Building Standards Technical Handbook	Occupants on fire floor and the floor immediately above	Not Applicable	Next two adjoining upper floors
Technical Guidance Document B			On a sequential basis
Technical Standards for Fire Prevention	Fire Starting Compartment		Other compartments

Considering the reviews conducted for other three continents, codes and standards in Oceania entirely lack any definitions or strategies related to phased evacuation. When the six acceptable solutions for New Zealand are reviewed, there are specific statements that they do not provide features to facilitate a delayed evacuation strategy. The GB/T 31593.9 Guidance on Evaluation of Behavior and Movement of People from China suggests phased evacuation should starts at areas threatened by fire in buildings with limited evacuation capacity, such as hospitals. Whereas the NFPA 101 Life Safety Code from the United States recommends that the evacuation process can be ordered or managed. These definitions are vague and highlight the lack of emphasis on phased evacuation in these regions. Fire safety designs in these regions typically assume a total evacuation once fire incident occurs.

4. Evacuation Modelling & Simulation

4.1. The Building Model Description

The multi-purpose residential building employed in this research is modified based on one of the exemplar floorplates from a continuous research project of Spearpoint et al. (2024a). The original floor plan is an eleven-floors residential building, with two one-bedroom flats, three two-bedroom flats and two three-bedroom flats on each floor. It is assumed that a bedroom accommodates two occupants, resulting in a total of 302 occupants in the original exemplar building. The descriptive floorplate plan is shown in the Figure 6.

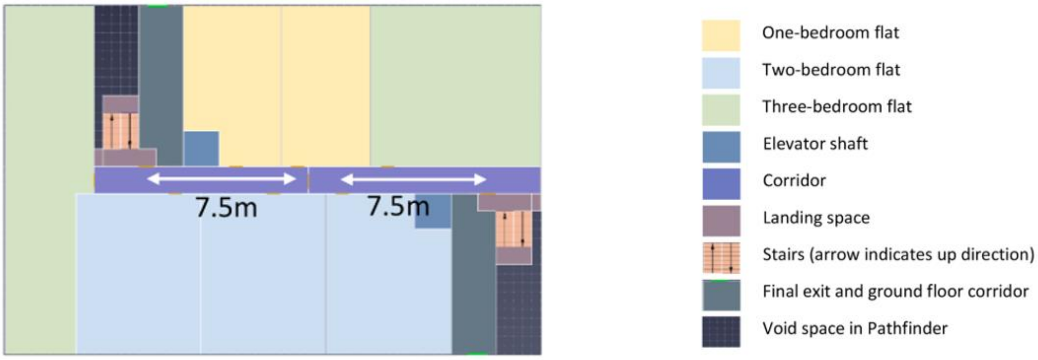


Figure 6. The building model employed in this research, figure taken from (Spearpoint et al., 2024b)

The overall design of the exemplar building is following the design guidance of Approved Document B, and design of stair steps is deemed as fulfilling guidance from Approved Document K (Spearpoint et al., 2024a). The corridor on each floor is maintained at a consistent length of 15 m, with the maximum travel distance to the stairs on either side of the corridor being 7.5 m. Occupants in the model usually go towards their nearest stair so the occupants' flow on each floor is approximately evenly split. A switchback stair layout has been chosen, each set of stairs between two floors comprises eight risers, totalling a height of 1.375 m, and a combined tread length of 2.0 m. Therefore, the height of each floor is 2.75 m, with a total building height of 30.25 m. The modifications based on existing building model lies in various occupant profiles, while geometrical configurations remain unchanged. Two building models in Pathfinder and Evacuationz can represent geometrical configurations. The ground floor plan serves as an instance, as shown in Figure 7.

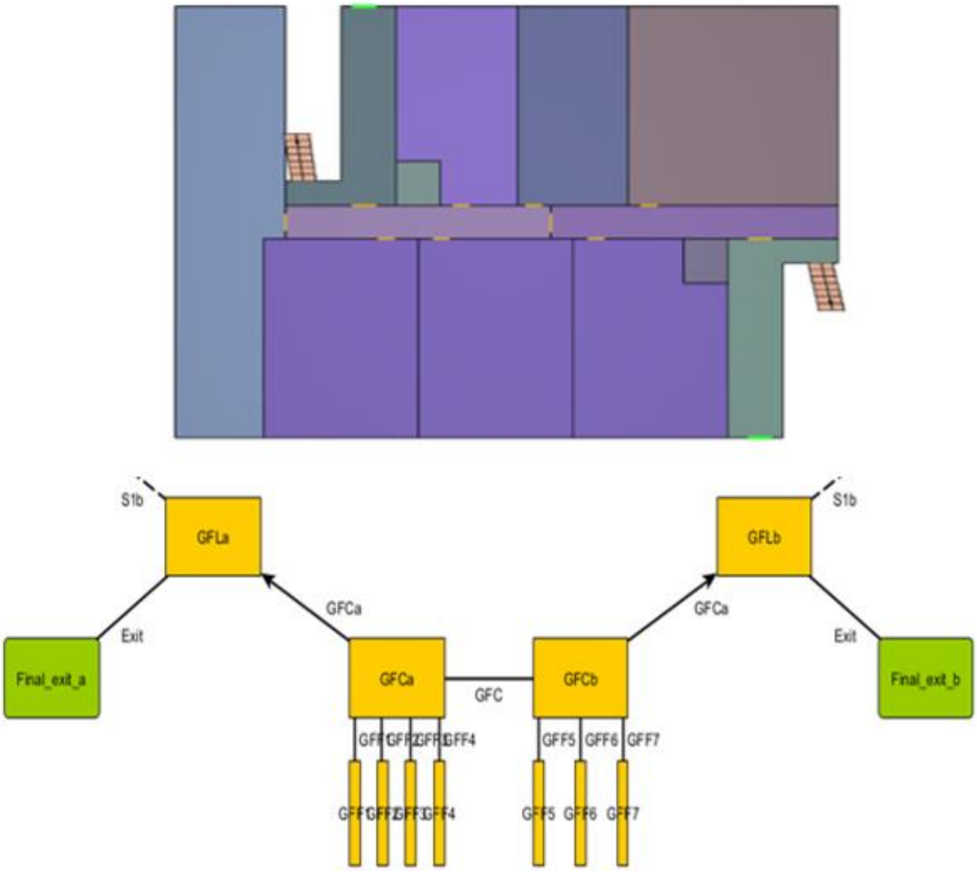


Figure 7. Pathfinder ground floor plan (Up) & Evacuationz ground floor plan (Down)

In this research, the residential building is converted to the multi-purpose residential building, with two assembly rooms on the tenth floor. The assembly rooms serve as multi-purpose spaces for sightseeing, community events, and recreational activities, making them accessible to visitors. Thus, both residents and visitors within the building are referred to as occupants in the research. Two assembly rooms locate on the original left-hand side 88.5 m^2 three-bedroom flat, and the original right-hand side 85.5m^2 three-bedroom flat. Following the room type change, assumed occupants' amount within the assembly room also changes on the basis of Table D1, Approved Document B. The recommended floor space factor for general assembly space is 0.5 m^2/person. Thus, 177 and 171 occupants are proposed to set at each of the two assembly spaces respectively. However, the stair width of the exemplar building is 1100 mm. Based on the Approved Document B design requirements for phased evacuation, this width can only serve maximum 120 occupants per floor. Thus, the occupants on each assembly space are limited to 52 to fit the original design. Therefore, there are 400 occupants placed in each building model. In addition, it is worth mentioning that the number of occupants is at the extreme in real-life scenarios, to make the following simulations more conservative.

According to the introduction of the downward walking speeds outlined in Section 1.4, the unimpeded speed of occupants with functional limitations exhibits differences compared to standard occupants, appearing lower. Thus, incorporating a certain proportion of occupants with functional limitations into the building model is more inclusive and reflective of real-world scenarios. These occupants are pre-assigned different walking speeds and pre-evacuation times based on their respective occupation types. It is through an ideal simplification, as unimpeded walking speeds are not the only factor that would be affected by functional limitations. There are usually around 10 percent occupants can be characterized by some form of functional limitations when there is no further detailed research can be employed (Spearpoint et al., 2024a). The final proportion of occupants with functional limitations among all occupants is assumed equal to 10%. They are randomly placed within each room. The layout of occupants on the tenth floors, as illustrated in Figure 8, provides an example.

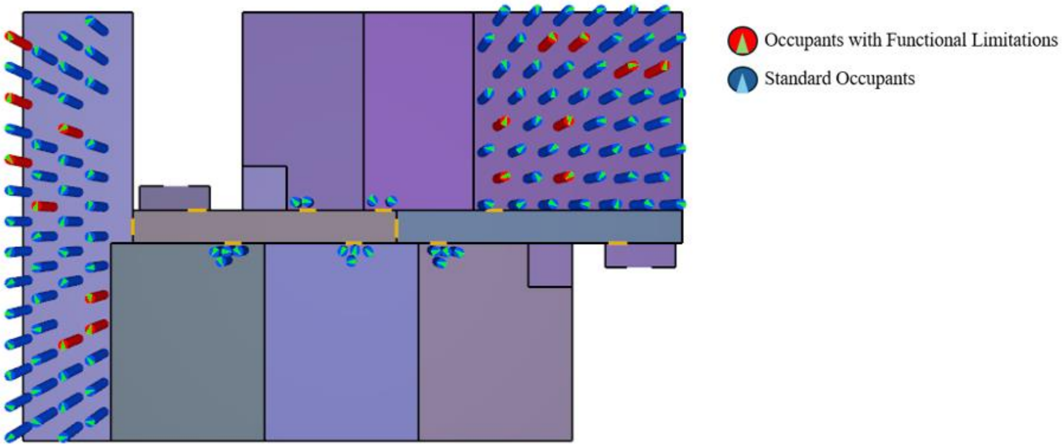


Figure 8. One occupants' layout on the tenth floor in Pathfinder

This research employs unimpeded walking speed data for standard occupants and occupants with functional limitations in a prior similar study (Ronchi & Nilsson, 2014). Spearpoint et al. (2024b) reviewed data and research findings from Gwynne & Boyce (2016), Lovreglio et al. (2019), etc., and then categorized various pre-evacuation delays based on level of impairment (impaired occupant, unimpaired occupant), occupant state (asleep occupant, awake occupant), and alarm type (voice, tone/bell, etc.). Therefore, the mean and standard deviation for pre-evacuation time under a well-performed voice alarm condition are derived from Spearpoint et al. (2024b). A lognormal distribution is suitable for representing pre-evacuation delays (Purser & Bensilum, 2001), but it has the mathematical property of extending to infinity (Spearpoint et al., 2024b). Then distribution is truncated by its maximum and minimum values, where the rough minimum value is determined by the absolute difference between the standard deviation and the mean, and the rough maximum value is the sum of the standard deviation and the mean. However, it is worth to note that this truncation is a simplification, as there are several ways to calculate the truncation, e.g., the empirical 68–95–99.7 rule (Port, 1986), and the Chebyshev inequality method (Port, 1986), etc. The unimpeded walking speed in this research is also employed lognormal distribution as well. Data for evacuation settings are shown in Table 6, differentiating based on various types of occupants.

Table 6. Unimpeded walking speed & pre-evacuation time, employed in the research

Occupant Type	**Room Type**	**Unimpeded Walking Speed (m/s)**				**Pre-Evacuation Time (s)**			
		Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation
Standard Occupants	Flat	0.29	2.29	1.29	1.00	50	310	180	130
	Assembly					40	220	90	130
Occupants with Functional Limitations	Flat	0.10	1.68	0.80	0.37	170	430	300	130
	Assembly					50	310	180	130

4.2. Scenarios Build-up

Following the review for codes and standards, most of them does not provide any guidance for time intervals during a phased evacuation or specific recommendations into how to plan for a phased evacuation. Additionally, these definitions generally do not specify whether phased evacuation should evacuate occupants throughout the entire building or only occupants on the fire floor and above. These findings contribute to the build-up of scenarios which necessary for further evacuation modelling study. Firstly, scenarios are divided into two groups based on total evacuation and partial evacuation. Total evacuation in the scenarios implies that all occupants are evacuated in phases, while partial evacuation involves only evacuating occupants on the fire incident floor and above. In addition, the scenarios setup considers the evacuation procedures. This setup is based on different phased evacuation procedures identified in Table 5, namely the evacuation procedure A and the evacuation procedure B. These two procedures are presented in Table 7. It aimed to explore the potential effects of systematically altering the first phase, phase interval, and subsequent evacuation across various scenarios. For example, if fire starts on the fifth floor, there are 6 phases if it is based on the evacuation procedure A, namely, Phase 1: floor 5 and all occupants with functional limitations, Phase 2: floor 6 and floor 7, Phase 3: floor 8 and floor 9, Phase 4: floor 10 and floor 4, Phase 5: floor 3 and floor 2, and Phase 6: floor 1 and ground floor. In Pathfinder, different evacuation phases are achieved through the "fixed value" in the "wait" action. In Evacuationz, however, different evacuation phases are achieved through different "fix value" in the delay feature of the “refuge area”. Additionally, it is worth noting that when occupants with functional limitations evacuate following the evacuation procedure A, the delay value for these occupants are fixed at zero.

Table 7. Two phased evacuation strategies identified in review, derived from Table 5

Evacuation Procedure	First Phase	Phase Interval	Subsequent Evacuation	Assumption
A	Occupants on fire floor and all occupants with functional limitations	Not Applicable	Two floors at a time	Evacuate two upper floors. Evacuate lower floors once upper floors evacuated.
B	Occupants on fire floor and the floor immediately above		Next two adjoining upper floors	

Subsequently, this research explores influences that the various criterion cause on the proposed phased evacuation strategy. First of all, scenarios are divided into two parts: the first part involves total evacuation, comprising 18 scenarios, while the second part involves partial evacuation, comprising 6 scenarios. The comparison between total and partial evacuation aims to explore whether not evacuating occupants from floors below the fire floor facilitates the fire floor evacuation, which faces the greatest threat from the fire. Following this, scenarios are categorized based on the two previously mentioned different evacuation procedures. This criterion allows for the exploration of whether evacuating the fire floor and the floor directly above at the first phase, as opposed to evacuating only the fire floor and occupants with functional limitations, results in different total evacuation times and floor clearance times. The fire floors are selected at distinct positions within the building, namely the ground floor, middle floor (the fifth floor), and top floor (the tenth floor). The selection of these three positions can be considered as representative for three distinct parts within the building. This is a simplified selection method, choosing fire locations based on a dedicated risk assessment is a more reliable approach in performance-based design. The final criterion for categorising scenarios is the phase interval, with three intervals proposed: 30 s, 60 s, and 90 s. This phase interval setting refers to the previously reviewed PD 7974, using its recommended lower limit of one minute as a benchmark, with an additional thirty seconds added or subtracted to explore the impact of different intervals on phased evacuation. A total of 24 scenarios are initially classified. The overview of these 24 scenarios is summarized in Table 8. Each scenario is assigned a name to identify them, using the initials of each category. For example, scenario 1 is labelled as TAG30 for identification purposes. The "T" represents total evacuation, "A" indicates the adoption of the evacuation procedure A, "G" signifies that the fire floor is the ground floor, and the number 30 denotes a phase interval of 30 s. There is no simultaneous evacuation scenario involved in this research.

Table 8. Simulation scenarios description

Evacuation Scope	Evacuation Procedure	Fire Floor	Phase Interval (s)	Scenarios
Total Evacuation (Evacuate all occupants)	A	Ground floor	30	S1 - TAG30
			60	S2 - TAG60
			90	S3 - TAG90
		Fifth floor	30	S4 - TAF30
			60	S5 - TAF60
			90	S6 - TAF90
		Tenth floor	30	S7 - TAT30
			60	S8 - TAT60
			90	S9 - TAT90
	B	Ground floor	30	S10 - TBG30
			60	S11 - TBG60
			90	S12 - TBG90
		Fifth floor	30	S13 - TBF30
			60	S14 - TBF60
			90	S15 - TBF90
		Tenth floor	30	S16 - TBT30
			60	S17 - TBT60
			90	S18 - TBT90
Partial Evacuation (Evacuate occupants on and above fire floor)	A	Fifth floor	30	S19 - PAF30
			60	S20 - PAF60
			90	S21 - PAF90
	B	Fifth floor	30	S22 - PBF30
			60	S23 - PBF60
			90	S24 - PBF90

However, before running these scenarios, it is necessary to determine how many times each scenario should be run, to ensure convergence of model results is met, given the fact that the evacuation models adopt a probabilistic approach. The reason for this step is that it is common to use pseudorandom sampling from distributions to reflect the variability of human behaviour in evacuation modelling, which is also known as behavioural uncertainty (Smedberg et al., 2021). Within this research, the employed pre-evacuation time and unimpeded walking speed of four types of occupants introduced such variabilities to simulations. To solve the issue, a multifactor variance assessment (MVA) method is employed, which has been devised by Smedberg (2019) and based on a previous quantitatively functional analysis for behavioural uncertainty in evacuation modelling (Ronchi et al., 2014b). Smedberg (2019) utilized functional analysis to investigate the convergence of evacuation simulation outcomes, aiding in determining the necessary number of simulations run for a single scenario. He also developed a calculation tool on the basis of Microsoft Excel enabling macros, which is free for use (Smedberg, 2019). The functional analysis aligns with three convergence metrics, i.e., Secant Cosine (SC), Euclidean Projection Coefficient (EPC) and Euclidean Relative Difference (ERD) (Ronchi et. al., 2014), for comparing combined occupant-evacuation time curves. Once the convergence metrics are computed, it is necessary to assess the results to determine whether convergence criteria have been satisfied. The method selects the evacuation time, the queuing time, the density, the flowrate, the spatial location and the used exit from simulation outputs as factors, while an additional Kolmogorov-Smirnov test is included as a complement for the above mentioned convergence criteria. The convergence criteria employed in this research is listed in Table 9.

Table 9. Convergence criteria for evaluation factors

Factor\Criteria	**TR_{Φ}**	**$\mathrm{TR}_{\mathrm{SDof}\Phi}$**	**$\mathrm{TR}_{\mathrm{ERD}}$**	**$\mathrm{TR}_{\mathrm{EPC}}$**	**$\mathrm{TR}_{\mathrm{SC}}$**	**b**	**α**	**k**
Total Evacuation time	0.1%	1.0%	0.1%	1.0%	0.1%	10	5%	5
Queuing time	1.0%	1.0%	1.0%	1.5%	0.5%	10	5%	5
Crowd density	1.0%	1.0%	1.0%	1.5%	0.5%	10	5%	5
Flowrate	0.5%	1.0%	0.5%	1.0%	0.5%	10	5%	5
Spatial location	0.5%	1.0%	0.5%	1.0%	0.5%	10	5%	5
Used exit	0.5%	1.0%	0.5%	1.0%	0.5%	10	5%	5

In the table, "Φ" The maximum tolerable change of Φ between two aggregated runs, whereas "SD of Φ" signifies the maximum tolerable change of standard deviation of Φ between two aggregated runs. The parameter "b" denotes the consecutive runs required to meet the criteria for considering the results as converged. Additionally, "α" signifies the confidence level at which the null hypothesis can be rejected in the Kolmogorov-Smirnov test, and "k" represents the consecutive runs that must pass the Kolmogorov-Smirnov test to consider the results as converged. It is notable that the convergence criteria utilized here follow the same value as in previous case studies (Smedberg, 2019). Despite Smedberg et al. (2021) indicating that these criteria are not universally recommended for application in other contexts, they are retained in this research as they are deemed fine reasonably conservative. If the recommended number of runs calculated by this method exceeds 20, that value is adopted. If the result is less than 20, twenty runs for each scenario is employed to ensure the simulation is sufficiently conservative.

This research initially adopts two computer-based models to simulate these phased evacuation scenarios, i.e., Pathfinder and Evacuationz. After the number of runs is determined, a comparative analysis for Pathfinder and Evacuationz is conducted in two scenarios, i.e., Scenario 1 TAG 30 and Scenario 10 TBG 30. This aimed to evaluate the extent of the result variability produced by the two tools and examine the consistency of their results. Following this step, the tool identified as more suitable for this research in the comparative analysis is employed for the subsequent simulations. Subsequently, a series of relative comparison analysis of first 24 scenarios is undertaken to assess different scenarios and propose a more suitable evacuation procedure for the residential building with assembly spaces. This includes the analysis of total evacuation time for each scenario, as well as the floor clearance time on each floor.

4.3. Simulation Results

After inputting all the criteria listed in Table 9 into the MVA tool from Smedberg (2019), this Excel macro-based tool automatically calculates how many runs of each scenario under the convergence criteria to achieve convergence, as shown in Table 10. The four factors, i.e., crowd density, flowrate, spatial location, and used exit are calculated at two final exits on the ground floor. These two exits are automatically labelled as MainExit1 and MainExit2 in the result table. The numbers in the table represent the convergence meets at which run under the corresponding criteria. The last row lists the maximum numbers in each column, indicating the convergence run for each criterion across all factors. The calculated number of runs is the largest number 18 in the last row, which means that all criteria are considered to have converged after 18 times runs. However, this is less than 20 runs, and in pursuit of more conservative results, 20 runs for each scenario are finally established for each scenario.

Table 10. Results for Evacuationz simulation run repeats, derived from the tool from Smedberg (2019)

Criteria/Factor	Total Evacuation Time		Queuing Time		MainExit1		MainExit2	
TR$_{\Phi}$	YES	13	YES	11	YES	16	YES	18
TR$_{SDof\Phi}$	YES	18	YES	12	YES	11	YES	12
TR$_{ERD}$	YES	12	YES	12	YES	15	YES	17
TR$_{EPC}$	YES	12	YES	12	YES	13	YES	15
TR$_{SC}$	YES	12	YES	12	YES	11	YES	12
Kolmogorov-Smirnov test (b, α, k)	YES	9	YES	11	YES	10	YES	13
Summary	**YES**	**18**	**YES**	**12**	**YES**	**16**	**YES**	**18**

The first set of results is the cross comparison of two evacuation scenarios, namely Scenario 1 - TAG30 and Scenario 10 - TBG30, simulated with Pathfinder and Evacuationz. Table 11 shows the comparison of total evacuation times and floor clearance times between these two evacuation modelling tools. The differences listed in the table are calculated based on comparing Evacuationz results with Pathfinder results. The comparison of total evacuation time and floor clearance time on each floor is further plotted in Figure 9. The “TET” in Figure 9 represents total evacuation time.

Table 11. Consistency comparisons between Evacuationz and Pathfinder

		S1 - TAG30		Difference	S10 - TBG30		Difference
		Pathfinder	Evacuationz		Pathfinder	Evacuationz	
Total Evacuation Time (s)		703	728	3.6%	716	752	5.0%
Floor Clearance Time (s)	**10**	490	544	11.1%	465	516	11.0%
	9	453	456	0.7%	437	428	-2.2%
	8	427	426	-0.1%	487	425	-12.7%
	7	443	436	-1.8%	406	415	2.4%
	6	398	402	1.0%	405	458	13.1%
	5	412	382	-7.1%	430	378	-12.1%
	4	391	363	-7.1%	433	396	-8.6%
	3	393	406	3.2%	390	413	5.9%
	2	377	348	-7.9%	416	371	-10.7%
	1	372	326	-12.3%	359	353	-1.7%
	G	348	312	-10.2%	337	314	-6.9%

In terms of total evacuation time, the difference between results of two tools are 3.6% and 5.0%, which are broadly similar. The difference shows the consistency between two tools. It also corresponds to the series consistency tests of Evacuationz and Pathfinder in a recent study (Spearpoint et al., 2024a), under the same geometrical configurations. As for floor clearance times, differences between Evacuationz results and Pathfinder results range from -12.3% to 13.1%. The consistency of the evacuation times generated by two tools is demonstrated on each floor level.

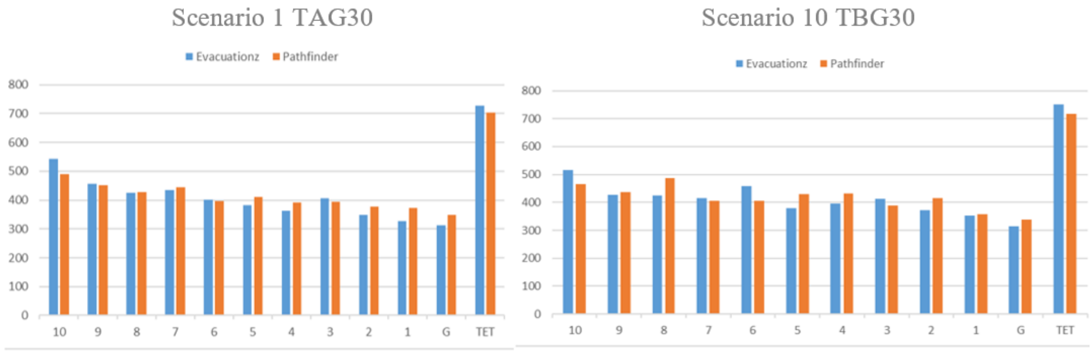


Figure 9. Floor clearance time & total evacuation time comparison between two tools

Additionally, the time consumed for running a scenario 20 times and results file storage consumed are examined and compared. The results are shown in Table 12. This research utilizes the same laptop for running simulations, the type of Central Processing Unit is “AMD Ryzen 9 6900HS” with 16 threads. It is worth emphasizing that these results are not considered universal and are only deemed valid within the building model run in this research on this laptop. Nevertheless, they can give an idea of the computational time required by those models for similar scenario configurations.

Table 12. Comparison of running times and file storage consumed between two tools

	Computational time for running a scenario 20 times (s)				**Result file storage (MB)**			
	S1-TAG30	S10-TBG30	Average	Difference	S1-TAG30	S10-TBG30	Average	Difference
Evacuationz	182	177	179.5	-70.8%	17.5	15.7	16.6	-98.7%
Pathfinder	609	622	615.5		1310.7	1300.5	1305.6	

According to the differences presented in the table, Evacuationz demonstrates an average reduction in running time of 70.8% compared to Pathfinder. Whereas the difference in result file storage is even more significant. The result file storage of Evacuationz is 98.7% smaller than Pathfinder. As these two tools demonstrate consistency in their generated results, and considering Evacuationz can complete an equivalent number of repeated runs in a sufficiently short time, this research only utilizes Evacuationz for running remaining 22 primary scenarios and 6 new scenarios.

The average total evacuation time of first 24 scenarios is listed in Table 13, and further plotted in Figure 10. The figure represents the results from the simulations of 24 scenarios where a standard error uncertainty range is shown for Evacuationz. The total evacuation time of the Scenario 12 is the longest, at 1323 s, while the shortest is the Scenario 7, at 614 s. Under the premise of total evacuation, starting evacuation from the ground floor increases the total evacuation time for all six groups. When evacuation procedure and phase interval remain unchanged, evacuating from the ground floor consistently results in the longest total evacuation time, followed by starting at the fifth floor, with evacuation commencing from the tenth floor giving the shortest total evacuation time.

Table 13. Total evacuation time of first 24 scenarios

Evacuation Scope	Evacuation Procedure	Fire Floor	Phase Interval (s)	Scenarios	Total Evacuation Time (s)	Group
Total Evacuation (Evacuate all occupants)	A	Ground floor	30	S1 - TAG30	728	1
			60	S2 - TAG60	1001	
			90	S3 - TAG90	1303	
		Fifth floor	30	S4 - TAF30	689	2
			60	S5 - TAF60	769	
			90	S6 - TAF90	958	
		Tenth floor	30	S7 - TAT30	614	3
			60	S8 - TAT60	658	
			90	S9 - TAT90	787	
	B	Ground floor	30	S10 - TBG30	752	4
			60	S11 - TBG60	1030	
			90	S12 - TBG90	1323	
		Fifth floor	30	S13 - TBF30	663	5
			60	S14 - TBF60	732	
			90	S15 - TBF90	832	
		Tenth floor	30	S16 - TBT30	619	6
			60	S17 - TBT60	708	
			90	S18 - TBT90	821	
Partial Evacuation (Evacuate occupants on and above fire floor)	A	Fifth floor	30	S19 - PAF30	666	7
			60	S20 - PAF60	746	
			90	S21 - PAF90	939	
	B	Fifth floor	30	S22 - PBF30	642	8
			60	S23 - PBF60	708	
			90	S24 - PBF90	796	

Among all 8 groups, the phase intervals of 30 s consistently yield the minimum total evacuation time. The smallest total evacuation time, achieved in Scenario 7, also occurs under the premise of a 30 s phase interval. Increasing the duration of the phase interval typically results in longer total evacuation time. Taking the Group 4 as an example, the total evacuation time for S11 increased by 37% compared to S10. Additionally, the total evacuation time for S12 increased by 27% compared to the total evacuation time for S11. When maintaining other variables unchanged, increasing the phase interval does not shorten the total evacuation time.

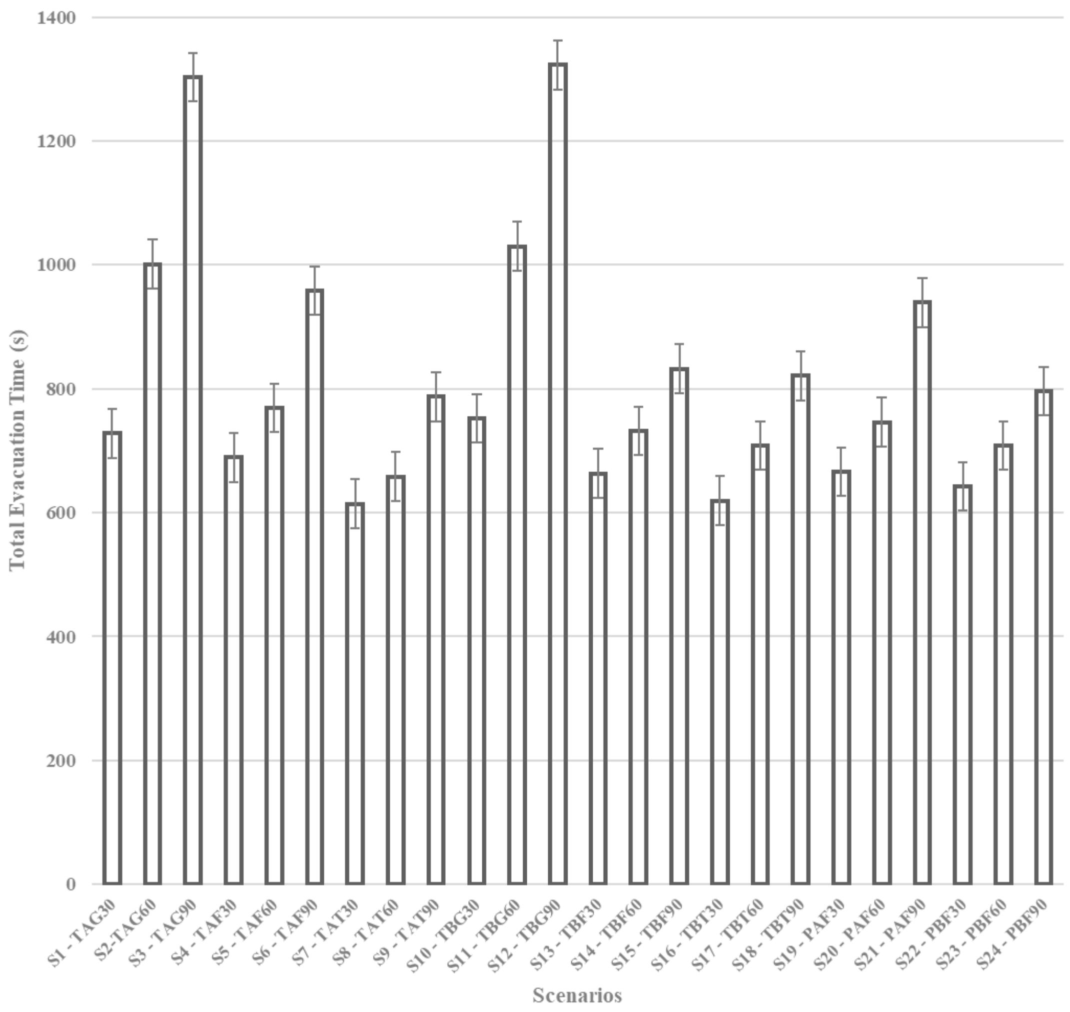


Figure 10. Total evacuation time across 24 scenarios

As for evacuation procedures, comparison is based on the first 18 scenarios, all of which with premise of total evacuation. It is shown in Table 14. When evacuation starts from both the first and tenth floors, scenarios based on the evacuation procedure B consistently exhibit longer total evacuation times compared to those based on the evacuation procedure A, ranged from 0.8% to 7.6%. However, if evacuation begins from the fifth floor, the situation reverses, with scenarios based on the evacuation procedure A showing slower evacuations. One assumption is that scenarios based on the evacuation procedure A evacuate the most crowded tenth floor at a later phase, which is examined in the subsequent discussion when floor clearance times on the fire floors are taken into consideration. Additionally, the impact of evacuating ten percent of occupants with functional limitations during the first phase on the total evacuation time changes for the evacuation procedure A based scenario remains unknown.

Table 14. Total evacuation time comparison between two evacuation procedures

Total Evacuation Time (s)								
Ground Floor			**Fifth Floor**			**Tenth Floor**		
S1 - TAG30	S10 - TBG30	Difference	S4 - TAF30	S13 - TBF30	Difference	S7 - TAT30	S16 - TBT30	Difference
728	752	3.3%	689	663	-3.8%	614	619	0.8%
S2 - TAG60	S11 - TBG60	Difference	S5 - TAF60	S14 - TBF60	Difference	S8 - TAT60	S17 - TBT60	Difference
1001	1030	2.9%	769	732	-4.8%	658	708	7.6%
S3 - TAG90	S12 - TBG90	Difference	S6 - TAF90	S15 - TBF90	Difference	S9 - TAT90	S18 - TBT90	Difference
1303	1323	1.5%	958	832	-13.2%	787	821	4.3%

The research also includes 6 scenarios related to partial evacuation, all of which initiate evacuation from the fifth floor. The partial evacuation only evacuates occupants on and above the fire floor. In other words, occupants from the ground floor to the fourth floor stay in their rooms during the simulation. In Table 15, scenarios with partial evacuation are compared with their corresponding total evacuation scenarios. Regardless of the evacuation procedure employed, partial evacuation consistently needs less time than total evacuation, with a range of reduction from 2.0% to 4.3%. However, there are 140 occupants required to stay in place, reducing the number of evacuating occupants by 35%. The percentage decrease in total evacuation time does not match the percentage decrease in the number of occupants. This mismatch is analysed in conjunction with the floor clearance time in following discussion as well.

Table 15. Total evacuation time comparison between total evacuation and partial evacuation

Total Evacuation Time (s)					
Evacuation procedure A			**Evacuation procedure B**		
S4 - TAF30	S19 - PAF30	Difference	S13 - TBF30	S22 - PBF30	Difference
689	666	-3.3%	663	642	-3.2%
S5 - TAF60	S20 - PAF60	Difference	S14 - TBF60	S23 - PBF60	Difference
769	746	-3.0%	732	708	-3.3%
S6 - TAF90	S21 - PAF90	Difference	S15 - TBF90	S24 - PBF90	Difference
958	939	-2.0%	832	796	-4.3%

In terms of floor clearance time, this research summarizes this parameter of every floor in all scenarios, as shown in Table 16. To make the data easier to understand the differences among floor clearance times, 24 demonstration figures are plotted for each initial scenario. All of these figures are placed within Appendix 2 and some of them are discussed in the next Section. The numerical values for the fire floor clearance time are highlighted in bold in the table.

Table 16. Average floor clearance time

	Floor Clearance Time (s)										
Scenarios/Floors	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**G**
S1 - TAG30	544	456	426	436	402	382	363	406	348	326	**312**
S2 - TAG60	742	590	537	542	490	498	419	420	374	371	**310**
S3 - TAG90	1041	738	653	669	579	574	499	471	425	389	**311**
S4 - TAF30	451	348	404	339	332	**310**	410	430	439	438	458
S5 - TAF60	562	423	430	359	377	**307**	487	535	548	597	619
S6 - TAF90	681	472	460	393	391	**313**	589	647	678	762	759
S7 - TAT30	**373**	333	406	367	365	390	406	435	431	433	467
S8 - TAT60	**360**	346	416	421	418	488	479	537	555	607	615
S9 - TAT90	**371**	401	427	489	482	569	592	661	671	736	770
S10 - TBG30	516	419	425	412	468	372	410	412	379	356	**314**
S11 - TBG60	739	546	575	485	559	438	473	422	385	386	**346**
S12 - TBG90	1038	661	581	488	641	491	512	447	442	380	**342**
S13 - TBF30	428	371	368	359	365	**321**	469	508	496	573	560
S14 - TBF60	492	428	405	397	380	**311**	546	533	546	626	631
S15 - TBF90	550	482	438	403	365	**326**	611	663	738	742	775
S16 - TBT30	**370**	303	399	353	411	386	433	473	493	487	503
S17 - TBT60	**368**	311	417	399	496	430	514	567	575	643	671
S18 - TBT90	**379**	324	419	442	548	498	625	647	722	735	785
S19 - PAF30	481	363	463	333	342	**312**					
S20 - PAF60	529	423	508	368	365	**310**					
S21 - PAF90	677	481	617	398	402	**317**					
S22 - PBF30	432	357	459	342	305	**310**					
S23 - PBF60	494	450	492	358	300	**319**					
S24 - PBF90	500	498	527	390	306	**310**					

In Figure 11, the demonstration of floor clearance times for Scenario 1 - TAG30 serves as an example to present composition of this series of figures. The series of graphs consists of four columns each. The first column displays the location of the fire floor, which in Scenario 1 is the ground floor. The second column introduces the number of occupants on each floor, which remains consistent across all subsequent scenarios. On the tenth floor, there are 16 occupants located in flats, while those in assembly spaces are 104 in total. The third column provides a visual representation of the floor clearance time, supplemented with specific time values to facilitate further comparison with other scenarios. The design of the final column indicates the phase in which each floor is evacuated, with subsequent time values indicating when each floor initiate evacuation after the simulation starts.

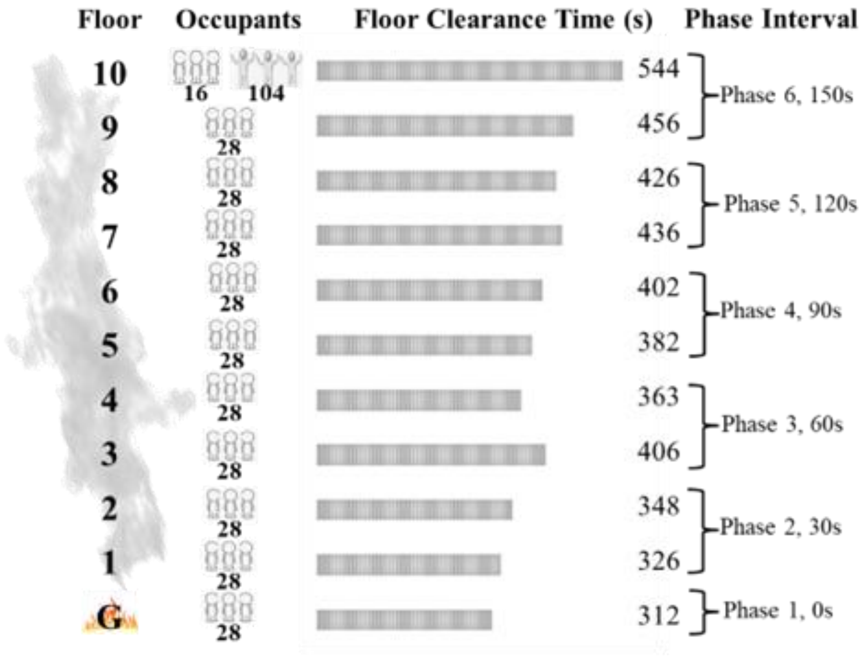


Figure 11. Floor clearance time of each floor and their respective phases on scenario 1 - TAG30

Additionally, to examine whether the most crowded floor influences fire floor clearance time, six new scenarios are designed, incorporating the evacuation of the most crowded floor into the first phase. The description of these six new scenarios are shown in the Table 17.

Table 17. Six new scenarios description

Evacuation Scope	Fire Floor	First Phase	Phase Interval (s)	New Scenarios	Control Group
Total Evacuation (Evacuate all occupants)	Ground floor	Evacuate ground floor, tenth floor and occupants with functional limitations	30	NS25 - TAG30	S1 - TAG30
			60	NS26 - TAG60	S2 - TAG60
			90	NS27 - TAG90	S3 - TAG90
		Evacuate ground floor, first floor, and tenth floor	30	NS28 - TBG30	S10 - TBG30
			60	NS29 - TBG60	S11 - TBG60
			90	NS30 - TBG90	S12 - TBG90

Each new scenario is also run twenty times. The fire floor clearance time and total evacuation time in the six new scenarios are summarized in Table 18, and comparisons are made with their respective control groups from the primary scenarios. In terms of total evacuation time, each new scenario demonstrates shorter evacuation times compared with their control groups. For the four new scenarios with phase intervals of 60 s and 90 s, total evacuation time decreases by over 20%. Scenario 30 exhibits the most significant reduction in total evacuation time, reaching 33.4%. However, what is more noteworthy is that the most affected fire floor evacuation is generally delayed, with increases ranging from around 0.9% to 8.2%. This indicates that when the populous floor is evacuated simultaneously with the fire floor, the total evacuation time is accelerated, but the evacuation of the fire floor is delayed. If a fire occurs on the ground floor, it appears to be a better option to evacuate only the fire floor and the floor with the most occupants in the first Phase. If only total evacuation time is considered in the comparison, this change would not be detected.

Table 18. Comparison between new scenarios and their control group

Fire Floor Clearance Time (s)			**Total Evacuation Time (s)**		
S1 - TAG30	NS25 - TAG30	Difference	S1 - TAG30	NS25 - TAG30	Difference
312	318	1.9%	728	670	-8.0%
S2 - TAG60	NS26 - TAG60	Difference	S2 - TAG60	NS26 - TAG60	Difference
310	315	1.7%	1001	788	-21.3%
S3 - TAG90	NS27 - TAG90	Difference	S3 - TAG90	NS27 - TAG90	Difference
311	318	2.1%	1303	925	-29.0%
S10 - TBG30	NS28 - TBG30	Difference	S10 - TBG30	NS28 - TBG30	Difference
314	340	8.2%	752	658	-12.6%
S11 - TBG60	NS29 - TBG60	Difference	S11 - TBG60	NS29 - TBG60	Difference
346	349	0.9%	1030	760	-26.2%
S12 - TBG90	NS30 - TBG90	Difference	S12 - TBG90	NS30 - TBG90	Difference
342	368	7.7%	1323	881	-33.4%

5. Discussion

There is lack of dedicated research on phased evacuation strategies for multi-purpose residential buildings, especially those with assembly spaces designed. While existing research mostly focuses on various types of high-rise buildings (Koo et al., 2013; Kadokura et al., 2015; Gravit et al., 2018; Home Office, 2022; Fang et al., 2023), the adoptability and suitability of phased evacuation in multi-purpose residential settings remain unexplored. This research initially reviews current codes and standards, then explores the use of evacuation simulations for phased evacuation. A series of comparative analysis across 30 scenarios are conducted.

The incorporation of phased evacuation strategies within international fire safety engineering design still remains an area of ongoing development. The review of 33 codes and standards reveals differences in the inclusion of phased evacuation-related content. These discrepancies highlight regional variations in the importance level placed on phased evacuation strategies. Notably, Europe, particularly the United Kingdom, emphasizes phased evacuation in its codes, standards and documents. Other regions like Oceania lack specific guidelines in this regard. Furthermore, a substantial portion of the reviewed codes and standards only offer a definition of phased evacuation without providing comprehensive guidance on its implementation. A popular definition of phased evacuation entail the initial evacuation of the fire floor and/or the floor immediately above, followed by subsequent evacuation of two additional floors in succession. BS 9999, Approved Document B, and PD 7974 suggests evacuating all occupants with functional limitations to evacuate at the first phase. However, whether this recommendation can be feasibly implemented in real-world scenarios remains unknown.

The evacuation tools employed in the subsequent evacuation modelling, i.e., Evacuationz and Pathfinder, utilize distinct modelling approaches to represent the evacuation process of phased evacuation. As early as 13 years ago, Ronchi and Kinsey (2011) concluded through an online questionnaire survey that practitioners of evacuation modelling often employ available model with limited justification to their suitability to assess the fire safety of buildings in performance-based design. While as suggested recently by Spearpoint et al. (2024a), practitioners should possess a comprehensive understanding of the capabilities of simulation tools and demonstrate proficiency in their utilization to ensure appropriate adjustments to input parameters.

The indiscriminate use of any evacuation simulation tool should not be encouraged. In this research, the MVA method is employed to address the variability in results generated by evacuation tools and obtained reliable quantitative outcomes. As this simulation study primarily focuses on total evacuation time and floor clearance time, a comparison is analysed based on total evacuation time and floor clearance time between Evacuationz and Pathfinder. The result demonstrates the consistency and similarity of results between them. Additionally, adopting the same computational power, Evacuationz demonstrates a faster running speed compared to Pathfinder. This is not surprising as it adopts a simpler and faster space representation, i.e., coarse network modelling. In the context of this research, practitioner can confidently justify their choice to utilize the most suitable tool for specific research and practical conditions through comparative study. This corresponds to the suggestions of Ronchi and Nilsson (2014), and Spearpoint et al. (2024a).

In the preceding result section, the two implemented evacuation procedures are compared based on their respective total evacuation times. When evacuations commenced from the ground floor and the tenth floor, scenarios based on the evacuation procedure B always gives longer total evacuation times compared to those based on the evacuation procedure A, whereas evacuations starting from the fifth floor yielded contrasting results. Figure 12 illustrates the floor clearance time for each floor within the building when evacuation starts from the fifth floor with phase interval of 30 s. The figure clearly indicates that the tenth floor with the highest population, begins evacuation 30 s later in Scenario 4 compared to Scenario 13. On the fire floor (fifth floor), Scenario 13 exhibits a 3.4% increase in clearance time compared to Scenario 4, whereas on the tenth floor, Scenario 13 demonstrates a 5.4% reduced in clearance time relative to Scenario 4. Additionally, the total evacuation time in Scenario 13 is reduced by 3.9% compared to Scenario 4. This indicates that, within this group of scenarios, evacuation of the tenth floor has a greater impact on the total evacuation time compared to evacuation of the fire floor. In Scenario 13, evacuation of the fire floor and the sixth floor together occurs in the first phase. In contrast, in Scenario 4, where only the fire floor and occupants with functional limitations are evacuated in the first phase, evacuation from the fire floor, which faces a greater threat from the fire, is facilitated. According to the Table 16, the same trends persist when the phase interval is increased to 60 s and 90 s. It shows that analysing solely on the total evacuation time for the whole building makes it difficult to grasp the dynamics of the evacuation process, especially concerning the most critical fire floor and most crowded floors.

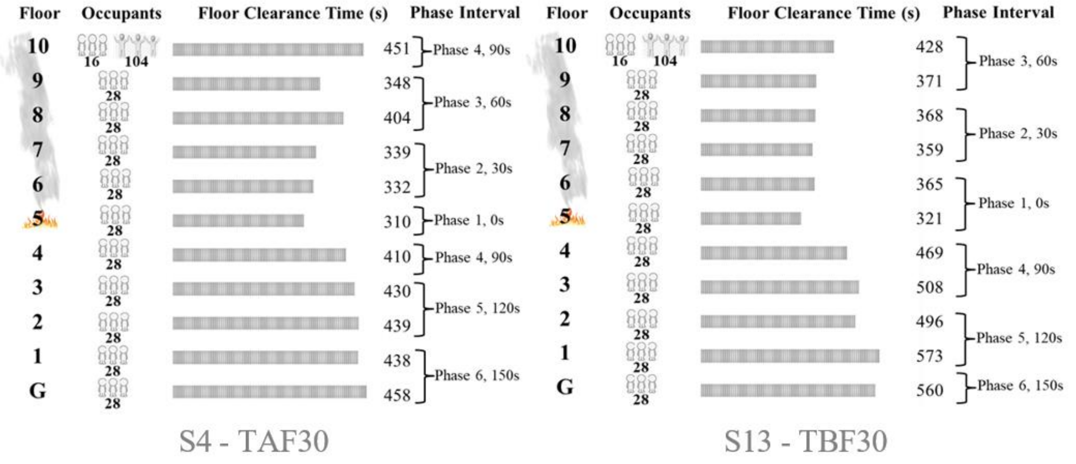


Figure 12. Floor clearance time comparison between two evacuation procedures

In Table 15, as expected, all scenarios employing partial evacuation strategies demonstrate shorter total evacuation times compared to total evacuation. However, the dynamics of evacuation for the fire floor cannot be inferred from the total evacuation time alone. Figure 13 illustrates both total evacuation and partial evacuation with both evacuation procedures, with a 30 s phase interval. For the fire floor clearance time, Scenario 19 with partial evacuation exhibits a 2-second increase compared to its control group Scenario 4, where total evacuation is employed. This difference is not significant. On the other hand, Scenario 22 shows a reduction of approximately 3% in the fire floor clearance time compared to Scenario 13. This reduction aligns with the degree of decrease in total evacuation time, but it still mismatches with the 35% decrease in evacuated occupants. The evacuation from the floors above the fire floor are attributed to more delays in total evacuation time and the fire floor clearance time. As depicted in Figure 13 adopting the evacuation procedure A primarily evacuates the fifth floor in the first phase, while the other procedure leads to the evacuation of both the fifth and sixth floors in the first phase. In other words, when the floor above the fire floor is evacuated in the same phase as the fire floor, the evacuation of the floor above delays the evacuation of the fire floor more significantly than the evacuation of floors below fire floor. It aligns with a previous phased evacuation experiment in a 25-story office building. Kadokura et al. (2015) examined the flow and congestion patterns in staircases and observed that congestion delays occurred due to the merging flows from the floor area and upper floors. It explains partial evacuation does not facilitate fire floor evacuation, due to congestion delays are more related to the merging flow on fire floor landing. The trends stay consistent when the phase interval is raised to 60 s and 90 s.

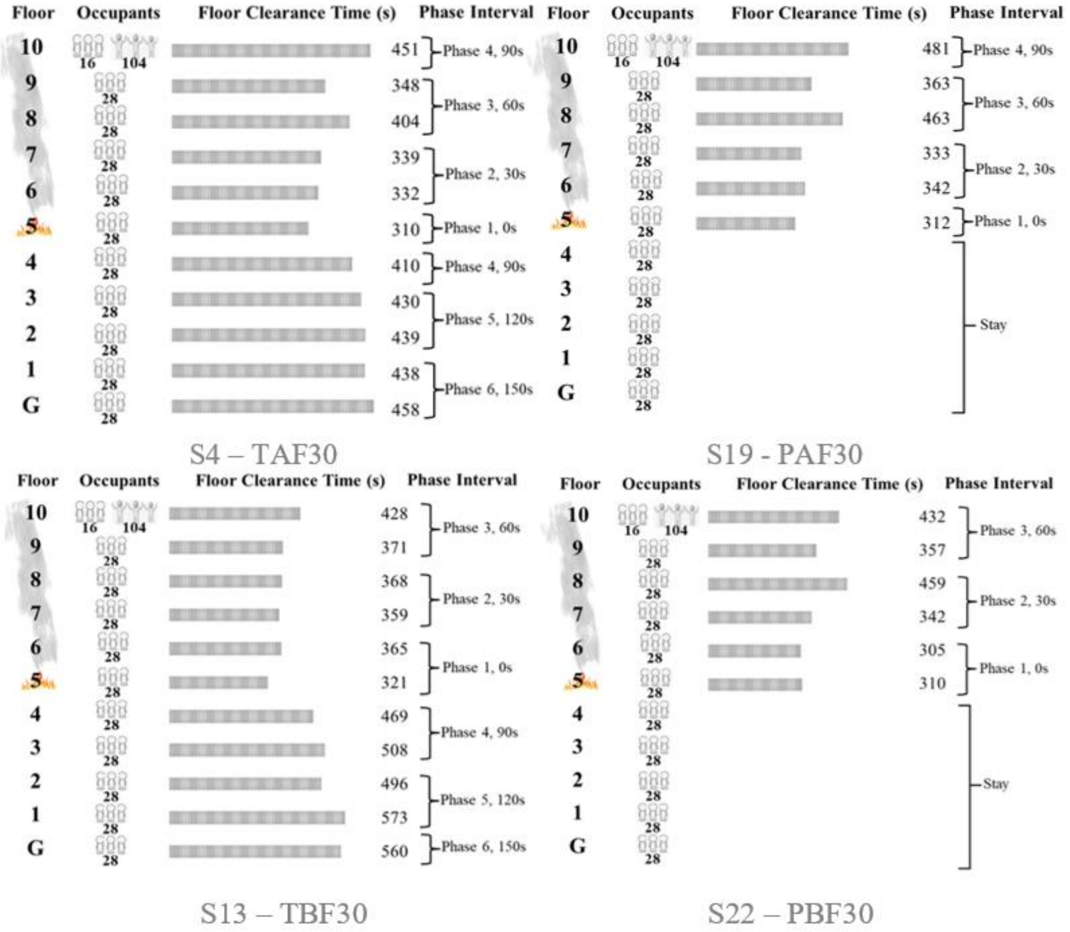


Figure 13. Floor clearance time comparison between total evacuation & partial evacuation

Additionally, it is worth noting that partial evacuation can reduce interruptions to occupants on less affected lower floors. Furthermore, it is supposed that under simultaneous evacuation strategy, partial evacuation may facilitate the evacuation of the fire floor relative to total evacuation. However, future research is needed to justify this idea.

Furthermore, a scatter plot depicting the correspondence between fire floor clearance time and total evacuation time for first 24 scenarios is shown in Figure 14 to facilitate data visualization. The scatter plot is divided into three series based on different fire floor: ground floor, fifth floor, and tenth floor. Cross symbols represent scenarios based on the evacuation procedure A across three series, while square symbols represent scenarios based on the evacuation procedure B. As discussed earlier, it is evident that across these three series, evacuating only the first floor and occupants with functional limitations usually demonstrates shorter fire floor clearance times compared to evacuating the fire floor and the floor directly above it. Several scatter points greatly deviate from each other in fifth floor series and ground floor series. This delay can result from an increase in phase interval or from the delayed evacuation of the most crowded floor. This is examined by introducing comparison of new scenarios' results in Table 18.

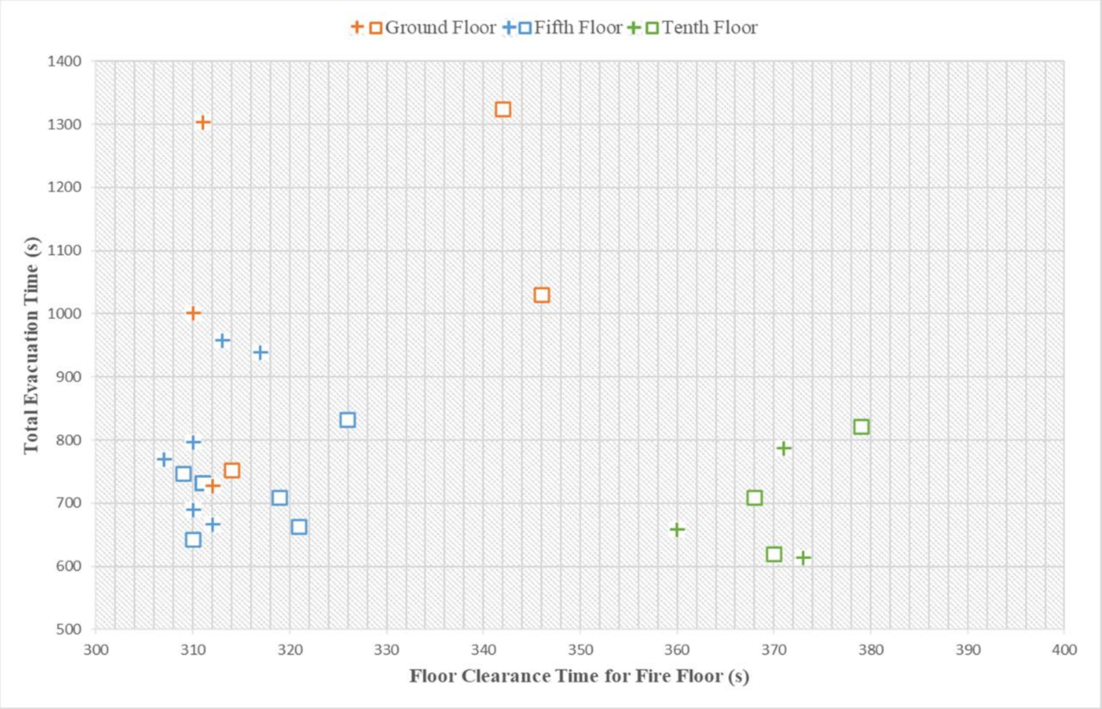


Figure 14. Fire floor clearance time vs. total evacuation time among 24 initial scenarios

The data from the new scenarios is plotted in Figure 15 with the primary scenarios. Blue crosses represent scenarios following the evacuation procedure A, whereas grey crosses show an extra tenth floor evacuation in the first phase on the basis of that. The blue squares indicate scenarios based on the evacuation procedure B, while grey squares an additional tenth floor evacuation in the first phase on the basis of this procedure. In new scenarios 28, 29, and 30, the evacuation of ground floor (fire floor) is delayed not only due to the evacuation of the first floor (floor immediately above) but also due to the evacuation of the most crowded tenth floor. This yields in a decrease in total evacuation time and significant delay in the fire floor evacuation compared to primary scenarios in their control group. On the other hand, the delay in new scenarios 25, 26, and 27 is not significant, as the evacuation of the ground floor (fire floor) is primarily delayed by the evacuation of the tenth floor. These delays are hypothesized again to be caused by merging flows from fire floor and the upper floors. However, this research fails to explore whether evacuating the most crowded floor during the first phase would result in prolonged fire floor clearance time, when the most crowded floor is located below the fire floor.

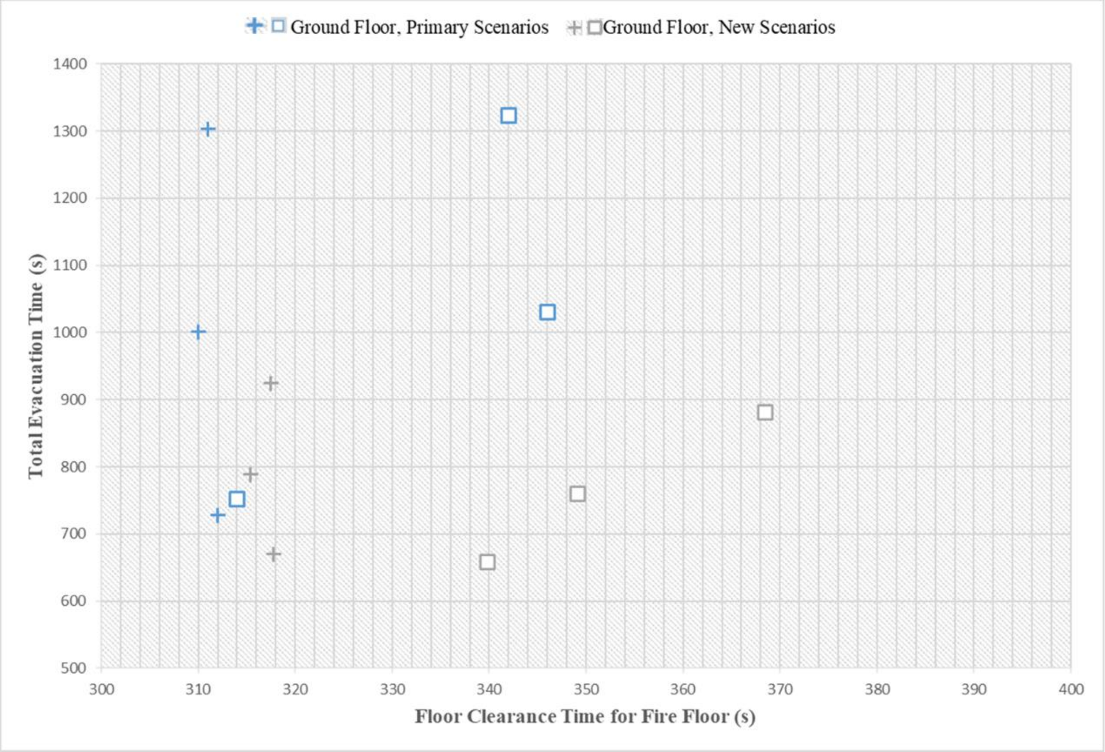


Figure 15. Comparison of new scenarios and their control groups

In addition, it is worth noting that this research employs three fixed time intervals: 30 s, 60 s, and 90 s. Undoubtedly, scenarios with a 30 s phase interval all exhibited shorter total evacuation times compared to scenarios with other same conditions. However, whether there is a more suitable phase interval than 30 s remains unknown as this interval might be scenario specific. A more appropriate method for determining the interval is to use the "trigger" action in evacuation models (and in real life through sensors-based or crowd management solutions) to automatically initiate the evacuation of the next phase after the evacuation of the current phase is completed. This approach also aligns more closely with the practice in real life, where evacuation intervals might be determined by building manager, fire brigade (if applicable) or fire control room manager (if applicable).

Furthermore, this research does not consider the scenario where a stair is filled by smoke. Although phased evacuation is typically based on the assumption that properly designed passive fire protection systems is well-functioned within the building (Home Office, 2022), system failures can still occur. If only one stair within a building is available for evacuation, the evacuation outcomes for the 30 scenarios may vary. During the course of the research, a new amendment to the Approved Document B was published (HM Government, 2024) in March, and the Government of Ireland (2024) published their new Technical Guidance Document B - Fire Safety (2024), Fire Safety – Volume 1 in March as well. They might have impact on this research, which needs to be considered in future research.

6. Conclusion

The research explores the current state of phased evacuation adoption worldwide while also examining the intricacies of evacuation dynamics under 30 various scenarios. More specifically, it includes not only a thorough review of 33 codes and standards in 11 nations but also extensive simulation-based analyses of 24 initial phased evacuation scenarios and 6 new scenarios using the Evacuationz simulation tool. Moreover, it suggests familiarizing the modelling tool to be utilized before commencing modelling, and to employ an appropriate method to address uncertainties inherent in the modelling process. By synthesizing findings from code review, simulations, and discussions on total evacuation time and floor clearance time, it can be concluded that there is no universally applicable phased evacuation strategy for all multi-purpose residential buildings. Stakeholders in building projects should employ dedicated simulations to grasp evacuation dynamics case by case and justify their decision-making with evacuation modelling. However, two key aspects are identified as requiring careful consideration: 1) Simulation tool should be carefully selected, and their uncertainties should be addressed before starting the simulation study, and 2) It could be beneficial to evacuate the fire floor first rather than evacuate it together with floors above and the most crowded floor at the first phase to avoid causing delays for the fire floor clearance.

The review of 33 codes and standards presented in Appendix 1 reveals the current landscape of phased evacuation-based means of escape design in international fire safety engineering. While phased evacuation is not yet a predominant approach in global fire safety engineering design, the review includes various types of documents, including codes, standards, guidelines, provisions, acceptable solutions, and verification methods. Notably, Europe, particularly the United Kingdom, emerges as a region with a stronger emphasis on phased evacuation, with 5 out of the 33 reviewed documents providing recommendations for phased evacuation based means of escape design. However, the majority of reviewed codes and standards do not include content related to phased evacuation, indicating a need for further research on justifying its effectiveness in various scenarios.

The comparative analysis of evacuation scenarios using Evacuationz and Pathfinder tools demonstrates their consistency in generating results. The difference in total evacuation time and floor clearance time ranges from -12.3% to 13.1%. Additionally, Evacuationz shows 70.8% faster running times and significantly 98.7% smaller result file storage consumed in average. This research primarily focuses on total evacuation time and floor clearance time, revealing insights into the dynamics of evacuation processes under 30 different scenarios. Phased partial evacuation scenarios consistently demonstrate shorter total evacuation times compared to corresponding phased total evacuation scenarios, resulting in reductions ranging from 2.0% to 4.3%, suggesting potential benefits in certain scenarios. However, the general delay in fire floor clearance time highlights the importance for fire engineers to consider congestions from merging flow. Moreover, the comparison of new scenarios incorporating the evacuation of the most crowded floor into the first phase reveals a notable acceleration in total evacuation time from 8.0% to 33.4%, but a delay in the fire floor clearance from 0.9% to 8.2%. This suggests the importance of considering both total evacuation time and fire floor evacuation dynamics when evaluating evacuation strategies. Additionally, the research states the need for further exploration of optimal phase intervals in a phased evacuation, aligning with future real-life practices where evacuation intervals could be based on sensors-based or crowd management solutions. Furthermore, future research should address scenarios involving one of staircases filled with smoke and consider the implications of the any recent and future amendment or new version, such as March 2024 Amendment of Approved Document B, and new volume of Technical Guidance Document B. Overall, this research emphasizes the importance of grasping evacuation dynamics and highlights areas for future exploration and improvement in evacuation modelling and design practices.

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Appendices

Appendix 1. Review Summary

Name	Applied Region	Category	Phased Evacuation Design	Notes
				Europe
BS 9999: 2017 Code of practice for fire safety in the design, management and use of buildings (BSI, 2017)	United Kingdom of Great Britain and Northern Ireland	Prescriptive code	Yes	1. Definition: The first people to be evacuated are **all those on the storey most immediately affected** by the fire, and **those on other floors with impaired ability** to evacuate. The remaining floors are then evacuated, usually **two floors at a time**, at phased intervals. 2. If phased evacuation is adopted, the code requires specific active and passive fire safety measures in 12.2.2. 3. In tall buildings over 30 m in height where phased evacuation is adopted, there is a potential that persons attempting to escape could be impeded by fire-fighters entering and operating within the building. (14.1.c) **Thus, this scenario could be considered in scenarios design.** 4. The **aggregate width of escape stairs** for phased evacuation should be **not less** than the greater of the following, unless additional fire protection measures are provided (Clause 18): a) the dimensions given in 17.4.1 b) the dimensions given in Table 13 for the appropriate risk profile and the maximum capacity on any two floors 5. Floors in a building designed for a phased evacuation strategy should be constructed as compartment floors. (31.3.1.4) 6. The most appropriate phasing of evacuation for any particular building should be determined on the basis of the mode of evacuation (phased, simultaneous or both), the nature of the occupants and the fire risk present. (B 3.3) 7. Annex M (normative) Phased Evacuation provides detailed procedure and guidelines for phased evacuation.
BS 9991: 2015 Fire safety in the design, management and use of residential buildings - Code of practice (BSI, 2015)		Prescriptive code	No	Nothing related to phased-evacuation-based means of escape design.
PD 7974-6:2019 Application of fire safety engineering principles to the design of buildings Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition (Sub-system 6) (BSI, 2019)		Performance based document	No	1. For buildings designed for phased evacuation, evacuation times for the fire floor may be increased if the floor above or below are also evacuated simultaneously, due to congestion in the stair and merging behaviour at the storey exits. (7. Estimation of travel times) 2. Also, the definition of phased evacuation is very similar to BS 9999, the difference is it added: "…, or at least that evacuation of the floor above is **delayed by 1–2 min** to facilitate initial clearance of the fire floor."
Approved Document B Volume 1: Dwellings (2019 edition incorporating 2020 and 2022 amendments) (HM Government, 2022)	England	Prescriptive document	No	Nothing related to phased-evacuation-based means of escape design.
Approved Document B Volume 2: Buildings other than dwellings (2019 edition incorporating 2020 and 2022 amendments) (HM Government, 2022)		Prescriptive document	Yes	1. Definition: The first people to be evacuated are those with **reduced mobility** and those **on the storey most immediately affected by the fire**. If needed, subsequent evacuation is done **two floors at a time**, reducing disruption in large buildings. (**Similar to BS 9999)** **2.** In tall buildings over 30 m in height where phased evacuation is adopted, there is a potential that persons attempting to escape could be impeded by fire-fighters entering and operating within the building. (3.20) (**The same as BS 9999)** 3. If phased evacuation is adopted, the document requires specific active and passive fire safety measures in 3.21. 4. The **minimum width of stairs** for phased evacuation and calculation equation are given in Table 3.3 in 3.22.
Building standards technical	Scotland	Prescriptive document	No	Nothing related to phased-evacuation-based means of escape design.

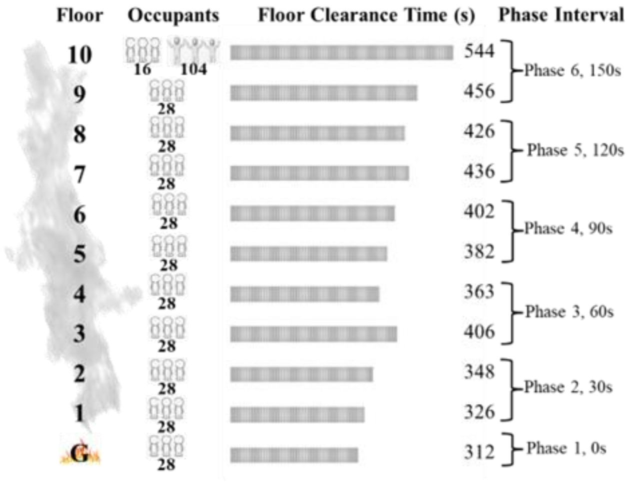
handbook 2022: domestic (Scottish Government, 2022)				
Building standards technical handbook June 2023: non-domestic - December 2023 addendum (Scottish Government, 2022)		Prescriptive document	Yes	1. Definition: The occupants first evacuated are those **on the storey of fire origin** and **those on the storey immediately above**. If further evacuation is required, this is done on the basis of the **next two adjoining upper storeys** to avoid congestion in the escape stairs. The remaining storeys would then be evacuated **two storeys at a time** however this would be dependent on the severity of the fire and any direction given by the fire and rescue service. (**Different from BS 9999 & Approved Document B Volume 2**) 2. **Escape stair width** is depended on number of stairs provided and whether the escape strategy is simultaneous evacuation or phased evacuation. 3. To calculate **appropriate capacity (AC)**, the specific evacuation strategy needs to be considered. AC is equal to the total occupancy capacity, less 20%, of each of the 2 adjacent upper storeys, served by the escape stair, or in the case of an escape stair serving a basement storey, the 2 adjacent basement storeys served by that escape stair, having in either case the greatest combined occupancy capacity. 4. For phased evacuation, designer is allowed to reduce the width of the escape stairs and disruption in large buildings can be minimised. However, it is only suitable for buildings where the **occupants are awake and familiar** with the building, for example, offices. 5. If vertical phased evacuation is adopted, the document requires specific fire safety measures in 2.9.31. One of them is the escape stairs should be entered from a protected lobby. 6. For phased evacuation, **calculation of effective width** is 5.3*AC/N, where N is number of escape stairs. As escape is based on phased evacuation, access to each protected zone containing the escape stair should be by way of a protected lobby. Therefore, there is no need to deduct 1 stair from the calculations. 7. If phased evacuation is adopted, the alarm system L1 to L5 with or without voice alarm should be installed. (2.11.3) 8. In summary, this document does not encourage residential buildings adopt phased evacuation strategy, because they are familiar with building but might be asleep.
Technical Guidance Document B - Fire Safety (2006) (Government of Ireland, 2020)	Republic of Ireland	Prescriptive document	Yes	1. Definition: Phased evacuation is based on evacuating persons on a **sequential basis**, commencing with those on the storeys most affected by the fire in its initial stages. That is the **storey of fire origin** and the **one immediately above**. 2. Required stairway widths less than those needed for total evacuation are possible. Minimum aggregate width of stairways for phased evacuation is regulated in Table 1.7, and the equation for calculation is provided afterwards.
Norme tecniche di prevenzione incendi (CNVVF, 2015)	Italian Republic	Prescriptive standard	Yes	1. Definition: a mode of evacuation for a structure organized with multiple compartments, in which the evacuation of occupants to a safe location occurs **successively after the evacuation of the first ignition compartment.** It is implemented with the assistance of active, passive, and managerial fire protection measures. (G.1.9.20) 2. The minimum width of the vertical evacuation route is calculated as follows: $L_V = L_U * n_V$ with: L_V, the minimum width of the vertical evacuation route. L_U, the unit width determined from table S.4-29 based on the reference risk profile R_{life} and imposing a total number of 2 floors served by the vertical evacuation route. n_V, the total number of occupants using that vertical evacuation route, originating from two of the serviced floors, considering the two floors, even if not consecutive, with the highest occupancy, under the most severe evacuation conditions (paragraph S.4.8.6). (S.4.8.8.2) **Note**: The clauses mentioned above are **unofficial translations**.
Boverket´s building regulations – mandatory provisions and general recommendations, BBR (BFS 2011:6 with amendments up to BFS 2018:4) (Boverket, 2019)	Kingdom of Sweden	mandatory provisions and general recommendations	No	Nothing related to phased-evacuation-based means of escape design.
		Asia		
GB 55037-2022 General Code for Building Fire Protection (MoHURD, 2022)	People's Republic of China	Prescriptive code	No	Nothing related to phased-evacuation-based means of escape design.
GB/T 31593.9-2015 Fire safety engineering—Part 9: Guidance on Evaluation of		Guidance	No	1. For buildings with limited evacuation capacity, horizontal or vertical phased evacuation strategies can be adopted. This involves evacuating people gradually from areas threatened by fire within the building. For example, buildings such as hospitals that are difficult to evacuate quickly can adopt a phased evacuation strategy, evacuating people to adjacent areas

behaviour and movement of people (AQSIQ & SAC, 2015)				for temporary shelter. (5.5) Notes: No Phased Evacuation Definition is proposed. Nothing related to phased-evacuation-based means of escape design. The clause simply recommends the suitable situation for phased evacuation and gives an example.
Code of Practice for Fire Safety in Buildings 2011 (June 2023 version) (Buildings Department, 2023)	Hong Kong Special Administrative Region of the People's Republic of China	Prescriptive code	No	Nothing related to phased-evacuation-based means of escape design.
Fire Code 2023 (SCDF, 2023)	Republic of Singapore	Prescriptive code	No	Nothing related to phased-evacuation-based means of escape design.
		America		
NFPA 101 Life Safety Code (2024) (NFPA, 2023a)	United States of America	Prescriptive code	No	1. This code mentioned that phased evacuation is the alternative term of staged evacuation, which are defined at A.4.8.2.1(3) which the evacuation process can be **ordered or managed** in accordance with an established priority in which **some or all occupants** of a building or facility clear their area and utilize means of egress routes. This is typically done so that the **more endangered** occupants are removed **before** occupants in **less endangered** areas. Notes: However, there is no guidance on which circumstances it should be used and how it should be carried out.
NFPA 5000 Building Construction and Safety Code (2024) (NFPA, 2023b)		Prescriptive code	No	Nothing related to phased-evacuation-based means of escape design.
National Fire Code of Canada 2020 (Canadian Commission on Building and Fire Codes, 2020)	Canada	Objective-based code	No	Nothing related to phased-evacuation-based means of escape design.
		Oceania		
National Construction Code Volume One (Building Code Australia) (ABCB, 2022a)	Commonwealth of Australia	Hybrid code	No	Nothing related to phased-evacuation-based means of escape design.
National Construction Code Volume Two (Building Code Australia) (ABCB, 2022b)		Hybrid code	No	Nothing related to phased-evacuation-based means of escape design.
Australian Fire Engineering Guidelines (ABCB, 2021)		Prescriptive Guideline	No	Nothing related to phased-evacuation-based means of escape design.
Fire Safety Verification Method Standard (ABCB, 2022c)		Verification Method Standard	No	Nothing related to phased-evacuation-based means of escape design.
C/VM2 Verification Method: Framework for Fire Safety Design For New Zealand Building Code Clauses C1-C6 Protection from Fire (MBIE, 2023a)	New Zealand	Code verification method	No	Nothing related to phased-evacuation-based means of escape design.
C1-C6 Protection from Fire Acceptable Solution C/AS1 Protection from fire for buildings with sleeping (residential) and outbuildings (risk group SH)		Code acceptable solution	No	Nothing related to phased-evacuation-based means of escape design. Notes: This acceptable solution allows for the "all out" evacuation strategy. It does not provide features to facilitate a delayed evacuation strategy." (1.1.2.5)

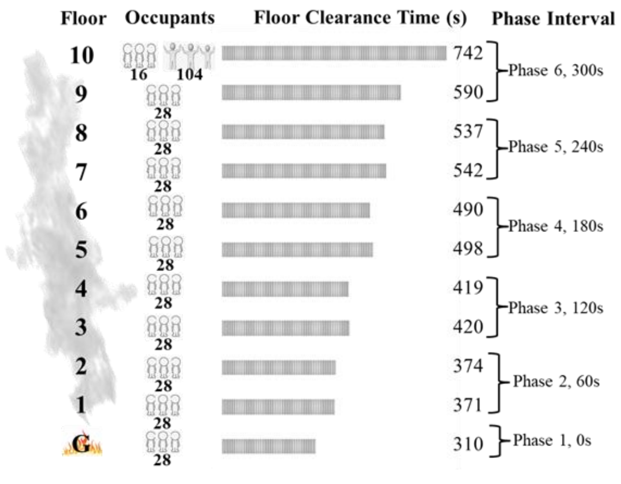
Second Edition (MBIE, 2023b)				
C/AS2 Acceptable Solution for Buildings other than Risk Group SH For New Zealand Building Code Clauses C1-C6 Protection from Fire (MBIE, 2023c)		Code acceptable solution	No	Nothing related to phased-evacuation-based means of escape design. Notes: Other than where permitted for risk group SI and for early childhood centres, this Acceptable Solution allows for an ‘all out’ evacuation strategy. It does not provide features to facilitate a delayed evacuation strategy. (1.1.4)
C/AS3 Acceptable Solution for Buildings Where Care or Detention is Provided (Risk Group SI) For New Zealand Building Code Clauses C1-C6 Protection from Fire (MBIE, 2014a)		Code acceptable solution	No	Nothing related to phased-evacuation-based means of escape design.
C/AS4 Acceptable Solution for Buildings with Public Access and Educational Facilities (Risk Group CA) For New Zealand Building Code Clauses C1-C6 Protection from Fire (MBIE, 2016a)		Code acceptable solution	No	Nothing related to phased-evacuation-based means of escape design. Notes: Other than where specifically required for early childhood centres, this Acceptable Solution allows for an ‘all out’ evacuation strategy only and does not provide features that would allow for delayed evacuation strategies. (1.1.3)
C/AS5 Acceptable Solution for Buildings used for Business, Commercial and Low-Level Storage (Risk Group WB) For New Zealand Building Code Clauses C1-C6 Protection from Fire (MBIE, 2016b)		Code acceptable solution	No	Nothing related to phased-evacuation-based means of escape design. Notes: This Acceptable Solution allows for an ‘all out’ evacuation strategy only and does not provide features that would allow delayed evacuation strategies. (1.1.3)
C/AS6 Acceptable Solution for Buildings used for High Level Storage and Other High Risk Purposes (Risk Group WS) For New Zealand Building Code Clauses C1-C6 Protection from Fire (MBIE,2014b)		Code acceptable solution	No	Nothing related to phased-evacuation-based means of escape design. Notes: This Acceptable Solution allows for an ‘all out’ evacuation strategy only and does not provide features that would allow delayed evacuation strategies. (1.1.3)
Others				
2021 International Fire Code (IFC) (ICC,2021b)	International	Hybrid Code	No	Nothing related to phased-evacuation-based means of escape design.

ISO 13943:2023 Fire safety — Vocabulary (ISO, 2023)		Terminology Vocabulary	No	1. Definition: The process by which different parts of a built environment (3.36) are evacuated in a **controlled sequence.** 2. Example: In a multi-storey building, the initially evacuated floors are usually **the fire floor, the floor immediately above**, **the floor immediately below and all basement floors**. Note 1 to entry: Those parts expected to be at greatest risk are evacuated first.
Fire Safety for Very Tall Buildings Engineering Guide Second Edition (SFPE & ICC, 2022)	Book	Guide	No	Definition: The typical phased evacuation philosophy adopted within many **medium-height buildings** and above is the **initial evacuation** of the **fire floor + a number of stories above + a number of stories below the fire floor**. Other floors "stay-in-place" and do not evacuate. Local codes of practice and opinion may differ on how many stories below the fire floor require to evacuate in the first phase; however, between two and three floors (i.e., fire floor + floor above or fire floor + the floor above and below) is common practice.
SFPE Guide to Human Behavior in Fire Second Edition (SFPE, 2019)		Guide	No	Nothing related to phased-evacuation-based means of escape design.
SFPE Handbook of Fire Protection Engineering Fifth Edition (Bukowski & Tubbs, 2016)		Handbook	No	Definition: Phased and partial evacuation strategies combine evacuating or relocating a portion of the occupants - those in immediate danger from the incident - with allowing occupants remote from incident to protect-in-place.

Appendix 2. Floor Clearance Time Plots



Scenario 1



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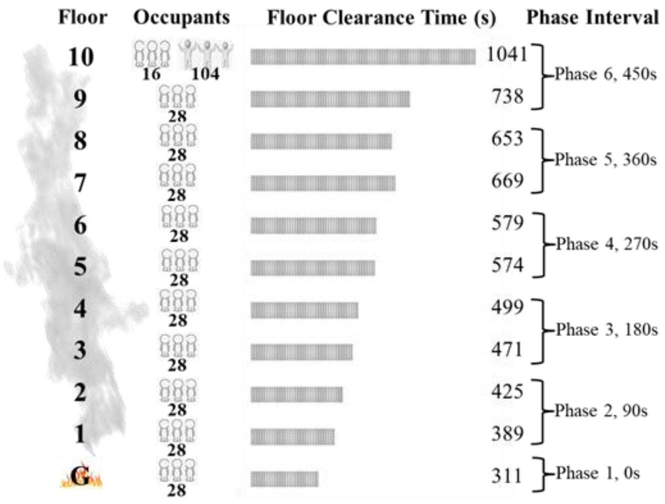

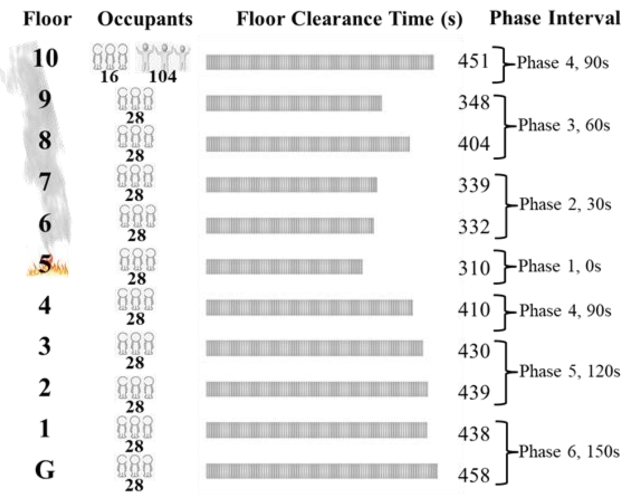

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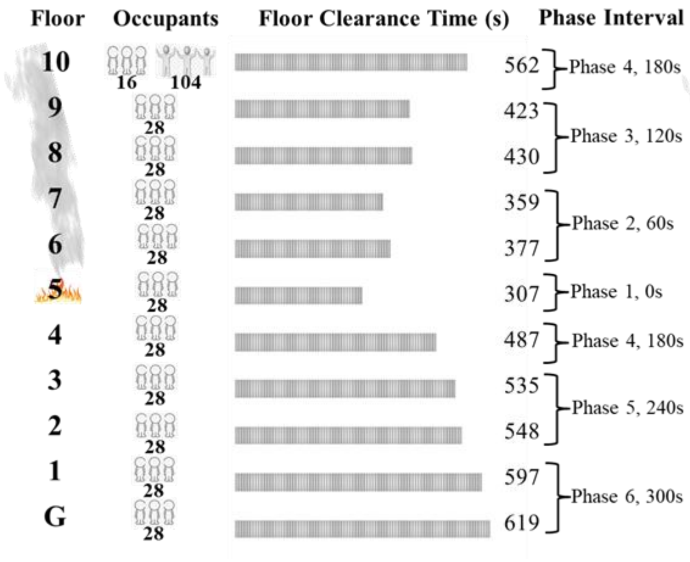
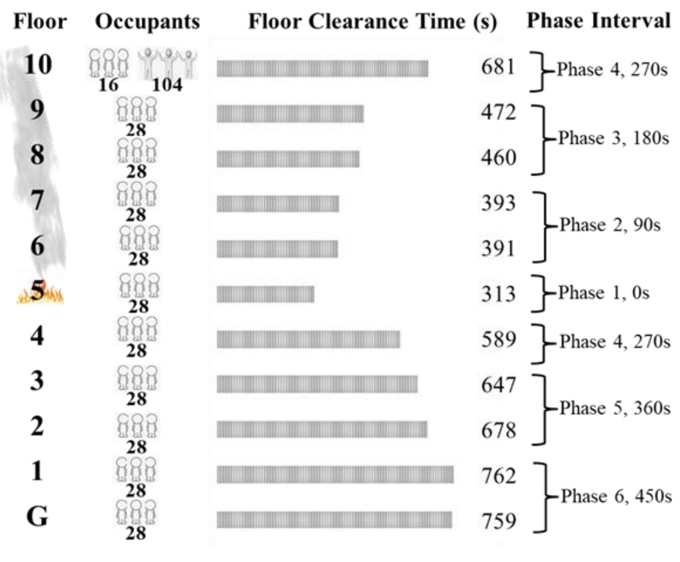
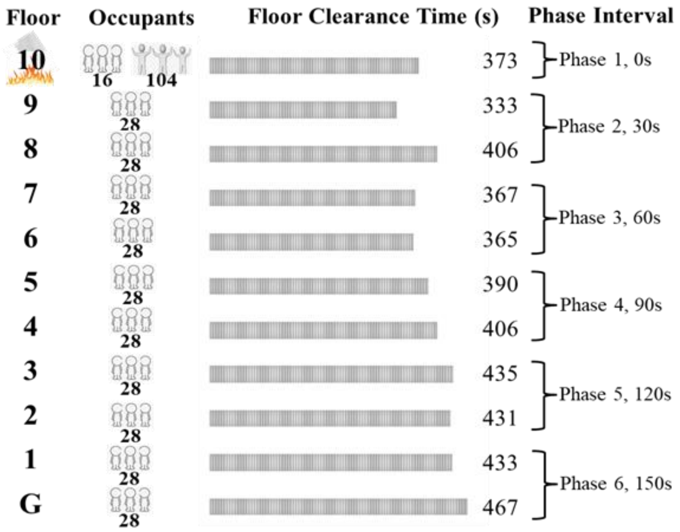




Scenario 5

Scenario 6



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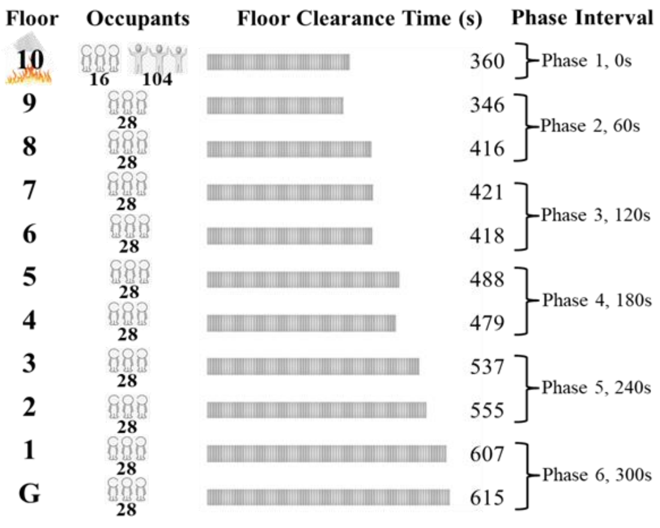

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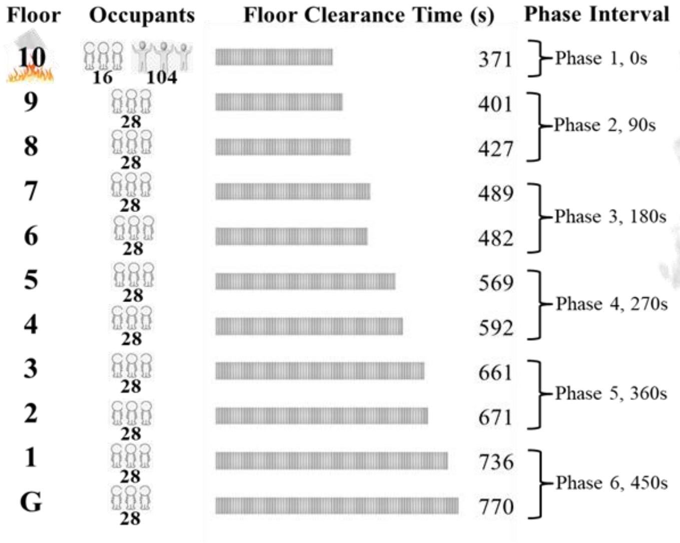

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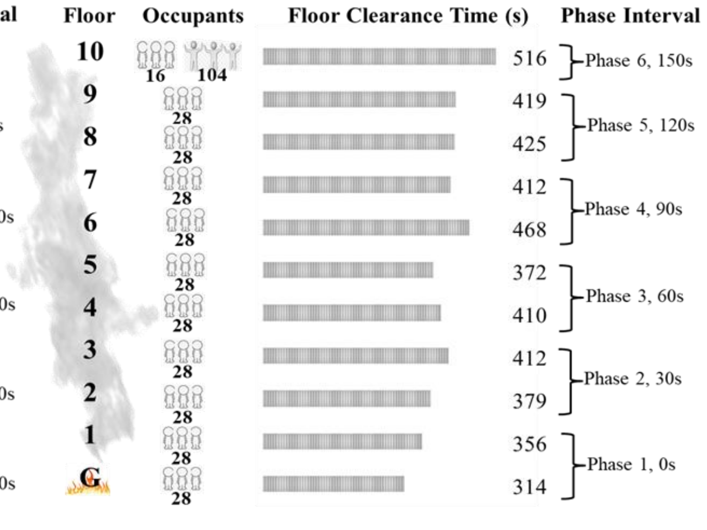

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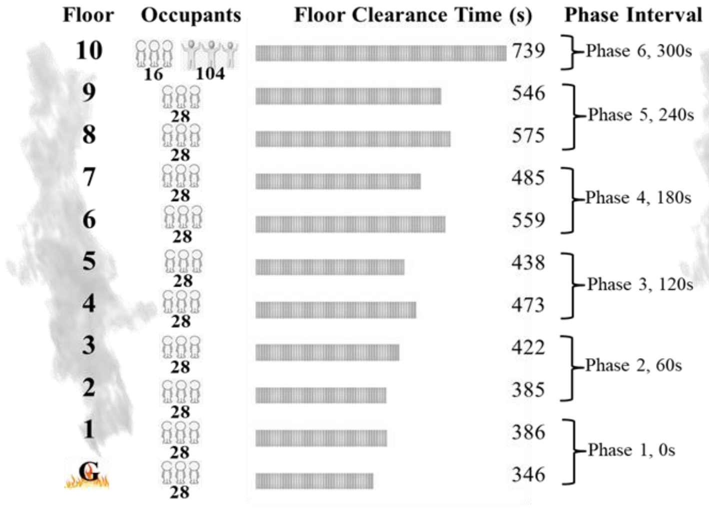

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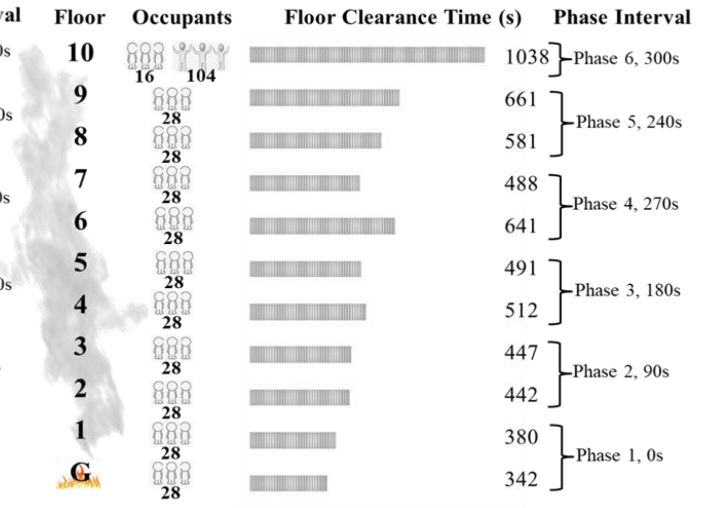

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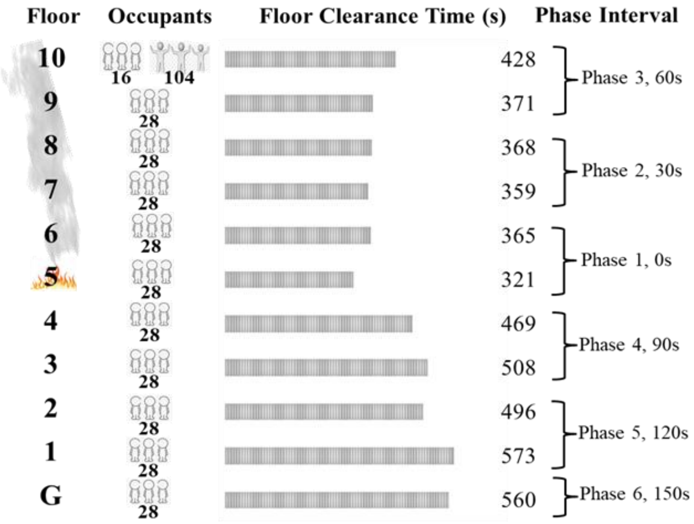
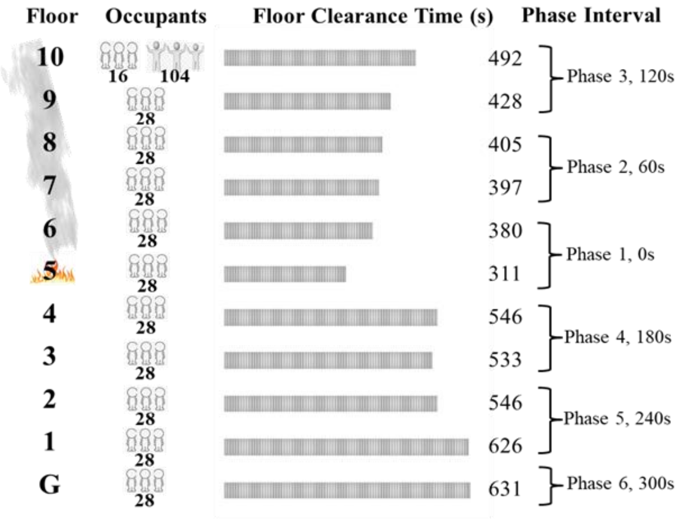


Scenario 13



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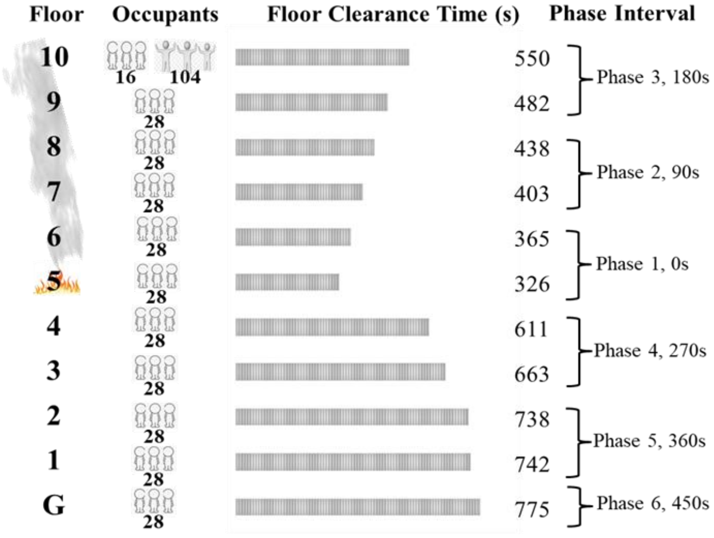
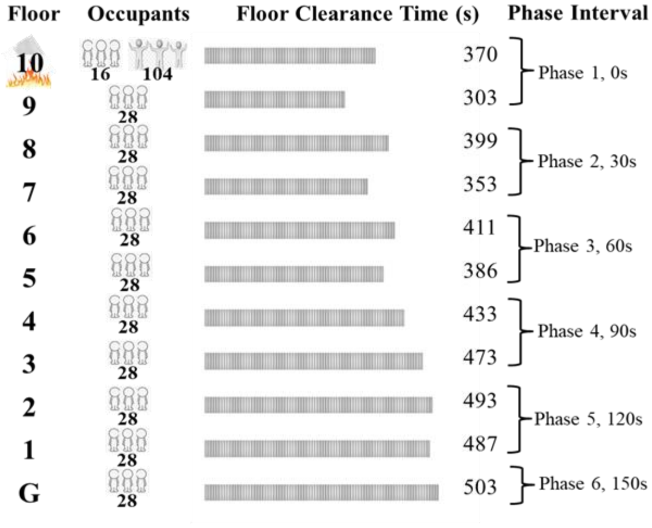
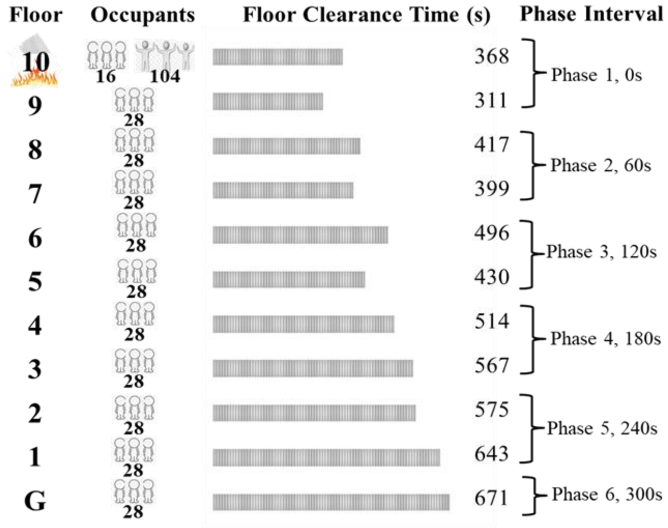


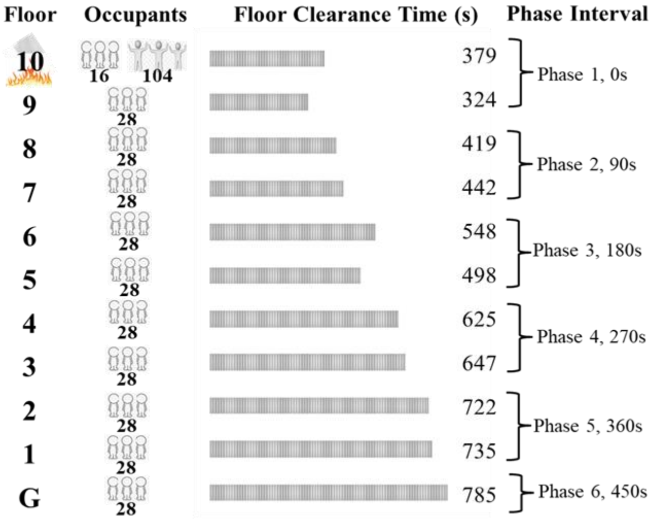
Scenario 15



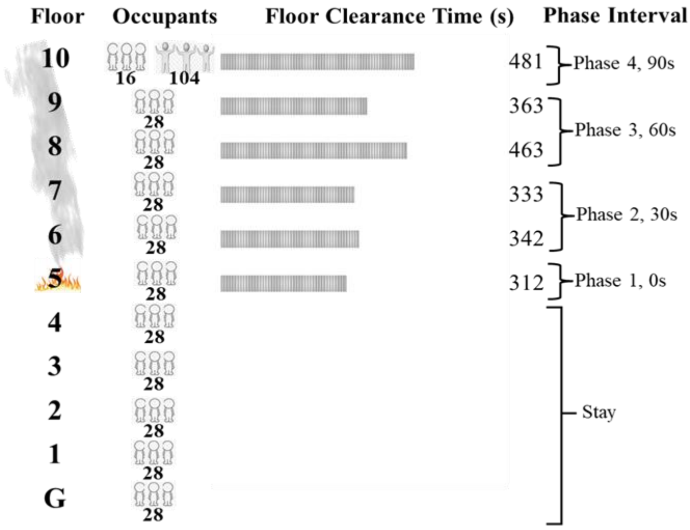
Scenario 16



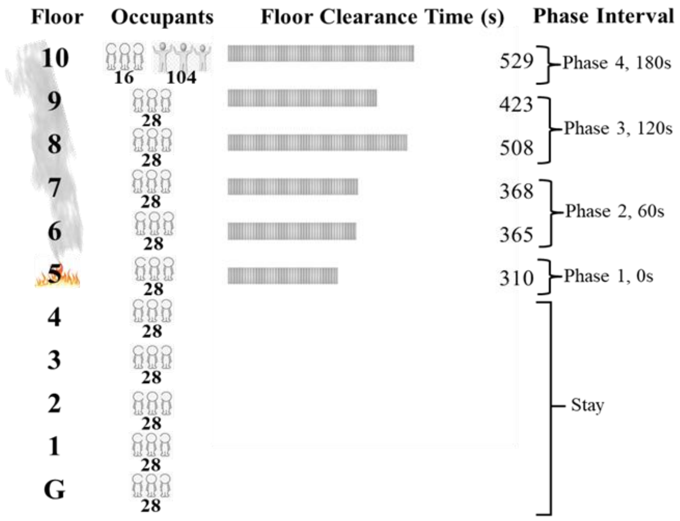
Scenario 17



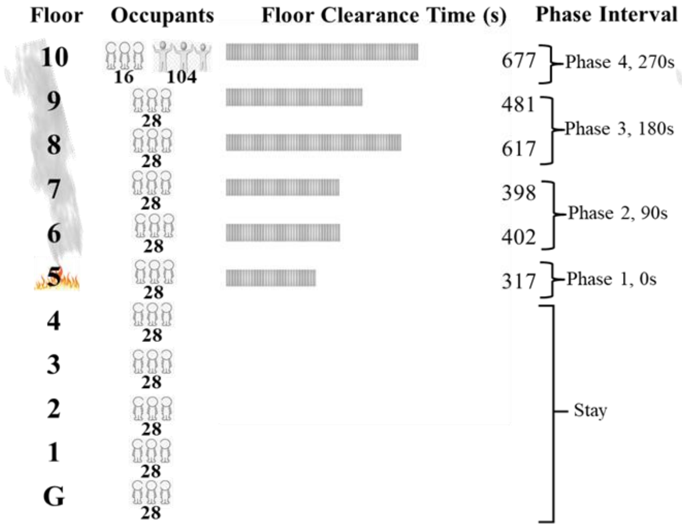
Scenario 18



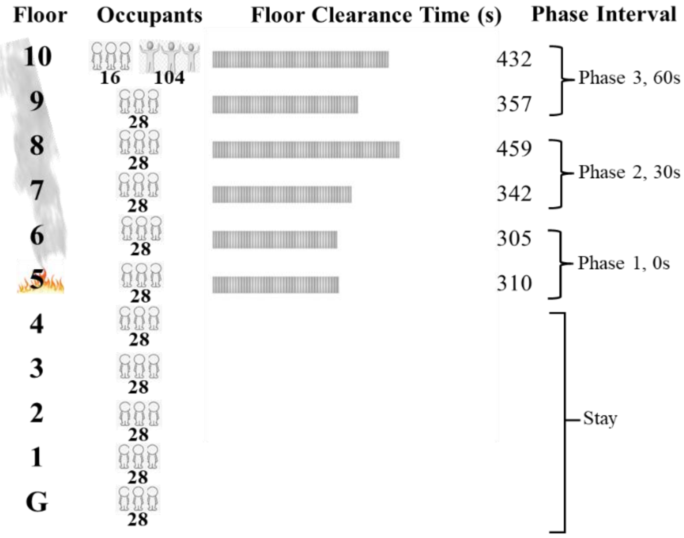
Scenario 19



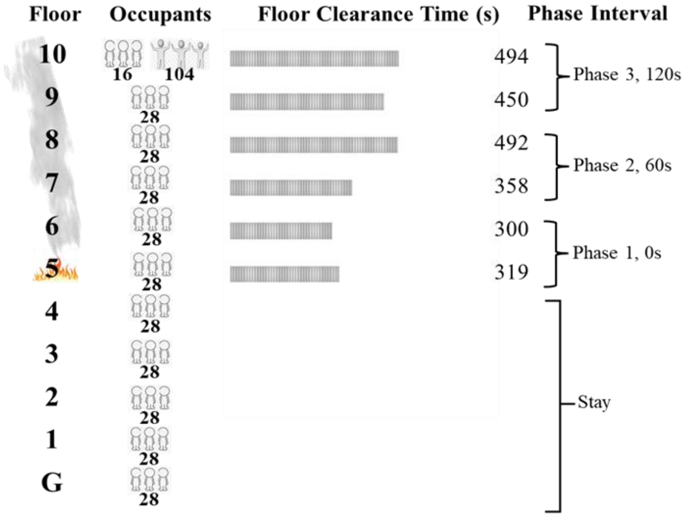
Scenario 20



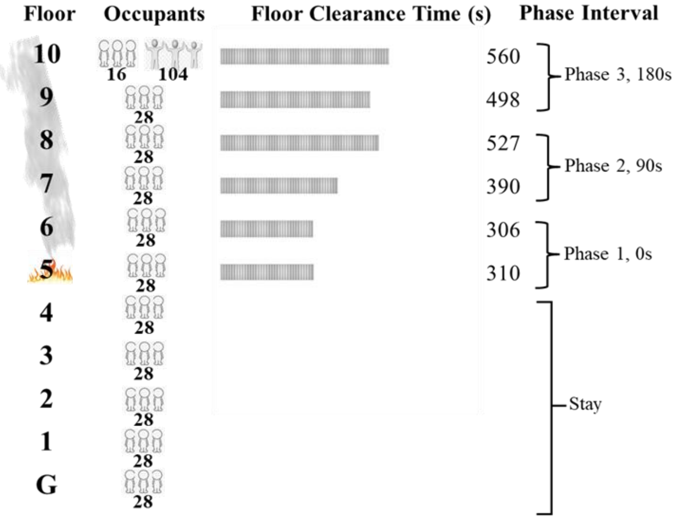
Scenario 21



Scenario 22



Scenario 23



Scenario 24