APPENDIX A3: QUANTIFY EFFECTIVENESS OF EVACUATION STRATEGIES

Authors: M Spearpoint[1], M Arnott[1], S Gwynne[2], H Xie[2]

Reviewers: J Torero[3], D Joyeux[3]

[1]OFR, [2]Movement Strategies / GHD, [3]UCL, [4]Efectis

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Executive summary

This report contributes to research that forms part of a wider technical review by the Building Safety Regulator (BSR) at the Health and Safety Executive (HSE)[1] of the statutory guidance for fire safety in buildings in England given by Approved Document B (AD B). The work addressed within this report is in response to the BSR's request to "*Evaluate evacuation strategies using a robust modelling approach considering the analysis of the effectiveness of physical design measures and human behaviour (including impact of public confidence and perceptions).*" **Therefore, the principal aim of this work is to quantify the evacuation performance of high-rise residential buildings using a representative set of egress scenarios that include challenging building smoke movement situations.** This allows an investigation of key design, procedural and response factors to deliver quantitative information that can enable a competent professional to evaluate the evacuation performance of high-rise residential buildings**.**

Two agent-based evacuation models have been applied to investigate evacuation in a quantitative manner across an array of different scenarios and system designs. A method has been developed to apply these models to deliver results in a structured and representative way. This involved reducing the scenario envelope enabling the capture of key results whilst operating within the constraints of the project. The simulations presented in this study address these design, procedural and response variables to investigate how each individually and collectively affect the evacuation of occupants from a range of different building configurations.

As part of this research, a review of the building evacuation literature followed by surveys of resident and fire and rescue service personnel related to evacuation from high-rise residential buildings has been carried out. The information collected (1) identified that residents might engage in evacuation (rather than staying put in their flat) and (2) affected the scenarios examined in terms of the factors used to create these scenarios and how they might be represented within the tools used. Variables affected were the initial delays, movement rates, proportions of agents deemed to be evacuating, and proportions of agents with movement impairments.

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[1] The research was originally commissioned by the Ministry of Housing, Communities and Local Government (MHCLG) which subsequently became the Department for Levelling Up, Housing and Communities (DLUHC) which then transferred its fire safety responsibilities to the Health and Safety Executive (HSE).

An exemplar building floorplate was previously produced as part of Objective A2 of this project to simulate a ‘common’ building configuration that meets the recommendations given by AD B. Based on this floorplate, the necessary design parameters for modelling a set of exemplar buildings have been developed to include three variants of the floorplate, the physical dimensions of rooms, corridors, and stairs across building heights ranging from 11 m to 140 m. Building heights have been chosen that reflect specific trigger heights given by AD B. The exemplar buildings have been configured to maximise the occupant load by defining heights just under each AD B trigger height and assuming a lower bound representative storey floor-to-floor height to maximise the number of storeys. The resident population and their response were derived from Objective A2. The response variables defined were pre-evacuation times, and baseline horizontal and vertical uncongested travel speeds derived from the research literature and guidance available, which were customised to suit different situations and scenarios (e.g., those agents that represent residents with movement impairments).

The extensive literature that describes fire development, toxic gas concentrations etc., illustrates that these are highly complex phenomena that are extremely sensitive to the underlying assumptions made (e.g., location, materials involved, air flow/ventilation, etc.). Rather than attempting to account for all these factors in this work, a relatively simplified approach has been adopted, which considers the movement of smoke as the primary fire effluent affecting evacuation performance – from detection to notification, route selection and availability, and movement rates. Using findings from the literature, a representative hazard scenario is proposed that presents a significant challenge to the evacuation strategy. The scenario adopted for this work is where fire and smoke spreads internally through the building via the stairs. The development of the smoke hazard scenario is discussed in Section A3-5, however it was not the objective of this study to assess the likelihood of such scenarios occurring or to determine the specific faults/failures that lead to these specific scenarios. Therefore, the quantitative results presented in this report are specifically linked to the set of failures described in Section A3-5. A situation in which fire and smoke spread is external to the building has not been specifically considered in this study although the internal fire and smoke spread scenario has been benchmarked against evidence from the Grenfell Tower inquiry expert evidence.

This report provides a brief discussion on the various evacuation strategies available to a high-rise residential building, namely: Stay put (as discussed in Section A3-4.8.1), evacuate to a place of safety within the building (as discussed in Section A3-2.4.1), and evacuate to the outside of the building. The focus of this study is the case in which an evacuation takes place – where stay put is not followed, and that specific building safety measures have failed to perform as intended leading to occupants being trapped if not given sufficient time to evacuate to the outside. Thus, the benefits expressed in this study of having wider stairs, more than a single stair, making lifts available for escape, providing various notification systems etc. are primarily relevant to this evacuation scenario.

A structured approach has been adopted to:

- Give confidence in the results produced by the models – their stability, sensitivity and similarity enabling quantitative comparison and assessment of a larger number of scenarios,

- Provide sensitivity of evacuation performance to certain factors informing selection of key factors,

- Assess the impact of varying key factors on performance focusing on core scenarios of interest, and

- Describe the detailed examination of interaction of key factors on performance enabling underlying dynamics to be explored.

Simulated results have been compiled across each scenario – exploring the outcomes produced and the underlying dynamics that affected these outcomes. The primary insight provided relates to the total time to evacuate a building – as the value of this insight is somewhat independent of other assumptions regarding the fire location and severity – and allows comparison within groups of scenario conditions. However, reducing the total evacuation time of a building alone should not necessarily be considered a metric of increased safety. Therefore, where additional insights are required, floor clearance times and the number of agents trapped are reported. A simple normalised measure has also been developed that produces a dimensionless relative measure of performance. This allows evacuation performance outcomes to be compared more widely across scenario conditions to better assess the impact of the underlying factors present. In scenarios in which not all agents were able to evacuate the building before the onset of sufficient smoke that would likely prevent further movement, the simulations determined the number of trapped agents. The quantitative outputs from the modelling depend on the many assumptions made regarding agent walking speeds, agent interactions, route selection, etc. Justifications for these assumptions are detailed in the main report, but were different assumptions made then the results would have changed accordingly.

The results are discussed in detail in Section A3-11. Broadly, the following conclusions can be derived from the results produced:

- **Time to enter stair:** Where sufficient capacity is provided on the staircase and landings to 'store' the occupants (for stairs to act as a refuge), the time needed for the population to enter the stairs is a function of the detection, response and horizontal movement times. The time is largely independent of the building height and floor location, given an absence of congestion limiting access into the stair on each floor. Conversely, if the stair floor area is insufficient to 'store' the population then congestion will likely occur in the common corridors leading into the stairs. In such situations, congestion will accumulate as building height increases – requiring evacuating populations to queue at the stair entrance beyond the protection afforded by the stair. In some of the scenarios considered for buildings over 30 m tall, congestion levels challenge current AD B corridor protection limits when expressed as a fire resistance rating, although this requires more detailed assessment.

  - **Stairs might provide refuge for the occupants of a floor where (1) there is sufficient stair floor area to host the design occupant load on each storey and (2) it is assumed that people are willing to remain stationary inside the stair therefore occupying less space (see Section A3-11.1).**

- **Building height:** As would be expected, where the evacuation of a building is considered, and in the absence of congestion, then as buildings increase in height, so they produce progressively longer total evacuation times. However, total evacuation time does not increase in line with building height (i.e., the constant of proportionality between total evacuation time and building height is less than one). Movement impaired occupants will likely increase total evacuation times due to expected longer pre-evacuation delays and slower unimpeded movement speeds when compared to unimpaired occupants. Impaired occupants may also slow the movement of unimpaired occupants by blocking movement, particularly on stairs. A more representative stair demand (with initial delays reflecting a detection and notification system in place and varied agent movement capabilities) produces prolonged evacuation times, with the conditions on the stairs being more complex, and the floor clearance times not simply being driven by stair congestion.
  - **The total evacuation time of taller buildings is proportionally less than for shorter buildings considering movement in isolation or when other behavioural factors are included in the cases examined that interact in complex ways (see Section A3-11.2).**

- **Stair width:** Stairs with sufficient capacity to 'store' the expected occupant load of a building allows occupants to enter the stairs without producing congestion in the common corridors. The introduction of wider stairs only reduces the overall total evacuation time to a modest extent. Once the stair width exceeds that needed to 'store' the occupants then further widening has little material impact on evacuation performance. Providing a stair width that allows for evacuee overtaking may have a benefit on evacuation times depending on the extent of the fire, the prevalence of slow-moving individuals and those using movement devices, and the effectiveness of other fire protection measures to keep the stair available. Wider stairs may also benefit arriving fire and rescue service personnel and reduce their negative impact on evacuating occupants (although this is not investigated in this study but is the subject of work conducted by the University of Central Lancashire in a separate project commissioned by the Home Office referred to as “Strategies Aiming at Effective Fire Evacuation in High Residential Buildings”).

    - **Increasing stair width beyond 1.5 m only reduced the overall evacuation time where there was insufficient space in the staircases to store the occupants of a floor in the cases examined (see Section A3-11.3).**

- **Number of stairs:** Where stairs are assumed to be a place of safety, two stairs would provide an additional benefit only if a single stair did not have sufficient capacity to ‘store’ the occupants (e.g., when associated with amenity spaces or extended floorplates and larger floor populations). Providing a building with two stairs rather than a single stair has been shown to reduce the total evacuation time depending on the proportion of agents that use each stair and the assumed distribution of pre-evacuation times. Should residents respond in a narrow time window, increasing demand for stair capacity, then a second stair will improve evacuation times. However, much of the gain in time occurs while occupants are within the stair which is already a place of safety. The introduction of more effective notification systems did not significantly affect the degree by which the second stair reduces the total evacuation time. The reduction in total evacuation time is further reduced when evacuation is dominated by pre-evacuation delays (e.g., when people are asleep) and occupant movement speeds (e.g., where people with movement impairments are present, where longer distances are involved, etc.). There is little difference in the potential for occupants to become trapped when two stairs are provided instead of one for buildings up to 30 m tall. Providing a second stair gives a measure of resilience to a building where it is assumed that smoke can enter a stair, as this allows for an alternative place of safety. However, if smoke can enter one stair it may eventually enter other stairs – depending on the building configuration, stair positioning and the fire protection measures afforded to the stairs. In buildings much taller than 30 m (i.e., 140 m in this study) the benefit of additional stairs becomes more complex as the ability of occupants to reach the outside is impacted by the required travel distance. This was not explored in this study and therefore the question of at what building height the effect of the travel distance becomes evident cannot be answered here.
    - **Where stairs are assumed to be a place of safety, two stairs would provide a benefit only if a single stair did not have sufficient capacity to ‘store’ the occupants. Under certain circumstances, such as where the demand on the stairs was increased by the narrowing of the distribution of pre-evacuation times, a second stair may offer an alternate place of safety, although this may only be for a limited duration (see Section A3-11.4).**

- **Detection and notification:** A building-wide tone alarm when coupled with corridor smoke detection provides no obvious advantage over a reliance on social notification (i.e., occupant communication after only those intimate with the fire have been notified), given the assumptions made in this work. A building-wide voice alarm reduces total evacuation time over a reliance on social notification when coupled with either a corridor smoke detection (to a lesser extent) or with a flat heat detector (to a greater extent). The benefits of introducing more effective detection and notification increase as the building increases in height. Where there is corridor smoke or flat heat detection then voice notification effectively provides an opportunity for all occupants to egress buildings between 11 m and 30 m in height. In buildings much taller than 30 m in height there is an increased likelihood that occupants could become trapped irrespective of the type of notification provided.
    - **The introduction of voice notification reduced the overall evacuation times and the number of people trapped in all the cases examined (see Section A3-11.5).**

- **Lifts:** Lifts offer a means of egress for occupants who are unable or unwilling to use stairs. The benefit of providing lifts as a means of building evacuation increases with building height for those using the stairs (i.e., those that might self-evacuate), while having a consistent benefit for those using the lift system (for those unable to self-evacuate). Providing two lifts rather than a single lift has a benefit to those using the lifts (i.e., those with movement impairments) but not to those using the stairs. The findings given here are only for a specific lift use behaviour and may not be universal to all lift use strategies. Other strategies may result in less beneficial outcomes; conversely, the lift use here was not optimised to exploit the lift space available (for others to use) or to ensure more efficient evacuation strategies within the building.
    - **The introduction of a lift reduced overall evacuation times for those using the lift system and those using the stairs in the cases examined. The introduction of a second lift reduced overall evacuation times for those using the lift system in the cases examined (see Section A3-11.6).**

- **Stay put:** This strategy was not the focus of this work as it is predominantly reliant on the ability of a building to mitigate the movement of heat and smoke where occupants of non-fire affected flats stay within their residence. However, the stay put strategy does not require that occupants stay in their flats. In some circumstances, some may choose to evacuate even though dedicated evacuation provisions are not in place (e.g., global notification systems may not be present). In buildings with local detection and notification in the flat of fire origin, incident awareness may not be limited to the flat of origin - other building occupants might become aware of the incident. Assuming incremental communication between occupants enabling wider evacuation to take place, then only a small number of occupants are likely to become trapped for buildings between 11 m and 30 m in height. However, given the variability of communication that might actually occur (especially where audibility, intelligibility and comprehension are factors that may influence the outcome), social communication between occupants should not be relied upon as a primary means of response, should a full building evacuation be necessary. Further, encouraging the social notification process is beyond regulatory guidance – although might be enhanced through local outreach and education.

The interpretation of the results should always consider the conditions simulated and factors excluded (e.g., the capabilities of the simulation models, the configuration of the scenarios and the associated assumptions). Thus, the benefits expressed in this study of having wider stairs, more than a single stair, making lifts available for escape, providing various notification systems etc. are primarily relevant to this evacuation scenario. Some of the limitations and omissions of the work were through prioritisation of scenarios to model, given the time and resources available. Several suggested areas of further work are provided in Section A3-12.

A3-1 Introduction

The principal aim of this **Objective A3** is to quantify the evacuation performance in response to a representative set of scenarios and to then quantify the effectiveness of different evacuation strategies. The scenarios developed in this study were configured using findings from the literature review of available material and data in **Objective A1** (see Appendix A1) and using the findings of the resident surveys in **Objective B2** (see Appendix B2). The development of these scenarios has been broken into two explicit aspects: the building design and occupant numbers, and the occupant characteristics / behaviour.

Previously **Objective A2** (see Appendix A2) established an exemplar building floorplate for the simulation of a 'common' building through a probabilistic assessment of the relevant data and a configuration that meets the recommendations given by Approved Document B (AD B). It is not the aim of this work to explicitly address details regarding fire development, toxic gas concentrations etc., as these are highly complex phenomena and extremely sensitive to the underlying assumptions made. Instead, the fire is represented in a simplified form in terms of its impact on escape, as discussed in Section A3-5.

Appendix A2 also gives the background to the two evacuation modelling tools used in this work described herein.

Figure A3-1 shows the interaction between the various objectives and how these objectives combine within the project. The stage of the process corresponding to this note is shown in grey, capturing the items relevant to the modelling stage.

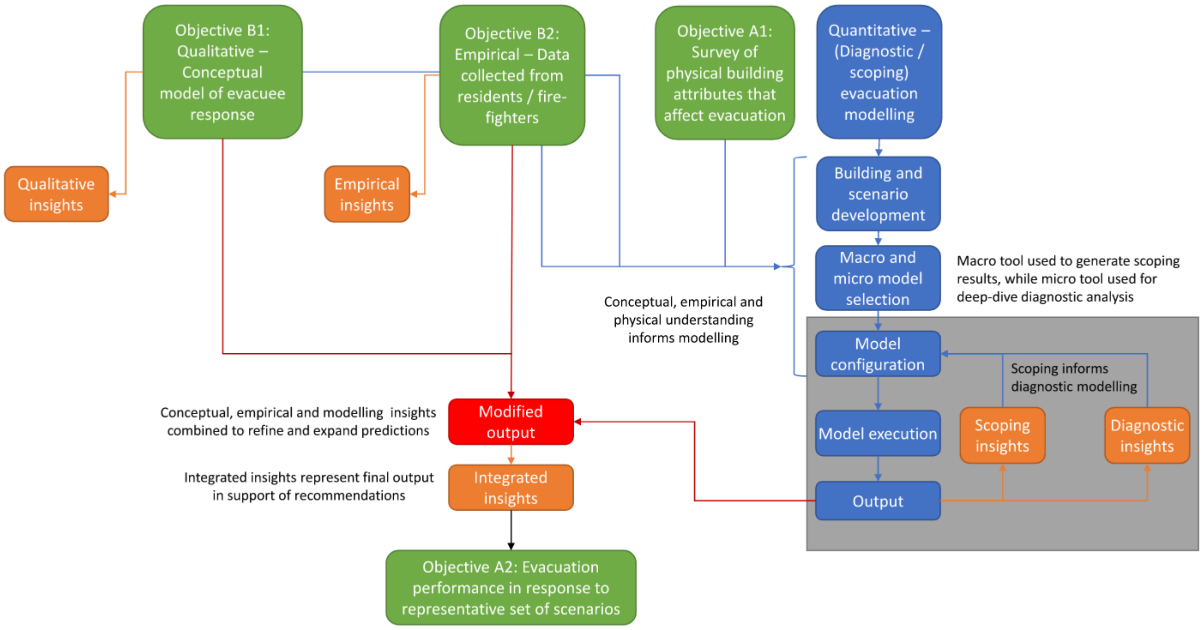


Figure A3-1 Flow chart showing the integration of the objectives, current stage shown in grey

It may be argued that there are broadly three evacuation strategies available to a high-rise residential building, namely:

- Stay put: Occupants separate from the flat of fire origin **should** be able to stay within their flat if they feel safe to do so and are not directed by the emergency services to leave. In an incident in which heat and smoke from a fire in a flat remains within that compartment then there is no specific need for anyone other than the occupants of the flat of fire origin to evacuate. Therefore, should occupants remote from the flat of fire origin remain in their flat, then the notion of a time for them to evacuate and reach a place of safety is irrelevant. The stay put strategy is discussed in Section A3-4.8.1.

- Evacuate to a place of safety within the building: High-rise residential buildings use the stairs as a protected space that allows occupants to enter and remain in a protected space - by preventing the entry of heat and smoke by active and passive fire protection measures (i.e., barriers and smoke control systems). To do so, the stairs are configured to have sufficient capacity to 'store' all the building occupants and therefore should occupants evacuate from their flats it is only important to assess the time at which they enter the stair. Thereafter whether occupants decide or are able to proceed to the outside of the building, the time to do so is irrelevant. The use of stairs as a place of safety is discussed in Section A3-2.4.1.

- Evacuate to the outside of the building: Should the various fire protection measures present in the building not perform as intended and the response of the FRS also does not adequately mitigate the effects of a fire then it might be necessary for occupants to have sufficient time to evacuate to outside of the building.

The focus of this study is the last of these approaches such that stay put is not universally followed (i.e. some or all occupants intend to evacuate the building), and that the building safety measures have failed to perform as intended leading to the potential of having occupants trapped if not given sufficient time to evacuate to the **outside**. Thus, the benefits expressed in this study of having wider stairs, more than a single stair, making lifts available for escape, providing various notification systems etc. are primarily relevant to this scenario. In those cases where occupants are in a building in which there is a fire and they may wish to leave, there are three fundamental factors which come into play:

- Awareness – how do the occupants become aware of the incident?
- Response – how do the occupants respond to the situation?
- Capability – do the occupants have the capability to undertake the selected actions?

The simulations presented in this study address these factors to investigate how each individually and collectively affect the time it might take for occupants to evacuate a range of different building configurations. However, the extent of scenarios that could be considered means it has not been viable to simulate every possible building nor the potential complexity of the interaction between building occupants themselves, between building occupants and the fire and rescue service (FRS), etc. An informed method of narrowing the scenario envelope has been developed to capture key results whilst operating within the constraints of the project.

In the next section, the exemplar building (the basis of which is described in Appendix A2) is introduced and the baseline scenarios that have been simulated in each of the two models are described. Figures of the baseline geometries are also presented from each of the models.

A3-2 Exemplar high-rise residential building

Previous work has established an exemplar building floorplate for the simulation of a ‘common’ building through a probabilistic assessment of the relevant data and the use of an example in Approved Document B: Volume 1 (AD B), see Appendix A2. Based on this floorplate, the necessary design parameters for modelling the exemplar buildings are finalised and introduced in this section. These include three variants of the floorplate, the physical dimensions of rooms, corridors, and stairs of the exemplar buildings.

A3-2.1 Exemplar floorplate

A floorplate comprising a mix of seven 1-, 2- and 3-bedrooms flats and a single staircase has been chosen as the basis for modelling a representative high-rise residential building for this project based on the work of Hopkin [1] and Hopkin et al. [2] (see Section A2-2.1 in Appendix A2). Three variants of this floorplate are proposed to study the potential impact of varying the number of staircases and the occupancy level on evacuation performance.

Table A3-1 Four floorplates designed to build the exemplar high-rise residential buildings for this research

	Floorplate 1	Floorplate 2	Floorplate 3	Floorplate 4
Number of stairs	1	2	1	2
Number of flats per floor[2]	7	7	21	21

The first variant includes an additional staircase, and the other two floorplates extend the corridor of the two 7-flats floorplates (with either one or two staircases) to 30 m, with the number of flats tripled to 21 (see Table A3-1). The floorplate with 30 m long corridors and a single staircase (Floorplate 3) would not meet the recommendations of AD B and is included in this study to test elements of the guidance beyond its

[2] The terms ‘floor’ and ‘storey’ are used interchangeably within this report. ‘Floor’ is typically used when referring to evacuation procedure, while ‘storey’ is used when discussing the physical properties of the building.

current limits given expected design trends. These four floorplates (see Figure A3-2 and Figure A3-3) are used to build the building representations with four different heights (see Section A2-2.2 in Appendix A2) in the selected simulation software, Pathfinder and Evacuationz (see Section A2-4 in Appendix A2).

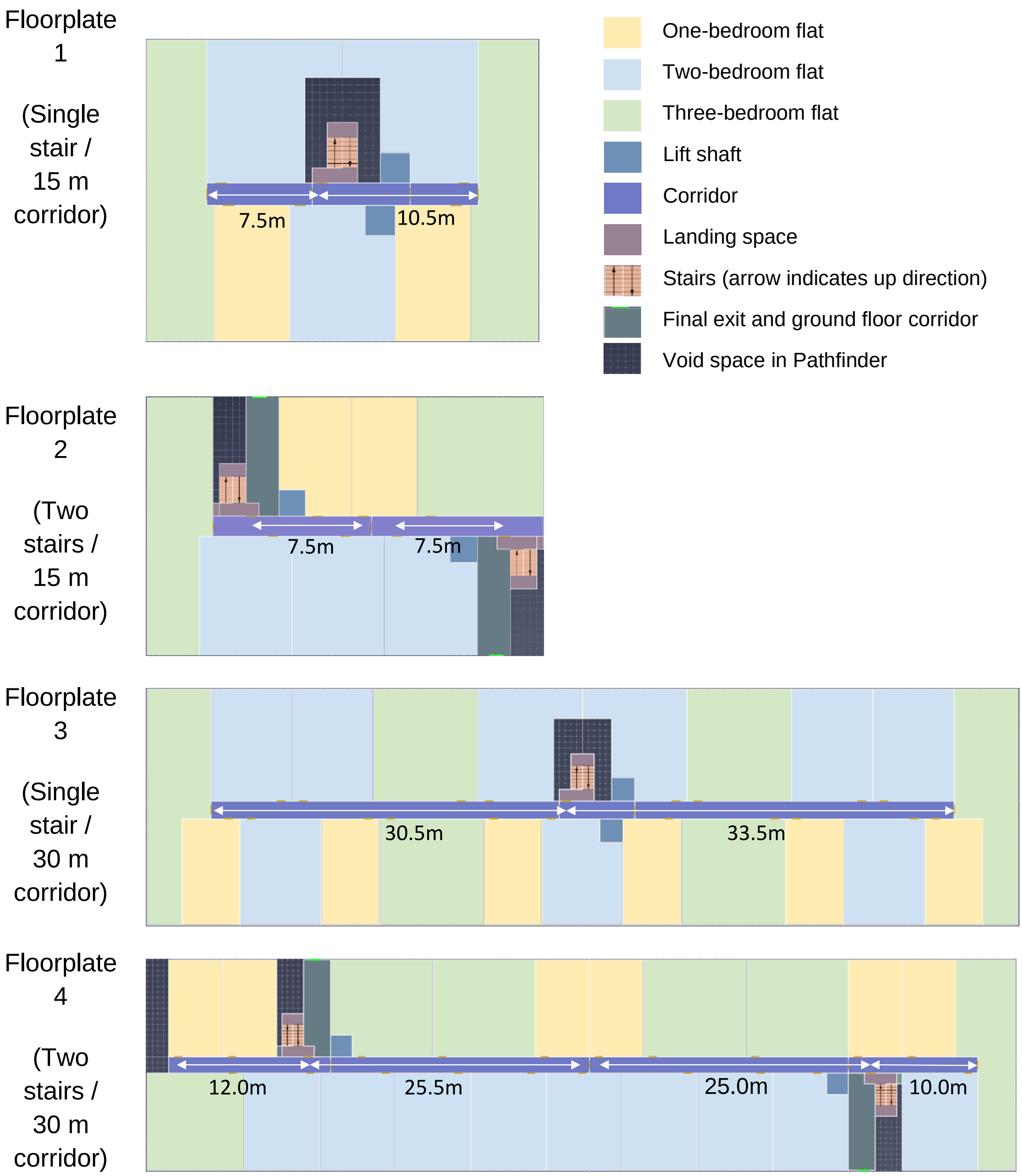


Figure A3-2 Four floorplates modelled in Pathfinder to construct the exemplar buildings for analysis (not to scale)

Figure A3-2 and Figure A3-3 show the primary floorplates used in the analysis. Figure A3-2 is the geometry setup in Pathfinder with the various flat sizes indicated by the green, yellow and blue areas along with the common corridors, stairs and lifts. Figure A3-3 shows the equivalent floorplates used in the Evacuationz simulations defined as networks. Room nodes are shown in yellow with final exits shown in green, stair connections are shown by dotted lines and corridors by solid lines. Room and connection properties have been specified in the input files.

In addition to the four floorplates described above, an additional parameter, amenity spaces, has also been considered. Given that such spaces could feasibly be located anywhere within the building, three options for the location of the amenity spaces have been considered. These are either lower in the building (e.g., at ground floor) where merging flow at the final exit may be a factor, mid-level or upper / roof. The latter two options will see a greater utilisation of the escape stair(s). Although architecturally unrealistic, for simplification in the modelling, and to retain a consistent number of residents, the amenity space is simply appended to the floorplate of the building rather than taking up space that would otherwise be flats.

Floorplate 1

Floorplate 2

Floorplate 3

Floorplate 4

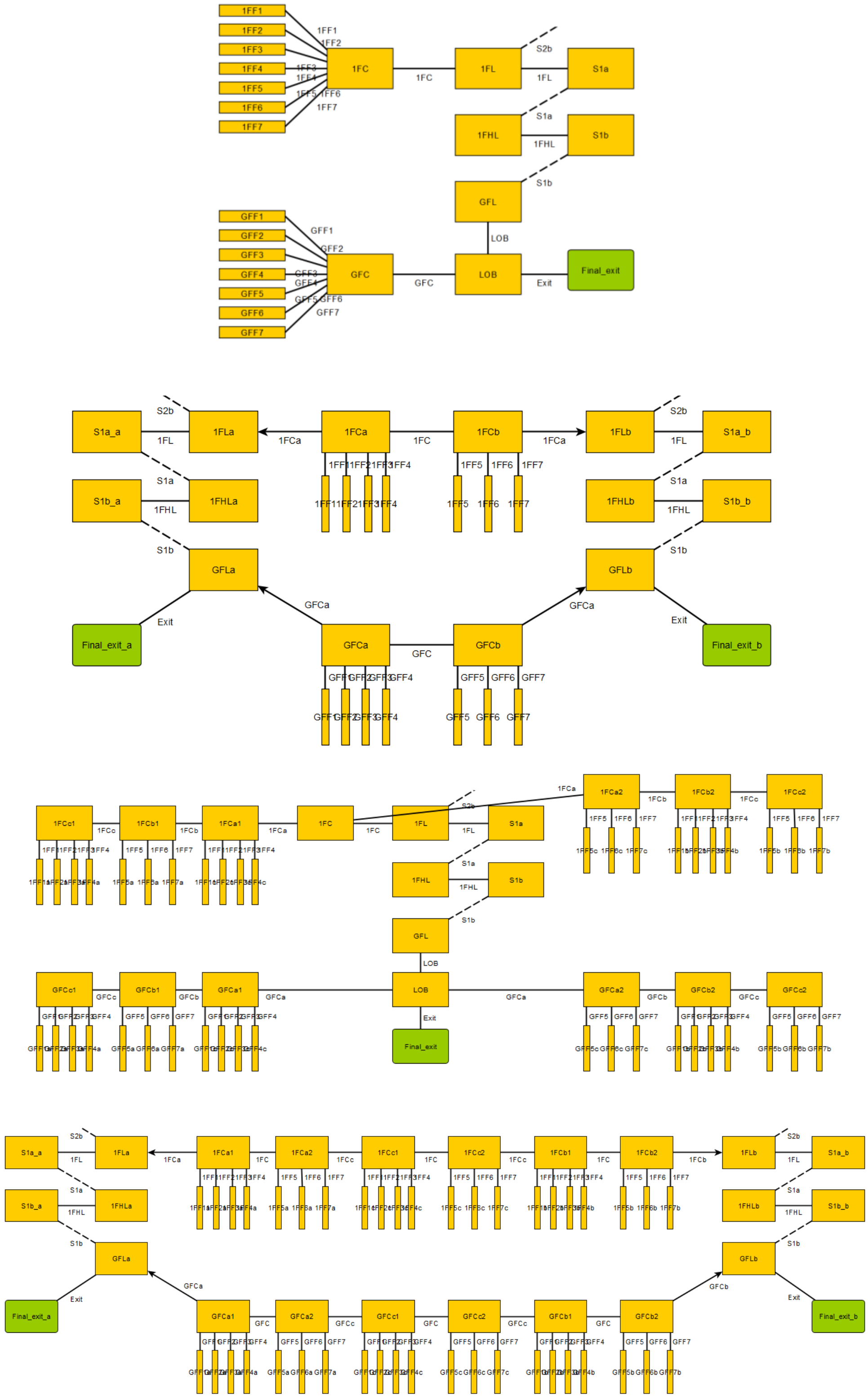


Figure A3-3 Four floorplates modelled in Evacuationz showing ground and first floor in each case. Dotted lines indicate stair connections between room nodes, solid lines indicate corridor connections. Green room nodes indicate the final exit points for agent movement

Amenity spaces have been considered along with the number of stairs and the extended corridor, in which 60 additional agents are modelled in the amenity space in short corridor cases and 180 agents in long corridor cases. In Pathfinder, these are simply added through 1 or 3 source nodes in each of the floorplate variants at corresponding levels (low/mid/high). In Evacuationz, these amenity spaces are modelled as additional nodes that connect to the corridor in a similar method. An example of the amenity space with Floorplate 3 in Evacuationz is shown in Figure A3-4.

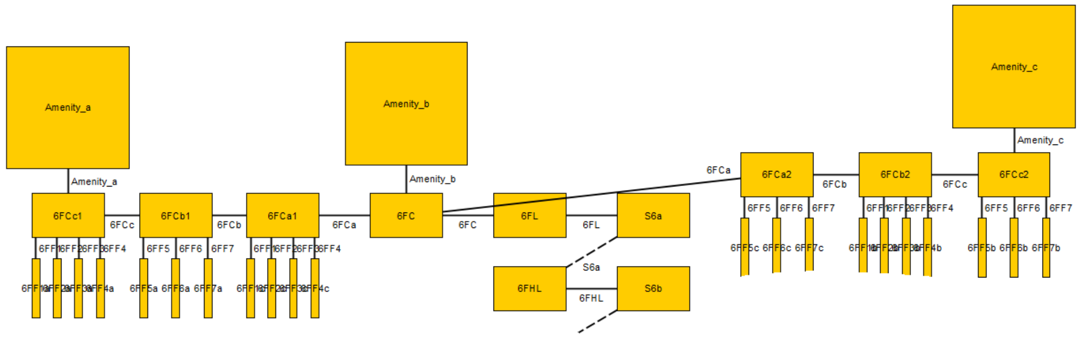


Figure A3-4 Example floorplate modelled in Evacuationz showing amenity spaces connecting to the top level

A3-2.2 Exemplar building heights

Appendix A2 discusses the derivation of the building heights used in this study. These are largely taken to correlate with ‘trigger heights’ given in contemporary guidance that have fire safety implications on the building design (see Table A3-2). The corresponding number of storeys are based on the distance from ground floor, assumed to be the FRS access level, to the floor level of the upper most qualifying storey that does not exceed the four building heights given in Table A3-2.

Table A3-2 Trigger height and their corresponding design implications

Building height	Relevant ADB design implications
11 m G+4 storeys	The height at which a sprinkler system should be provided in new building construction; and The minimum period of fire resistance is increased to 60 min from 30 min.
18 m G+6 storeys	The height at which it is recommended to include a firefighting shaft; and The minimum period of fire resistance is increased to 90 min.
30 m G+10 storeys	The minimum period of fire resistance is increased to 120 min.
140 m G+51 storeys	The tallest proposed (in terms of number of storeys), single stair residential building that could be identified at the time of writing [3].

A3-2.3 Doors

Doors within the models are in line with the recommendations given in contemporary guidance (e.g., AD B) and the authors' experience within fire safety building design. The models adopt the following widths:

- Doors to flats – 750 mm;
- Doors to stairs and cross-corridor doors – 850 mm; and
- Doors at base of stairs and final exit doors – equal to the stair width.

Pathfinder uses a 'steering mode' to navigate the space (or alternatively could be used in its 'SFPE' mode). For door flow, the flow limit is specified to a maximum of 1.33 agent/s per m effective width, as is commonly adopted for maximum flow capacity [4]. However, the actual achieved flow rate in steering mode will often be less than the specified limit (i.e., be a conservative estimate). This is due to the acceleration model and occupant avoidance used in steering mode, i.e., when an occupant is stopped at a door, they have to accelerate again to leave the doorway and allow another occupant to enter [5]. In Evacuationz, agent flow through doors is calculated from the hydraulic model as presented in the SFPE Handbook Chapter 59 [6]. The maximum flow is also set as 1.33 agents/s per m effective width. Actual door flows will depend on the presentation rate of agents and therefore will likely be less than the maximum values.

A3-2.4 Stairs

A3-2.4.1 Capacity

In a previously published international comparison of fire safety provisions for means of escape, Hagiwara and Tanaka [7] note that:

> "*Means of escape are usually composed of two parts. The first part consists of unprotected area from fire, such as a habitable room, and protected area for short time, such as a corridor. The other part is completely protected area such as a staircase and a corridor with smoke barriers. If a fire starts in a room, an exit door cannot be used for escaping from the fire room. If corridors connected with the fire room are logged with smoke, they cannot be used for escaping from rooms in the fire floor. So, it is not sufficient to provide two means of escape only. The arrangement of means of escape is also very important.*"

Stairs are often solely seen as a means that support occupant movement that allows them to escape from a building. However, the concept of using the stairs in a building as a place to 'store' occupants within a protected enclosure during a fire dates back to the early 20th century [8]. The floor area capacity of the stairs is based on the population of a single floor such that those occupants will fit entirely within the space provided to the floor below. By maintaining an adequate fire and smoke separation between the floor and the stairs (and assuming a building remains structurally intact) allows for the evacuation of occupants, or for the occupants to simply stay in place and use this stair capacity as a temporary refuge. In agreement with the survey findings collected earlier in this work, Bukowski and Tubbs [8] note that people are unlikely to stay still but prefer to proceed outside.

Thus, in designing a building, the objective is to maintain a safe means of egress for an adequate duration, in which Malhotra [9] noted that a fully protected zone should never theoretically achieve critical conditions if smoke barriers perform satisfactorily and there are effective smoke control systems. Therefore, the stair capacity strategy means that the number of floors in a building is irrelevant as is the time it takes for people to move outside of a building. This also means that where the capacity of a stair is sufficient for the number of occupants on a given floor, then making a stair wider or providing more than one stair provides no additional benefit. Wider stairs may be of some advantage where emergency services need to pass through and/or set up firefighting equipment in the stairs to access and tackle a fire although this benefit may only be realised in cases where those stairs are occupied to their full design capacity.

Furthermore, on the assumption that where the type of occupancy is the same throughout a building then the potential fire severity on any floor is the same as any other floor. For example, in a residential building it is not unreasonable to assume that the contents of a flat will not statistically differ from one floor to another regardless of the height of a building. Thus, the characteristics of a fire will be equivalent and therefore the level of separation protection needed between the floor and the stairs can be the same irrespective of the height of a building. This separation needs to be sufficient to contain heat and smoke within the flat for the duration of the fire, i.e., the time to burn out, or extinguishment by the fire and rescue service.

Clearly the protected zone needs to maintain its function for an ‘adequate’ (ideally indefinite) duration. Concerns may be expressed that if a building only has a single stair, then it could be become compromised for some reason (e.g., flat doors not being closed, doors in the common areas not performing adequately, and/or stairs doors being opened by emergency responders, etc.). Such concerns do not immediately lead to the solution of adding more stairs (which themselves may be subject to the same failure conditions) but to address the failure mechanisms directly. This can be done, for example, by having flat doors with working self-closers, providing doors with adequate separation performance, emergency responders having the means to use portable smoke barriers, ensuring occupants are aware of the building design functions, etc. It should be noted that the provision of more stairs does not address the evacuation of those with movement disabilities as some may not be able to descend and stand on the stairs. The use of stair capacity as a refuge is briefly examined here (see Section A3-10.10), it is not the focus of this work.

A3-2.4.2 Single stair vs two stairs

In their comparison of fire safety provisions for means of escape, Hagiwara and Tanaka [7] go on to note that:

> "*For a building with a limited height and for a room with a limited area, a single means of escape is usually allowable, because it is physically impossible or economically difficult to require two stairs for every building, and two doorways for every room. When a fire occurs in a small room or a low-rise building, the occupant will become aware of the danger within short time, and will be able to escape quickly. If a fire blocks the only means of escape, nobody will be able to escape. So, it is considered that we have accepted the risk that a small number of persons cannot escape under a certain condition. Every means of escape has the risk to be blocked by fire. This kind of risk, in other words, the availability of means of escape from any point in a building in fire, is one measure of life safety level. Single means of escape must be allowable based on the concept of this risk*."

One question specifically addressed in this study is whether including a second set of stairs (or more broadly, more than one stair) provides an additional benefit when compared to a similar building that only has a single stair in terms of evacuation performance. If so, under what circumstances does the second set of stairs provide such benefit and by what margin?

In a report on new thinking on egress from buildings published in 2009, Bukowski [10] points out that historically stairs provided sufficient access in buildings because they were not particularly tall. As such, experience in single stair (primarily residential) buildings provided adequate means of escape so long as the fire did not block access or directly affect the stair. In earlier work Malhotra [9] stated that:

> "*All buildings over 2 storeys in height, except domestic buildings, should have two stairways for escape purposes but with low occupancy loading and up to the height of the normal rescue ladder, 15 m, buildings may have only one internal escape stairway provided the windows are designed to serve as emergency exits or special balconies are available and are accessible for rescue purposes*."

Similarly, in a 1991 study on means of escape in multi-storey buildings, Wade [11] concluded that other than in small, low-rise buildings with restricted travel distances, floor areas and occupant loads, there should be two means of escape. Wade does not differentiate between domestic (residential) buildings and other occupancy types as Malhotra does.

Recent changes to the guidance in Scotland mean that residential buildings over 18 m are expected not to have a single stair. It is interesting to note that in the report of the review panel [12] that:

> "*The introduction of such new guidance should not be taken to indicate […] that existing high domestic buildings with a single stairway were unsafe. It was simply the intention to ensure future buildings were even safer*."

Furthermore, as part of the regulatory impact study [13] for the change in building design guidance in Scotland to expect a second stair it was noted that:

> "*Due to the success of the 'stay put' policy, the need to fully evacuate a high rise domestic building is a rare event. Anecdotal evidence from Fire and Rescue Services suggests that in these rare events evacuation has been successfully carried out without any issue and without any significant injury in single stair domestic buildings, therefore there is no cost benefit attributable to this initiative. However, in an unforeseeable 'worst case' fire scenario, perhaps similar to Grenfell Tower, a second stair may prove invaluable in ensuring the safe evacuation of the occupants in the event of a full (simultaneous) evacuation*."

The above discussion suggests that the benefits of providing more than one stair is a topic of debate. Where buildings are of limited height, where there are adequate provisions to support a stay put strategy, where there are adequate measures to protect the stairs, then the benefit of having more than one stair is uncertain. On the other hand, when considering the discussion by Hagiwara and Tanaka, including more than a single stair in a building provides a measure of resiliency and redundancy. This resiliency and redundancy may address issues of building maintenance, interaction with FRS personnel during an incident and contribute to resident perception of their safety. However, the provision of more stairs does not address the evacuation of those with movement disabilities.

For any case in which a second stair is introduced into a building it would be necessary that it be sufficiently separated from the first set of stairs. This separation is achieved by having additional fire door(s) along the horizontal escape paths (corridors) that may extend the time at which the second stair becomes affected by fire and smoke. In a building in which there are not additional fire doors between the first and second sets of stairs, it is unlikely an additional benefit would be accrued as both may become compromised at comparable times. For example, if the two sets of stairs were both located in the same central core of the building (e.g., scissor stairs, as in the case of the 2 Forest Laneway incident [14]).

Further, a second set of stairs would not benefit those occupants that cannot or are unwilling to use them, or that are not aware of the second set of stairs within the building. Where two stairs are considered in the analysis, an approximate equal use of each is assumed, with no preference for familiarity.

The provision of stairs within a building as a means of escape from fire cannot be treated in isolation but must also account for other fire safety measures such as automatic fire detection and alarm systems etc. If occupants are not made aware of a fire, they then cannot make a decision to leave the building and thus the number of stairs is irrelevant. Similarly, it might be that the operation of an automatic detection and alarm system ensures that everyone is immediately alerted and begin to leave, then the addition of a second set of stairs does not necessarily provide any more benefit over a single set of stairs. This is especially true in situations where there is time for people to reach the stairs, the stairs have sufficient capacity to accommodate the occupants and/or heat and smoke does not spread beyond the flat of fire origin.

A3-2.4.3 Modelling

Where stairs are considered a key part of the means of escape in high-rise residential buildings it is important to appropriately represent stairs in the building models. Appropriately simulating occupant evacuation behaviour on stairs is crucial for assessing the overall evacuation performance. This section introduces the stair design used in the modelling, which has been adopted based on relevant design guidance recommendations. This section also discusses the performance indicators of the stair design.

For all the exemplar buildings modelled, a representative storey height of approximately 2.75 m has been chosen to maximise the number of floors in each case (see Section A2-5.2.2 in the Appendix A2. A switchback stair configuration has been selected to build the stairs connecting any two floors (see Figure A3-5). Each flight of stairs has 8 risers with a total riser height of 1.375 m and a total tread length of 2.0 m. This design yielded a riser height of 172 mm and a tread length of 286 mm. The riser height is 2 mm above the maximum recommended riser height (170 mm) for general access stair set in Approved Document K (AD K) [15], although only exceeds this by a small margin. The tread length is within the corresponding recommended range of 250 mm and 400 mm, given in the latter document. These dimensions also meet the recommended normal relationship in AD K, i.e., twice the riser height plus the tread length is between 550 mm and 700 mm.

This design is considered acceptable for the modelling purpose and representative of building design in practice as the excess in riser height above the recommended value in AD K is limited. Moreover, it is the stair slope (defined as stair riser/tread length) that determines agent travel speed on stairs in Pathfinder, rather than the height alone, which is in line with the guidance of AD K.

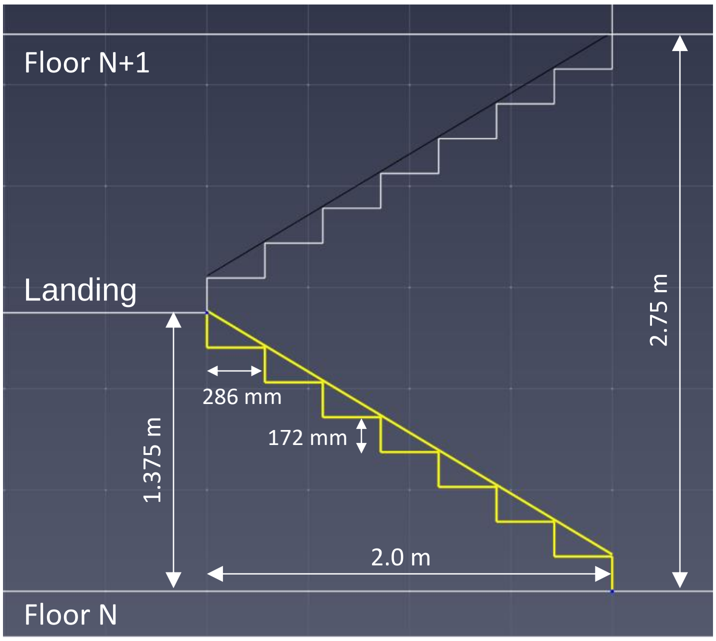


Figure A3-5 The switchback stair design used in modelling the residential buildings in Pathfinder

Pathfinder calculates agent travel speed on stairs using their unimpeded maximum speed (v_{max}) on level terrain, a density speed fraction ($v_f(D)$) as a function of density (D) and a terrain speed fraction (v_{ft}) [5], i.e.,

$$v = v_{max} * v_f(D) * v_{ft}.$$

The terrain speed fraction is defined as

$$v_{ft} = \frac{k}{1.4},$$

where k is a function of the stair slope which is specified in SFPE handbook [6]. The stair slope and the corresponding k value of the stair design are 0.60 and 1.11, respectively, which produce a speed fraction of 0.79. Note that this speed fraction is used for all types of agents, regardless of their original level of mobility or the model of travelling (assisted or unassisted).

Evacuationz models the movement of agents on stairs in a similar way to Pathfinder. The calculated speed (S) of agent movement in m/min uses the equations given in the Fire Engineering Design Guide [16] (equivalent to what is published in the SFPE Handbook) such that

$$S = k_s (1 - 0.266\ D)$$

where:

$$k_s = 51.8\sqrt{T/R}$$

and D is the occupant density on the stairs, T is the stair tread dimension and R is the stair riser dimension. Evacuationz compares the calculated stair speed with the unimpeded speed (as discussed in Section A3-3.1) and uses the lower of the two values.

In modelling the Baseline scenarios (see Section A3-7), it was found that Evacuationz overestimated the distance travelled by agents on the stairs. This is attributed to the method in which the model calculated the effective travel distance between nodes. The default method, 'centre-to-centre' determines this length by calculating the square root of the half dimensions of the two connected nodes, essentially calculating the hypotenuse of the plan distance from the centre of the node to its corner, then from the corner of the adjacent node to its centre. This is shown graphically in Figure A3-6.

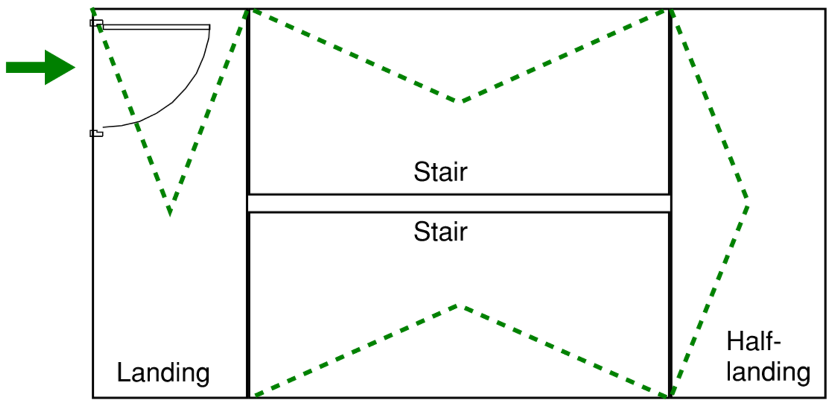


Figure A3-6 Default path length calculation (centre-to-centre) in Evacuationz

Using this default mode resulted in extended travel distances and subsequent evacuation times when compared to Pathfinder. It was found that using a fixed length (2.43 m based on the diagonal length of the stair) for the stair travel in lieu of the default calculation led to more comparable evacuation times between the two models, as discussed in Section A3-7.2.1. The resulting path length is shown graphically in Figure A3-7. This makes a nominal change in the time taken to descend a single storey; however, this difference is compounded for every storey, becoming substantial for taller buildings.

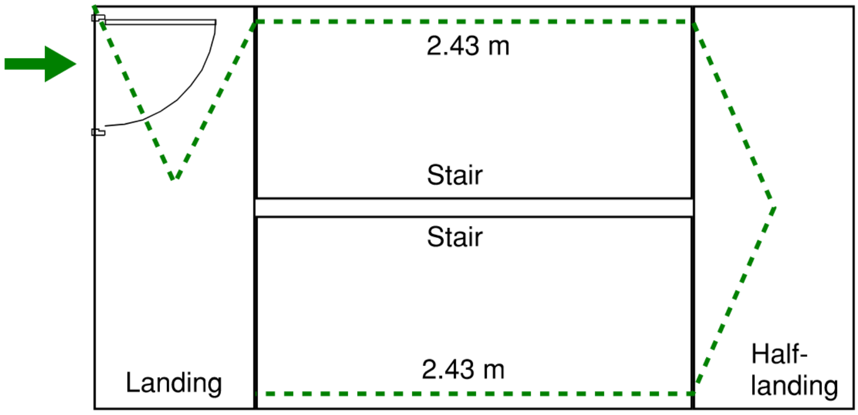


Figure A3-7 Adjusted path length used in the Evacuationz analysis

It should be noted that the specific impact of fatigue is not considered during the Pathfinder and Evacuationz modelling as neither model (nor any other similar model as far as the authors are aware of) currently includes this impact.

A3-2.5 Route selection

In the exemplar buildings with only a single stair there is clearly only one route choice available to the agents. However, when it comes to the building geometries that include two stairs or a combination of stairs and lifts there are options available. Scenarios that include lifts are discussed in more detail in Section A3-10.9.

The SFPE Handbook [17] notes that "*It is well-recognized that people tend to use the main exit in case of emergencies*" although the Handbook does not give any specific numbers that can be used. Design guidance generally does not have much in the way of specific requirements related to exit selection. Clause 3.2.7 of C/VM2 [18] does recognise that a higher proportion of occupants might use a primary entrance by stating:

> "*3.2.7 Exit doors*
>
> > *Where a primary entrance can be identified the primary entrance shall be designed to egress 50% of the total occupant load of the space and the remaining occupants are evenly distributed in proportion to the number of exits.*
> >
> > *Where there is no primary entrance the occupant load shall be distributed to the available exits with no more than 50% to one exit.*"

The use of multiple stairs in residential buildings on a day-to-day basis may depend on several factors such as how close they are to resident's flats, whether one discharge point leads to a more desirable location etc. As such it may be that one stair is designated or effectively used as a 'main' exit or that residents do not have a preferred stair. Clearly in terms of exit capacity then, having people use the stairs in equal numbers provides the most optimum outcome and conversely if everyone only goes to a single stair then the second stair serves no immediate purpose. For the simulations conducted in this study it is assumed that where there are two stairs available then the agents use their nearest stair, leading to an approximately equal split in stair utilisation. Were one stair to be used in preference to the other then, all other things being equal, the evacuation time will be dominated by the more utilised stair. Although, the occupant split between stairs might normally be considered optimistic, it allows the analysis to determine the maximum benefit of introducing two stairs upon evacuation performance, with the other extreme (all occupants using a single stair) equivalent to the case where only one stair is present. Severely imbalanced use of two stairs would eventually approximate the use of a single stair, so the range of conditions are bounded by the scenarios conducted here.

When considering the possibility of a stair being affected by smoke (such as discussed in Section A3-5.1) then the use of a second stair may need to be factored into an analysis. The presence of a second stair and the impact of smoke is presented in Section A3-8 through to Section A3-10.

A3-3 Occupant parameter selection

A3-3.1 Unimpeded movement speed

Previous work in support of this project (as discussed in Appendix A2) proposed indicative baseline horizontal and vertical travel speeds derived from the research literature and guidance available (Table A3-3). It was noted in Appendix A2 that the baseline values will need to be modified for sub-populations with movement impairments and Table A3-3 shows the indicative modifiers that were suggested. Thus, the precise nature of the distributions employed for these speeds need to be defined for the scenarios examined, the representation of the building demographic and within the building spaces represented.

Table A3-3 Indicative travel speeds

Direction	Baseline speed (m/s)	Impairment modifier
Horizontal	1.20 ± 0.20	0.50
Vertical	0.70 ± 0.20	0.40

This section develops the selection of unimpeded travel speeds for the agents used in the simulations which needs to consider the capabilities of building occupants in relation to their age, level of fitness and any movement impairments. In the resident survey conducted as part of this project (see Appendix B2), 8.5% of the participants identified themselves with having some form of movement impairment.

The draft report into the demographics and ergonomic requirements of the population of England issued to DLUHC by Arup [19] notes that 20% of the population has a disability or long-term condition that has an impact on their life. The report notes that around 10% of the population have some form of mobility-related impairment, but this increases to around 30% in older people (those aged 65+). Consequently, in this study it is assumed that **20%** of agents have some form of mobility-related impairment to reflect the age demographic. Impaired agents are further split into two sub-groups: those that can use stairs unaided and those that require the assistance of others. In the report on means of escape for disabled people published by BRE [20] it is stated that 0.5% of the population find stairs impossible, 1.8% of the population use wheelchairs and 0.5% use mobility scooters. The BRE report further notes that 5% of the population experience some difficulty using stairs. BS EN 81-76 [21] (the design guidance for evacuation of persons with disabilities using lifts, noting this is in draft form at the time of writing) and the London

Plan [22] recommend that, in the absence of more detailed information, it should be assumed that 10% of the population of the building have some form of disability and may be unable to use stairs. Therefore, in the simulations presented in this work the 20% of impaired agents that account for movement impaired persons (MIPs), is split into **15%** that can descend stairs unaided, referred to herein as a ‘movement reduced person’ or MRP, and **5%** require assistance, referred to herein as a ‘movement dependent person’ or MDP. It has been assumed that MDPs always have assistance available to them to allow them to move. Longer pre-evacuation delays are assigned to these agents (as discussed in Section A3-4.5) to include accounting for the time needed for that assistance to arrive or for other preparatory activities. The above reference information [19]–[22] dates from 2019 to 2021, therefore indicating current trends in the demographic of the population of England. However, in England, as it is worldwide, the population is ageing. Census 2021 results show a 2.2% increase in the number of people over 65 compared to 2011. This trend will highly likely increase the number of people having some form of mobility-related impairment.

In terms of stair descent speed, the work of Hunt et al. [23] identified that carry chairs would move at 0.58 ± 0.12 m/s and evacuation chairs move at 0.83 ± 0.04 m/s. These speeds are not less than those already proposed for the horizontal movement of impaired agents. It should be noted that in the trials conducted by Hunt et al. to generate these speeds, those assisting passage were hospital staff and therefore had sufficient training. This might not always be the case in residential properties. However, previous work by Spearpoint and MacLennan [24] on the effect of sex, age and body mass index (BMI) on walking speed found that the predicted bottom 5% of the data for males and females were in the range of 0.20 m/s to 0.48 m/s. Boyce et al. [25] give the descent speed of people with a walking stick as 0.11 to 0.49 m/s, with a mean of 0.32 m/s and standard deviation 0.12 m/s. Therefore, for MDP agents a uniform distribution of **0.1 m/s to 0.5 m/s** is used in the simulations as a representative range for both unimpeded horizontal and stair descent speeds. A summary of the agent unimpeded movement speeds used in the simulations is given in Table A3-4.

Table A3-4 Type of population and unimpeded movement speed used in the simulations

Population type	Percentage of population*	Horizontal speed	Stair descent speed
Non-MIPs	80%	Pathfinder and Evacuationz: Uniform distribution of 1.0 m/s to 1.4 m/s	Pathfinder: calculated through stair speed fraction (see Section A3-2.4.3) Evacuationz: calculated through comparison of hydraulic flow method and unimpeded speed (see Section A3-2.4.3)
MIPs - Movement reduced person (MRP)	15%	Pathfinder and Evacuationz: Uniform distribution of 0.4 m/s to 0.8 m/s	Pathfinder: calculate through stair speed fraction (see Section A3-2.4.3) Evacuationz: calculated through comparison of hydraulic flow method and unimpeded speed (see Section A3-2.4.3)
MIPs - Movement dependent person (MDP)	5%	Pathfinder and Evacuationz: Uniform distribution of 0.1 m/s to 0.5 m/s	Pathfinder: calculate through stair speed fraction (see Section A3-2.4.3) Evacuationz: calculated through comparison of hydraulic flow method and unimpeded speed (see Section A3-2.4.3)

* In scenarios where MIPs are fully represented.

Using a uniform distribution rather than a normal distribution (or similar) is a simplification that will mean there will be a greater likelihood of having agents with the lowest speed (and also with the highest speed) but it is the lower speed that will likely be more critical. Further simulations could be carried out to assess the impact of using a non-uniform distribution, for example see Lord et al. [26] for walking speeds as a function of age, ability and movement direction (horizontal, downward or upward). Values are given for the average, standard deviation, maximum and minimum speeds along with suggested distribution shapes for horizontal movement. However, given the time and resources available, it was decided to examine a wider array of scenarios with a representative set of speeds, rather than reduce the scenarios examined and explore the impact of varying travel speeds on the overall performance.

Movement speeds for people performing a one-person walk assist (see Section A3-3.2) have not been found from the literature. It is considered herein that people walking with the aid of a stick are sufficiently representative of a one-person walk assist.

A3-3.2 Body width

There are various types of assistance that could be given to those that need aid using stairs ranging from evacuation chairs, carry chairs, or people who need help by another person by having their arms over their shoulders to provide one-person walk assist (Figure A3-8).

Figure A3-8 One-person walk assist, taken from https://www.wikihow.com/Perform-First-Aid-Assists-and-Carries

Hunt et al. [23] identified the number of stair lanes occupied by various assistance devices for male and female users. Evacuation chairs required a single lane for either sex whereas two lanes will be occupied by females using a carry chair. The number of people needed to use such chairs will depend on the design, the characteristics of the occupant and the strength of the operators. A carry chair has four handles - with small wheels - likely requiring two or more people to operate, whereas an evacuation chair has a dedicated stair track generally requiring one person to operate. Where occupants are being assisted via a one-person walk then two lanes would be occupied. Consequently, for the purposes of the Evacuationz simulations, it is assumed that the body size of MDP agents is wider than those that can descend unaided such that the default body size is increased from 0.35 m to 0.74 m. For consistency the 0.74 m width is the same as the wheelchair width used in the Pathfinder simulations to represent a movement dependent person (Figure A3-9). These increased widths will affect the passage of other evacuees (e.g., those that might be able to travel more quickly), either requiring them to queue, or manoeuvre around the assisted individual – delaying their progress.

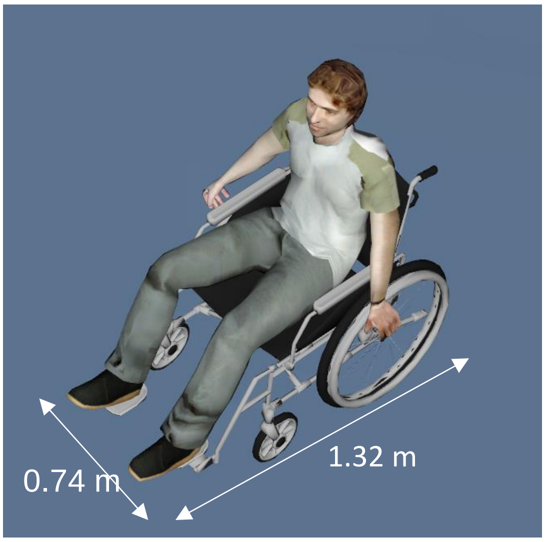


Figure A3-9 Dimensions of wheelchair used by MDP agents modelled in Pathfinder

One artefact of the default Evacuationz agent creation and simulation process is that agents are processed in a random order at each iteration. This can mean that an agent that is blocked by another agent may be able to 'over-take' when transitioning from one node to another if they are processed before the blocking agent even where the nodes are in theory not wide enough for this to happen. It is possible to set the agent processing order in Evacuationz, but this still might result in a blocked agent being processed ahead of a blocking agent. One could debate whether this over-taking behaviour is a 'feature' or a 'failing' of Evacuationz. It may be reasonable to assume non-MDPs could 'squeeze' past an MDP or an MDP might make room for a non-MDP to pass. This kind of behaviour was noted by Shields et al. [27] during the WTC evacuations, albeit in this case it was non-injured people squeezing to the side to allow injured people to pass. The 'over-taking' of blocking agents in Evacuationz makes comparisons between it and Pathfinder more complex when such agents are present.

A3-3.3 Movement in smoke

The effect of smoke on occupants has been previously discussed in in **Objective B1** (see Appendix B1) in which it was noted that the presence of smoke alone may not indicate a sufficiently severe incident to prevent the use of a route. For instance, smoke in a stairwell may slow an evacuating resident down but may not prevent them using the route. The work of Jin [28] reports the impact of smoke density and irritability on the movement of occupants in which a relationship between the two is given (Figure A3-10). It is clear that there is considerable scatter in the data, but still provide an indication of the impact of smoke on movement rates that can be applied to an analysis.

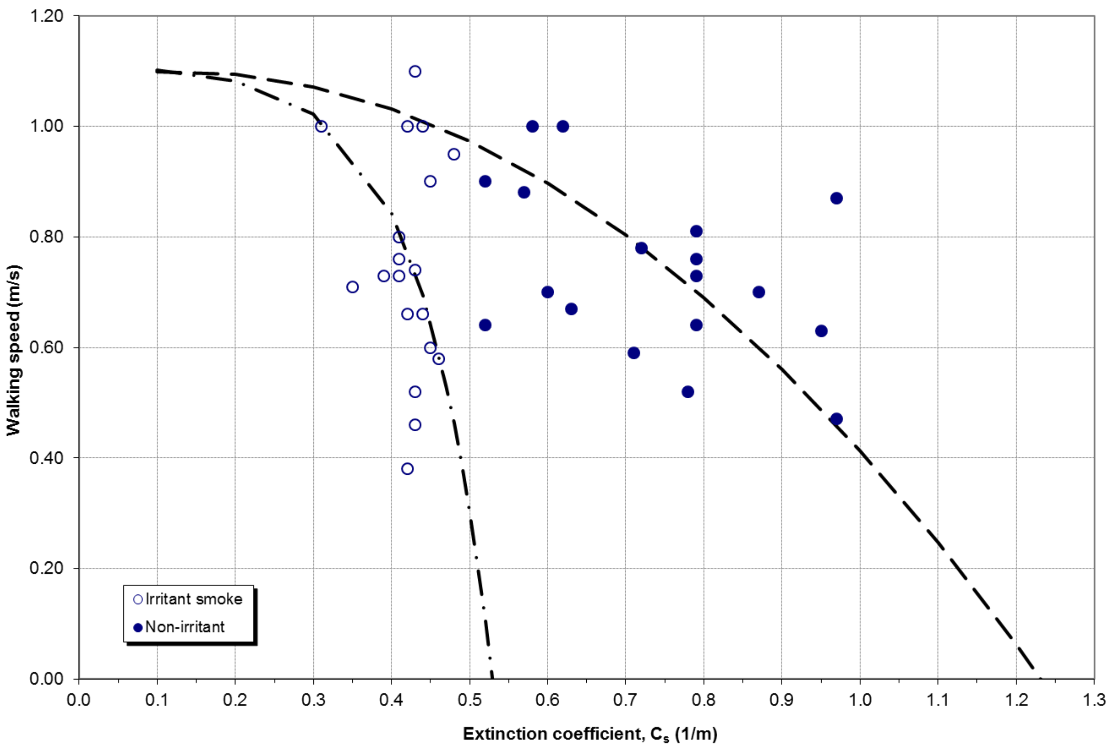


Figure A3-10 Walking speed in irritant and non-irritant smoke (adapted from Jin)

Evacuationz has the capability to apply Jin's model on the movement of agents where the user has to define the smoke density in each node as a function of time. However, since the movement of smoke around the exemplar buildings has been represented in a simplified manner in this study (see Section A3-5) the effect of smoke on the movement of agents in Evacuationz is accounted for by a universal reduction factor to 30% of their calculated speed as determined by the occupant density, the travel mode (horizontal or vertical) and the agent unimpaired speed. A 30% reduction has been selected to reflect the lower bound of the data recorded by Jin as illustrated in Figure A3-10. Therefore, for example, the travel speed of an MDP agent in smoke may be as low as 0.03 m/s where their unimpeded speed is at the lower boundary of 0.1 m/s (Table A3-4).

A similar approach in representing the impact of smoke on agent travel speed has been adopted in the Pathfinder model. A speed modifier of 0.3 which takes effect at t = 33 min is defined for all walkable space within the exemplar buildings. This effectively reduces the maximum desirable speed of every agent, who is still in the evacuation process, to 30% of their unimpaired speed. The time of 33 min is the moment at which evacuation is hindered by smoke accounting for movement within the building (see Section A3-5.1.5).

A3-4 Pre-evacuation delay behaviours

A3-4.1 Pre-travel delay

According to BS PD 7974-6 [4] the pre-travel (or pre-evacuation) delay may be broken into a recognition time and a response time (Figure A3-11). For the purpose of this research, it is assumed the recognition time is broken into an ‘arousal time’ (i.e., waking when agent is asleep) and an ‘assimilation time’ (i.e., the time needed to understand / verify a message). The ‘response time’ is broken down into a ‘contact time’, representing the time to make a phone call / use a messaging application / speak to those in the same property, and the remainder of the activities such as getting dressed etc. The portion of the response time not covered by the contact time is referred to as the ‘residual delay time’, or simply the ‘residual time’. This approach has been adopted to provide sufficient flexibility to represent the set of scenarios defined earlier. It also allows the available data to be interpreted and to produce the modularity needed to repurpose the data to represent different initial situations.

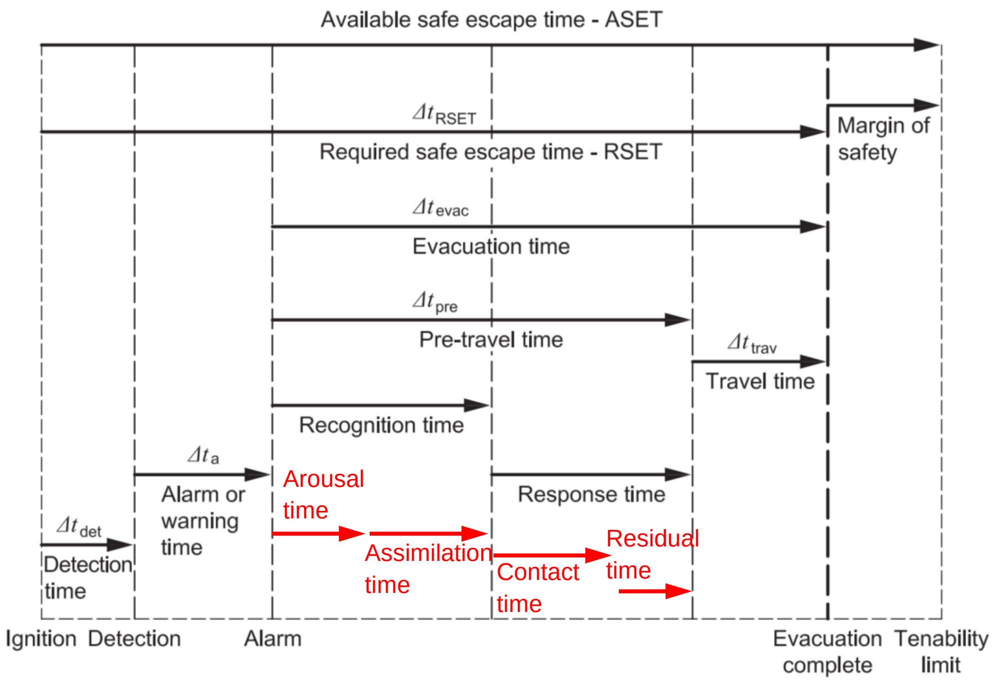


Figure A3-11 Representation of the available safe escape time vs. required safe escape time with times used in this research shown in red

A3-4.2 Awareness

For occupants of residential buildings to respond to a fire they first need to become aware of the incident. People in the flat of origin can be generally assumed to become aware of the fire fairly quickly if they are awake due to the presence of fire cues, although such occupants may be engaged in focused activities such as working and be on video conference calls while wearing headphones, etc.[3] However, sleeping occupants (or those otherwise impaired by medical or recreational drugs), whether in the flat of fire origin or remote from it, will need to be aroused before they begin to take further action. Automatic detection and alarm systems provide one means of alerting occupants. These are discussed in Section A3-4.3.

Occupants remote from the flat of fire origin will be less likely to become aware of the fire through direct fire cues at least during the early stages of the incident. Where the fire cues remain within the flat of fire origin then remote occupants will be highly unlikely to receive these cues unless detection / building-wide notification systems are in place. As a result, occupants remote from the flat of fire origin become aware of an incident via cues such as hearing a local alarm in a close-by neighbouring flat, via contact by those who are already aware of the incident (such as by phone or other communication means in the form of text messages), posts on social media, the presence of the FRS or other emergency services, or building-wide notification systems, etc. The likelihood of occupants to enact means of communication, the delays incurred to the occupants participating in these means of alerting, or on the effectiveness of getting a response from the receiving occupants have not been extensively researched in the literature.

A3-4.3 Alarm activation

Where people are sleeping (or awake) an automatic smoke and/or heat detection (along with other means of detection such as carbon monoxide, etc. as discussed in the Literature Review Report) and alarm system can provide them with a warning. Detection of a fire in a flat can raise a local alert to the flat occupants. However, it is not often practical to raise the alarm throughout a residential building on the detection of a fire in one of the flats, as too many false / unwanted alarms might be produced - likely reducing the response of residents to a genuine incident (and may cause an unacceptable nuisance to occupants). For example, unpublished findings of alarm system activations in New Zealand from the mid- to late-2000s found that 95% of activations were false alarms and smoke detectors were twice as likely as heat detectors to be the cause. In the work by Chagger and Smith [29], of the top 30 causes of false alarms, 16 specifically identify smoke detectors vs. 4 specifically identifying heat detectors. Detection in common areas that raise a building-wide alarm are more likely to be practical but will result in a delay when compared to detection in a flat. In incidents where smoke and fire are restricted to the flat of fire

[3] The number of people engaged in such activities may have recently increased as a result of the COVID-19 pandemic.

origin it is possible that the detection in the common areas will not be aware there has been a fire.

Building-wide alarms could be raised via the activation of manual call points by occupants, although the provision of such may be subject to anti-social behaviour such as vandalism [30]. Buildings can be provided with an alarm system that can be operated by the fire and rescue service (FRS), such as an evacuation alert system (EAS). Clearly, the activation of an EAS-type system relies on the arrival of the FRS, and their decision to initiate an alarm, either building wide or on strategic floors. There would also seem to be no technological reason why a building could not have an alarm system remotely activated by a third party, whether that be a building manager, or some form of alarm receiving centre. Either way, FRS or remotely monitored alarm systems would be subject to response delays.

The type of alarm notification is likely to affect the response of occupants both in terms of their likelihood to act on the notification and then how quickly they complete any actions if they decide to act. It is typical within the literature that these two elements are represented by different pre-evacuation delays, for example the pre-evacuation delay for a voice alarm is shorter than for a tone alarm. The approach of using a different delay to distinguish between types of alarm notification is adopted in this work (Section A3-4.5); however, no distinction is made on the likelihood of acting on the alarm notification even though it might be postulated that a voice alarm may increase the probability that a resident will initiate a particular response when compared to a tone alarm.

In terms of the simulations presented in this study, the time at which a fire is first detected, and the alert provided is assumed equivalent across all cases. This is assumed as (a) the detection phase is largely a technological issue and (b) it is only after the occupants become aware of the incident that they can respond, with the focus of this work is on the impact of the building systems on the evacuation process. To give a sense of what kind of times might be typical Tan et al. [31] determined detection and alarm times of the order of 25 to 211 s using the B-RISK zone model within the flat of fire origin. However, warning delays are relevant to this work where those delays have occurred between the initial occupants becoming aware of the fire and those initial occupants then alerting others (see Section A3-4.6). It is unclear how Tan et al. addressed the alerting of building occupants remote from the flat of fire origin and whether they included any delays subsequent to their initial detection and alarm time.

A3-4.4 Occupant interaction

Once building occupants become aware of a fire they may alert other occupants by various means, and those that have been alerted in turn alert further occupants. Occupants may also contact the fire and rescue services (FRS), with the FRS then alerting further occupants at their discretion. This occupant-to-occupant interaction could create a cascade of alerting and notification actions as illustrated in Figure A3-12. Whether occupants make contact with others and by what means is discussed further in this report such as in Section A3-4.6.3 and Section A3-4.8.2.

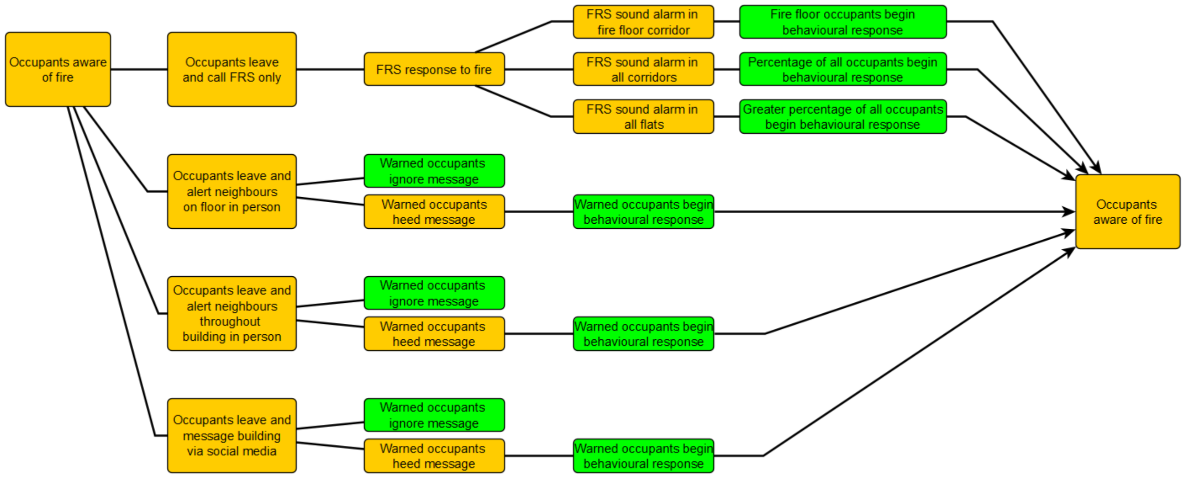


Figure A3-12 Interaction between occupant alerting and notification

A3-4.5 Implied pre-evacuation times

Reference mean pre-evacuation values for different means of alerting are provided in Table A3-5. These have been derived based on state (whether an individual is awake or asleep), notification system in place, and level of impairment (whether an individual has an impairment or not). These values were proposed in Appendix A2 and were determined using data provided in the literature for example the SFPE Handbook chapter Engineering Data [32], C/VM2 [18] and PD7974 [4] guidance, with particular reference to work by Lovreglio et al. [33], Geoerg et al. [34] and Pearson and Joost [35]. The resultant pre-evacuation times employed were derived from the reviewed empirical data and from general evacuation theory reflected the following relationships:

- Pre-evacuation times (asleep) > Pre-evacuation times (awake)
- Pre-evacuation times (with impairment)[4] > Pre-evacuation times (without impairment)
- Pre-evacuation times (tone alarm) > Pre-evacuation times (voice/in person notification)[5]

[4] Where delay includes possible preparatory actions.

[5] Where voice alarm is likely accompanied by initial alerting tone.

The numerical interaction between these factors in specific scenarios is then informed by the reviewed data. For instance, agents with impairments typically have pre-evacuation times approximately twice that of agents without such impairments, etc.

Table A3-5 Reference mean pre-evacuation times for different means of alerting for residents based on state and impairment

Level of impairment	State	Implied pre-evacuation time (s)				
		Voice	Tone/Bell	Person	FRS	Smoke cues
Impaired	Asleep	300	600	300	240	240
	Awake	180	300	180	120	120
Unimpaired	Asleep	180	360	180	120	120
	Awake	90	180	90	60	60

The research literature often suggests that a skewed distribution such as lognormal or Weibull is appropriate to represent pre-evacuation. The challenge with these shapes is that they mathematically extend to infinity and therefore can present some computational intricacies. One solution is to truncate the functions, but another is to use a triangular distribution with characteristics that provide a satisfactory match to a lognormal or Weibull shape. A previous evacuation modelling study [36] showed that this approach is reasonable.

In the paper by Lovreglio et al. [33] a lognormal best-fit statistics for multi-occupancy residential buildings (Cluster 1) with a mean of -0.009 min and a standard deviation of 1.432 min was suggested. For a generally poor alarm system performance (Cluster 2) Lovreglio et al. give a mean of 2.031 min and a standard deviation of 1.268 min. Using these findings, it is reasonable to use 1.3 min (78 s) as a representative standard deviation. Therefore, what are referred to herein as ‘implied’ lognormal pre-evacuation distributions applied in the simulations use the mean values in Table A3-5 with a standard deviation of 1.3 min.

A3-4.6 Component pre-evacuation times

Often in the literature only the overall pre-evacuation delay time is given rather than the component parts. This can be sufficient for some circumstances but is not always the case. For example, where there is a desire to consider the specific conditions represented within the scenario coupled with the procedure employed, then only having the overall pre-evacuation delay time will not provide the ability to adequately investigate the relationship between the procedure and the scenario and it may be necessary to break the pre-evacuation into elemental delay times.

Previous work by Vistnes et al. [37] examined how elemental time delays could be combined to create an overall delay, and a similar methodology is used as part of this work. As discussed in Section A3-4.1, the pre-evacuation delay is broken into four components: arousal, assimilation, contact and residual. Using these components allows the simulations to encompass the risk perception research conducted in this project and the baseline pre-evacuation distributions given in Section A3-4.5.

The selection of mean and standard deviation values for the arousal, assimilation and contact times are discussed in the following sections.

A3-4.6.1 Arousal

Spearpoint et al. [38] reviewed the literature on waking time of adult occupants to alarms and found that a best-fit lognormal distribution with a mean of 21 s and a standard deviation of 12 s is representative of people who are 'familiar' with their location. Vistnes et al. [37] suggest that waking time can be represented as a log-normal distribution with a mean of 60 s and a standard deviation of 18 s.

Work referenced by Bruck and Ball [39] show that average response times increase when people are under the influence of alcohol. Response times generally doubled up to 336 s when the blood alcohol content (BAC) was 0.05% compared to no alcohol, although the increase in response times was less when the BAC was 0.08%. In addition, it was also found that sound levels need to be increased to initiate a response from those who had consumed alcohol. Bruck and Ball note at the time of writing there was only one experimental study had examined the ability of smoke alarms to awaken people who had taken hypnotics. Furthermore, Bruck and Ball discuss research which has shown that children are less likely to respond to the sound of smoke alarms, and older adults may have impaired hearing. These factors illustrate some of the complexity related to waking people using audible signals.

The waking times given by Vistnes et al. [37] are adopted in this work. However, it is likely the waking times used in this study are optimistic where occupants are impaired by alcohol (and there is most likely a similar impact where prescription or recreational drugs are involved). Although were such factors to be included then a likelihood of occurrence would need to be considered. Furthermore, for practical reasons, this study has not distinguished between the characteristics of adults and children, whether that be in terms of movement, route choice, social clustering or response behaviours.

A3-4.6.2 Assimilation

In the work of Nagarajan et al. [40] they suggest a normal distribution with a mean of 10 min and standard deviation of 4 min for the time it takes for a household to understand the warning message and decide how to respond. Nagarajan et al. considered house-to-house communication in response to be informed of a flood or similar. Compared to the proposed mean pre-evacuation times in Table A3-5 their values are considerably longer and so are not considered further herein.

More relevant work by Kobes et al. [41] on hotel fires give reaction times of around 95 ± 70 s to a spoken message alert to the guests via a telephone. Kobes et al. used a telephone message such they noted that "… *it is found that a fire alarm using a spoken message, or a communication system using personnel directives, is taken most seriously by occupants present in a building*."

In this work the reaction time from Kobes et al. is used as a fixed 'assimilation time' irrespective of the means of automatic alert since the benefit of a voice alarm over a tone alarm is already reflected in the implied mean pre-evacuation delay times given in Section Table A3-5. Where the alert is provided through the awareness of smoke or fire, or by contact with another person, the reaction time of Kobes et al. may be conservative. Therefore, it is proposed herein that the mean and standard deviation be approximately halved from 95 ± 70 s to an assumed 50 ± 35 s for these cues in a familiar, residential setting.

A3-4.6.3 Contact

Kobes et al. [41] suggest that the time needed to dial a phone and put it down might be up to 34.1 ± 31.1 s. However, Kobes et al. do not specify the distribution shape; therefore, a simple triangular distribution with a lower bound of 3 s, a most likely value of 34 s and an upper bound of 65 s could be applied. Spearpoint et al. [38] found that a triangular distribution with a minimum value of 5 s, a most likely value of 20 s and a maximum of 105 s give a good fit for the times to make a phone call reported by Nober et al. [42]. Vistnes et al. [37] suggest the time to get to and make a telephone call has a log-normal distribution with a mean and standard deviation of 30 ± 9 s. In this work the contact time of Vistnes et al. is adopted for contact made by phone / social media.

An alternative means of contact is through face-to-face communication and, in the context herein, this represents where occupants might leave the flat they are in and knock-on neighbours' doors to warn them of the incident. This means of contact requires the agent to travel to the neighbouring flat, knock-on the door (or ring a doorbell, etc.) and wait for a response and as such will be dependent on the travel distances involved and the speed of travel. Thus, the contact time would likely be longer than that adopted from Vistnes et al. [37] to make a telephone call. As an approximation it is assumed neighbours travel an average of 10 m to the stairs, ascend or descend one flight of stairs (noting that there will be some occupants who would not be so able to do this, such those that are mobility impaired) and then travel another 10 m to a neighbour. At a 'typical' walking speed of 1 m/s this would take around 30 s. In addition, there would be waiting for the time for the neighbour to respond (which may mean waking them up) plus the communication time. A mean value of 10 s and standard deviation of 10 s is given by Vistnes et al. [37] for the time to notify others. Assuming the same 60 s arousal time as previously and 10 s to communicate with the neighbour then the total average time would be 30 + 60 + 10 = 100 s. Furthermore, it might be assumed this time would vary depend primarily on the travel distance (from an immediate next-door neighbour to one a double the distance) suggesting that the time be varied by 40 s. Thus, the time delay for face-to-face communication adopted in this study has a mean of 100 s (1.7 min) with a standard deviation of 40 s (0.7 min).

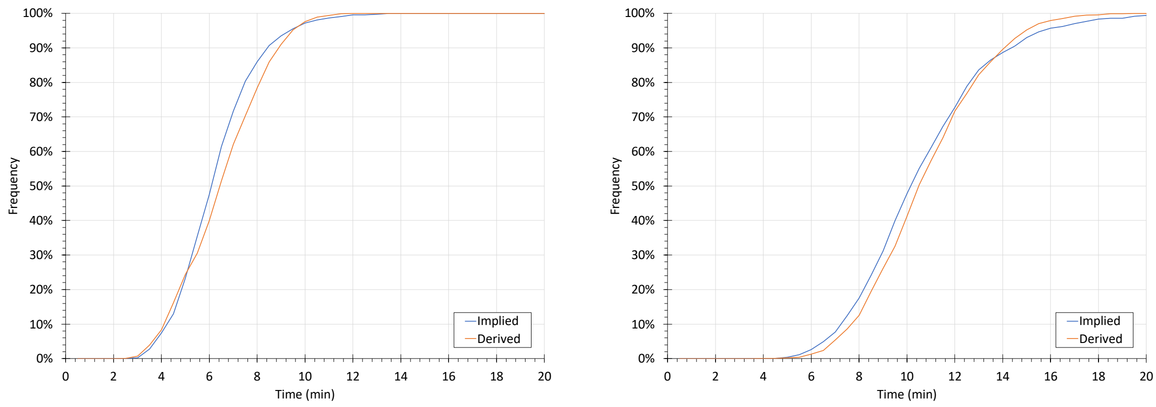
In comparison, the SFPE Handbook chapter "Human Behavior in Fire" [43] reports that the analysis made by Kuligowski of the WTC disaster found that occupants spent 3 min (180 s) communicating with others. Therefore, 100 ± 40 s might be seen as somewhat optimistic although the circumstances are quite different.

A3-4.7 Comparison between implied and component pre-evacuation times

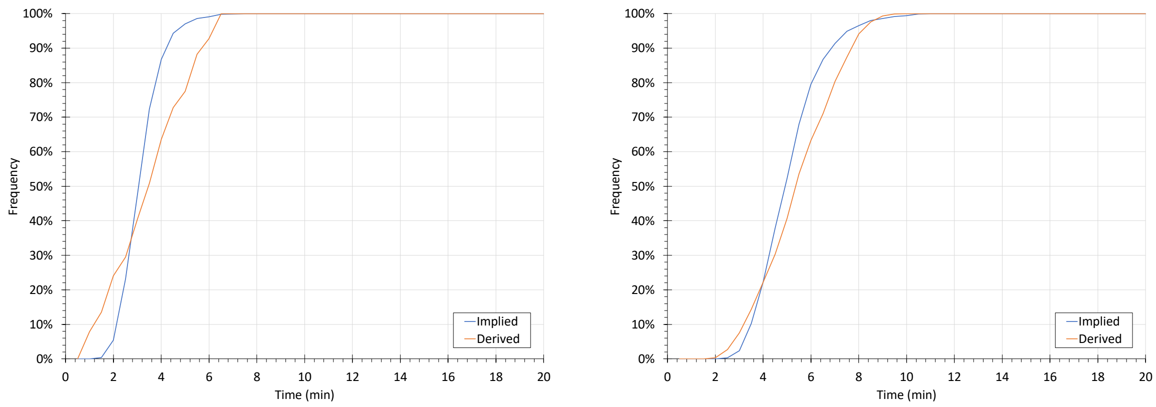
As discussed in Sections A3-4.5 and A3-4.6, pre-evacuation delays are represented either as 'implied' values (i.e., a delay can be represented by a single distribution) or by a combination of 'component' values. In either case, the values are assumed to come from lognormal distributions with mean and standard deviations derived from the literature. A summary of the implied and component values is given in Table A3-6 to Table A3-8 for different agent responses.

One reason to represent a pre-evacuation delay as a single distribution is that Pathfinder cannot easily break the delay time into component delays but is able to represent a delay as a lognormal distribution. In contrast, Evacuationz has been developed to allow the user to construct a pre-evacuation delay as a combination of component delays. However, when comparing results from the two simulation tools it is important to assess whether the findings are comparable when applying the two methods of representing the pre-evacuation delays. Thus, the purpose of this section is to compare the generation of the pre-evacuation delays using the two approaches to show that they result in similar outcomes.

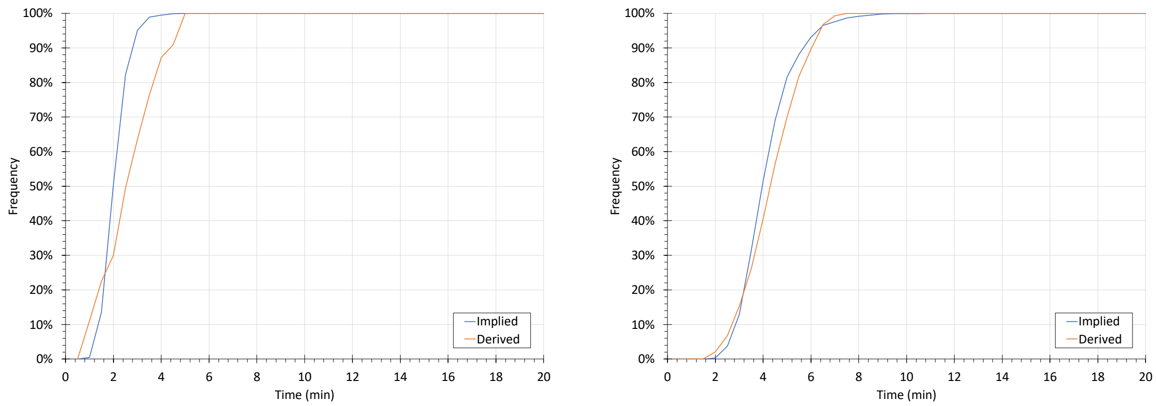
For the component delay the residual mean is taken to be the implied mean in Section A3-4.5 minus the mean values for the arousal, assimilation and contact times. For example, for the tone alarm, adding the mean values for the arousal, assimilation and contact time gives 60 + 95 + 30 = 185 s (3.1 min) if the agent is asleep, or 125 s (2.1 min) if awake. Thus, the residual mean is 600 – 185 = 415 s (6.9 min) when they are asleep. Where the residual time is found to be less than zero, then it is assigned to be zero. As noted previously in Section A3-4.5, it is reasonable to use 1.3 min as a representative standard deviation (SD) for the implied pre-evacuation delays. In the absence of any other evidence from the literature it is assumed that the standard deviation for the residual time is also 1.3 min.



(a) Tone alarm, asleep with social media contact: unimpaired and impaired agent



(b) Voice alarm, asleep with social media contact: unimpaired and impaired agent



(c) Smoke, asleep with social media contact: unimpaired and impaired agent

Figure A3-13 Comparison between using the implied and component delay methods

To illustrate the outcomes of using the two methods, exemplar pre-evacuation delays for the various combinations of alerting cue, wakefulness and impairment have been generated. Randomised simulations have been carried out in a spreadsheet for (an arbitrary) 200 iterations. For the implied method, the mean and standard deviation have been used to generate the pre-evacuation delay times. For the component method, the mean and standard deviation for each component (arousal, assimilation, contact and residual times) have been used to generate four times which have then been summed to get the pre-evacuation delay. Adding several lognormal distributions can result in very long tails, therefore where any sampled value is greater than twice the mean, then a fixed value of twice the mean is used. Similarly, where any sampled value is less than one quarter the mean, then a fixed value of the quarter the mean is used. These arbitrary cut-offs have been calibrated against the comparison of the two methods to get a reasonable match. Results from 1000 sampling iterations for both the implied and component method are illustrated in Figure A3-13. Note that the match is not as good where the residual time in the component method is calculated to be less than 0 s and is therefore assigned a value of 0 s, e.g., unimpaired agent, voice alarm, asleep, social media contact.

The application of the implied and component pre-evacuation delays in Evacuationz using the procedure described above has been further investigated in Section A3-10.3.

Table A3-6 Implied and component pre-evacuation delays where agent makes no further contact

Factors			Implied pre-evacuation delay			Arousal		Assimilation		Calculated residual		Assigned residual			
Alert type	Agent physical ability	Wakefulness	Mean (s)	Mean (min)	SD (min)	Mean (s)	SD (s)	Mean (s)	SD (s)	Mean (s)	Mean (min)	Mean (min)	Maximum (min)	Minimum (min)	SD (min)
Voice	Impaired	Asleep	300	5.0	1.3	60	19	95	70	145	2.42	2.42	4.83	1.21	1.3
Voice	Impaired	Awake	180	3.0	1.3	-	-	95	70	85	1.42	1.42	2.83	0.71	1.3
Voice	Unimpaired	Asleep	180	3.0	1.3	60	19	95	70	25	0.42	0.42	0.83	0.21	1.3
Voice	Unimpaired	Awake	90	1.5	1.3	-	-	95	70	-5	-0.08	0.00	0.00	0.00	1.3
Tone	Impaired	Asleep	600	10.0	1.3	60	19	95	70	445	7.42	7.42	14.83	3.71	1.3
Tone	Impaired	Awake	300	5.0	1.3	-	-	95	70	205	3.42	3.42	6.83	1.71	1.3
Tone	Unimpaired	Asleep	360	6.0	1.3	60	19	95	70	205	3.42	3.42	6.83	1.71	1.3
Tone	Unimpaired	Awake	180	3.0	1.3	-	-	95	70	85	1.42	1.42	2.83	0.71	1.3
Person	Impaired	Asleep	300	5.0	1.3	60	19	50	35	190	3.17	3.17	6.33	1.58	1.3
Person	Impaired	Awake	180	3.0	1.3	-	-	50	35	130	2.17	2.17	4.33	1.08	1.3
Person	Unimpaired	Asleep	180	3.0	1.3	60	19	50	35	70	1.17	1.17	2.33	0.58	1.3
Person	Unimpaired	Awake	90	1.5	1.3	-	-	50	35	40	0.67	0.67	1.33	0.33	1.3
FRS	Impaired	Asleep	240	4.0	1.3	60	19	50	35	130	2.17	2.17	4.33	1.08	1.3
FRS	Impaired	Awake	120	2.0	1.3	--	-	50	35	70	1.17	1.17	2.33	0.58	1.3
FRS	Unimpaired	Asleep	120	2.0	1.3	60	19	50	35	10	0.17	0.17	0.33	0.08	1.3
FRS	Unimpaired	Awake	60	1.0	1.3	-	-	50	35	10	0.17	0.17	0.33	0.08	1.3
Smoke	Impaired	Asleep	240	4.0	1.3	60	19	50	35	130	2.17	2.17	4.33	1.08	1.3
Smoke	Impaired	Awake	120	2.0	1.3	-	-	50	35	70	1.17	1.17	2.33	0.58	1.3
Smoke	Unimpaired	Asleep	120	2.0	1.3	60	19	50	35	10	0.17	0.17	0.33	0.08	1.3
Smoke	Unimpaired	Awake	60	1.0	1.3	-	-	50	35	10	0.17	0.17	0.33	0.08	1.3

Table A3-7 Implied and component pre-evacuation delays where agent makes contact with other agent/s via telephone / social media

Factors			Implied pre-evacuation delay			Arousal		Assimilation		Social media / telephone contact		Calculated residual		Assigned residual			
Alert type	Agent physical ability	Wakefulness	Mean (s)	Mean (min)	SD (min)	Mean (s)	SD (s)	Mean (s)	SD (s)	Mean (s)	SD (s)	Mean (s)	Mean (min)	Mean (min)	Maximum (min)	Minimum (min)	SD (min)
Voice	Impaired	Asleep	300	5.0	1.3	60	19	95	70	30	9	115	1.92	1.92	3.83	0.96	1.3
Voice	Impaired	Awake	180	3.0	1.3	-	-	95	70	30	9	55	0.92	0.92	1.83	0.46	1.3
Voice	Unimpaired	Asleep	180	3.0	1.3	60	19	95	70	30	9	-5	-0.08	0.00	0.00	0.00	1.3
Voice	Unimpaired	Awake	90	1.5	1.3	-	-	95	70	30	9	-35	-0.58	0.00	0.00	0.00	1.3
Tone	Impaired	Asleep	600	10.0	1.3	60	19	95	70	30	9	415	6.92	6.92	13.83	3.46	1.3
Tone	Impaired	Awake	300	5.0	1.3	-	-	95	70	30	9	175	2.92	2.92	5.83	1.46	1.3
Tone	Unimpaired	Asleep	360	6.0	1.3	60	19	95	70	30	9	175	2.92	2.92	5.83	1.46	1.3
Tone	Unimpaired	Awake	180	3.0	1.3	-	-	95	70	30	9	55	0.92	0.92	1.83	0.46	1.3
Person	Impaired	Asleep	300	5.0	1.3	60	19	50	35	30	9	160	2.67	2.67	5.33	1.33	1.3
Person	Impaired	Awake	180	3.0	1.3	-	-	50	35	30	9	100	1.67	1.67	3.33	0.83	1.3
Person	Unimpaired	Asleep	180	3.0	1.3	60	19	50	35	30	9	40	0.67	0.67	1.33	0.33	1.3
Person	Unimpaired	Awake	90	1.5	1.3	-	-	50	35	30	9	10	0.17	0.17	0.33	0.08	1.3
FRS	Impaired	Asleep	240	4.0	1.3	60	19	50	35	30	9	100	1.67	1.67	3.33	0.83	1.3
FRS	Impaired	Awake	120	2.0	1.3	--	-	50	35	30	9	40	0.67	0.67	1.33	0.33	1.3
FRS	Unimpaired	Asleep	120	2.0	1.3	60	19	50	35	30	9	-20	-0.33	0.00	0.00	0.00	1.3
FRS	Unimpaired	Awake	60	1.0	1.3	-	-	50	35	30	9	-20	-0.33	0.00	0.00	0.00	1.3
Smoke	Impaired	Asleep	240	4.0	1.3	60	19	50	35	30	9	100	1.67	1.67	3.33	0.83	1.3
Smoke	Impaired	Awake	120	2.0	1.3	-	-	50	35	30	9	40	0.67	0.67	1.33	0.33	1.3
Smoke	Unimpaired	Asleep	120	2.0	1.3	60	19	50	35	30	9	-20	-0.33	0.00	0.00	0.00	1.3
Smoke	Unimpaired	Awake	60	1.0	1.3	-	-	50	35	30	9	-20	-0.33	0.00	0.00	0.00	1.3

Table A3-8 Implied and component pre-evacuation delays where unimpaired agent makes contact with another agent/s face-to-face by moving to their flat*

Factors			Implied pre-evacuation delay			Arousal		Assimilation		Face-to-face contact		Calculated residual		Assigned residual			
Alert type	Agent physical ability	Wakefulness	Mean (s)	Mean (min)	SD (min)	Mean (s)	SD (s)	Mean (s)	SD (s)	Mean (s)	SD (s)	Mean (s)	Mean (min)	Mean (min)	Maximum (min)	Minimum (min)	SD (min)
Voice	Unimpaired	Asleep	180	3.0	1.3	60	19	95	70	100	40	-75	-1.25	0.00	0.00	0.00	1.3
Voice	Unimpaired	Awake	90	1.5	1.3	-	-	95	70	100	40	-105	-1.75	0.00	0.00	0.00	1.3
Tone	Unimpaired	Asleep	360	6.0	1.3	60	19	95	70	100	40	105	1.75	1.75	3.50	0.88	1.3
Tone	Unimpaired	Awake	180	3.0	1.3	-	-	95	70	100	40	-15	-0.25	0.00	0.00	0.00	1.3
Person	Unimpaired	Asleep	180	3.0	1.3	60	19	50	35	100	40	-30	-0.50	0.00	0.00	0.00	1.3
Person	Unimpaired	Awake	90	1.5	1.3	-	-	50	35	100	40	-60	-1.00	0.00	0.00	0.00	1.3
FRS	Unimpaired	Asleep	120	2.0	1.3	60	19	50	35	100	40	-90	-1.50	0.00	0.00	0.00	1.3
FRS	Unimpaired	Awake	60	1.0	1.3	-	-	50	35	100	40	-90	-1.50	0.00	0.00	0.00	1.3
Smoke	Unimpaired	Asleep	120	2.0	1.3	60	19	50	35	100	40	-90	-1.50	0.00	0.00	0.00	1.3
Smoke	Unimpaired	Awake	60	1.0	1.3	-	-	50	35	100	40	-90	-1.50	0.00	0.00	0.00	1.3

* It is assumed that only unimpaired agents can undertake this action, as discussed in Section A3-4.6.3.

A3-4.8 Likelihood of response and alert

The previous discussion has focussed on how long it might take for a person to carry out certain actions but there is also the issue of whether a person decides to take any actions that leads to them evacuating a building. As discussed in the preceding part of this research project in **Objective B1** (see Appendix B1), in the model derived by Canter [44] for multiple occupancy properties, he identified that occupants may misinterpret or ignore strange noises before evacuating. Similarly, the reworking of the Kuligowski model for agent-based models includes a ‘continue working’ action. Not only is there a likelihood that a person will decide to take actions that lead to them evacuating but also whether they take actions to alert others.

It is also important to note that when a person receives a notification, they can decide at that instant to respond to or not. Clearly, the person has the option to change their mind at some later stage, either deciding to respond and evacuate, or to decide to no longer evacuate. Furthermore, a person may receive several notifications during an incident which will influence their decision-making. The effect of having multiple notifications is included in some of the scenarios simulated using the Evacuationz model (for example see Section A3-10.5.4). The simulations assume that once an agent decides to evacuate, they do not subsequently change their mind. It would be possible to include in the Evacuationz model the prospect that an agent decides to no longer evacuate but in doing so would add unwarranted complexity.

It is therefore appropriate to include a measure of the likelihood of agent action and this is discussed in this following sections. This discussion includes the results from a questionnaire survey conducted as part of this study (see Appendix B2) to better understand how occupants may behave when confronted by a fire incident in their building. The complexity of the interactions between building residents and between the residents and other parties such as fire and rescue service personnel has been further explored in the focus group interviews carried out as part of this project. Such complexities cannot easily be reproduced in agent-based simulations however sophisticated those tools are. The outcome of the discussion has led to appropriate representative probability values being adopted in the simulations conducted as part of this study.

A3-4.8.1 Evacuate or stay put

Following on from the Grenfell Tower fire there has been considerable debate across the industry and in the media surrounding the safety of the stay put guidance. It is beyond the scope of this work to comment on this debate in any detail although some of the simulations undertaken as part of this work represent elements of this guidance. For context, AD B vol 1, clause 3.3 states

> "*Provisions are recommended to support a stay put evacuation strategy for blocks of flats. It is based on the principle that a fire is contained in the flat of origin and common escape routes are maintained relatively free from smoke and heat. It allows occupants, some of whom may require assistance to escape in the event of a fire, in other flats that are not affected to remain.*
>
> *Sufficient protection to common means of escape is necessary to allow occupants to escape should they choose to do so or are instructed/aided to by the fire service. A higher standard of protection is therefore needed to ensure common escape routes remain available for a longer period than is provided in other buildings*."

It is worth noting that the guidance expects common escape routes to be 'relatively free of smoke and heat' suggesting that such routes need to allow for occupants 'in other flats' to escape but may contain some level of fire products likely due to the door of flat of fire origin being opened during evacuation. The key point within the guidance is that occupants may choose to escape from their flat, for whatever reason, or they may be advised by the fire and rescue services to do so.

A strategy that allows people to safely remain in their flats either throughout a whole incident or for part of the incident assumes that the building safety systems present mitigate any fire or smoke spreading from the flat of origin. However, the viability of a stay put strategy is not simply one of fire safety design, but is also reliant on the training, perception, response, and preferences of the resident population. In the current climate, some six years after the Grenfell Tower fire, residents still appear reluctant to remain in their flat during an incident where there is no apparent threat to those occupants. This is not to say that prior to Grenfell Tower a certain proportion of the residents of high-rise residential buildings elected to evacuate under similar circumstances. This desire to evacuate is amplified for those with movement impairments (whose numbers will increase given demographic changes) who have few options to get out of the building during an incident (likely fewer than those without movement impairments). This disparity in the number of options and the reliance on an approach that resulted with disastrous consequences in the Grenfell Tower fire (albeit without the design strictly adhering to the requirements in place) is apparent to those who might struggle to self-evacuate.

Should occupants elect or be advised to evacuate from their building then not only does their safety depend on the building and fire safety provisions but also on behavioural elements (of them and those around them) which include:

- When in an incident, do they become aware of the need to respond,
- During an incident, do they decide to escape (and then initiate escape movement),

- What routes are available to them and which route do they choose,
- How quickly can they move (in corridors and on the stair) and what resources are required for them to do so, and
- Whether they move directly out of a building or decide to take other actions such as warning neighbours, etc.

Of course, the movement involved and the potential exposure of evacuees to deteriorating conditions is not without risks. Therefore, asking whether ‘stay put is safe enough’ is not an easy one to answer from the perspective of carrying out egress modelling as it depends on what assumptions are made as to if and when occupants decide to leave, and whether in leaving their flat they expose themselves to a greater hazard had they not stayed. The decision to leave or not depends on information available to an occupant, their sense of safety, whether they have had prior fire safety education and/or training, etc. The extent of the hazard present to the evacuation occupant will depend on the building design, the fire safety provisions, the severity of the fire, the actions of others in the building, etc.

Given that the hazard scenario presented in this work assumes that smoke will eventually compromise every flat in the building (see Section A3-5) then if occupants never decide to leave it would suggest the stay put strategy would fail to achieve its goal. However, the hazard scenario has been deliberately created to give a worst case that may be argued to be less than a credible one. Even in the case of Grenfell Tower not every flat became comprised by smoke, let alone this happening after 86 min (i.e., just under one and a half hours) as assumed in this report.

What is clear from the survey of residents conducted in Appendix B2 carried out as part of this research is that it is wholly unrealistic (certainly given the current UK climate) to expect all occupants of a high-rise residential building will remain in their flat even where it is viable to do so once they are aware of a potential fire incident. This finding is borne out when examining some recent fire incidents in blocks of flats in England, elsewhere around the UK and further afield. On becoming aware of a fire incident in their building, some occupants will either immediately initiate an evacuation, or will initiate it at some time later. As already, alluded to above, this is not something that is only the case following the fire at Grenfell Tower. On the other hand, some occupants will remain in the building and therefore it is possibly unrealistic to expect a full evacuation will occur when they are made aware of an incident. For example, occupants may think it is a false alarm, may not feel sufficiently threatened, or may not have (or believe they have) the capacity to evacuate. As such stay put intrinsically exists, even in a building in which there is an expectation of full evacuation. Occupants that initially stay put may eventually decide to evacuate as the situation develops but this may ultimately require FRS intervention.

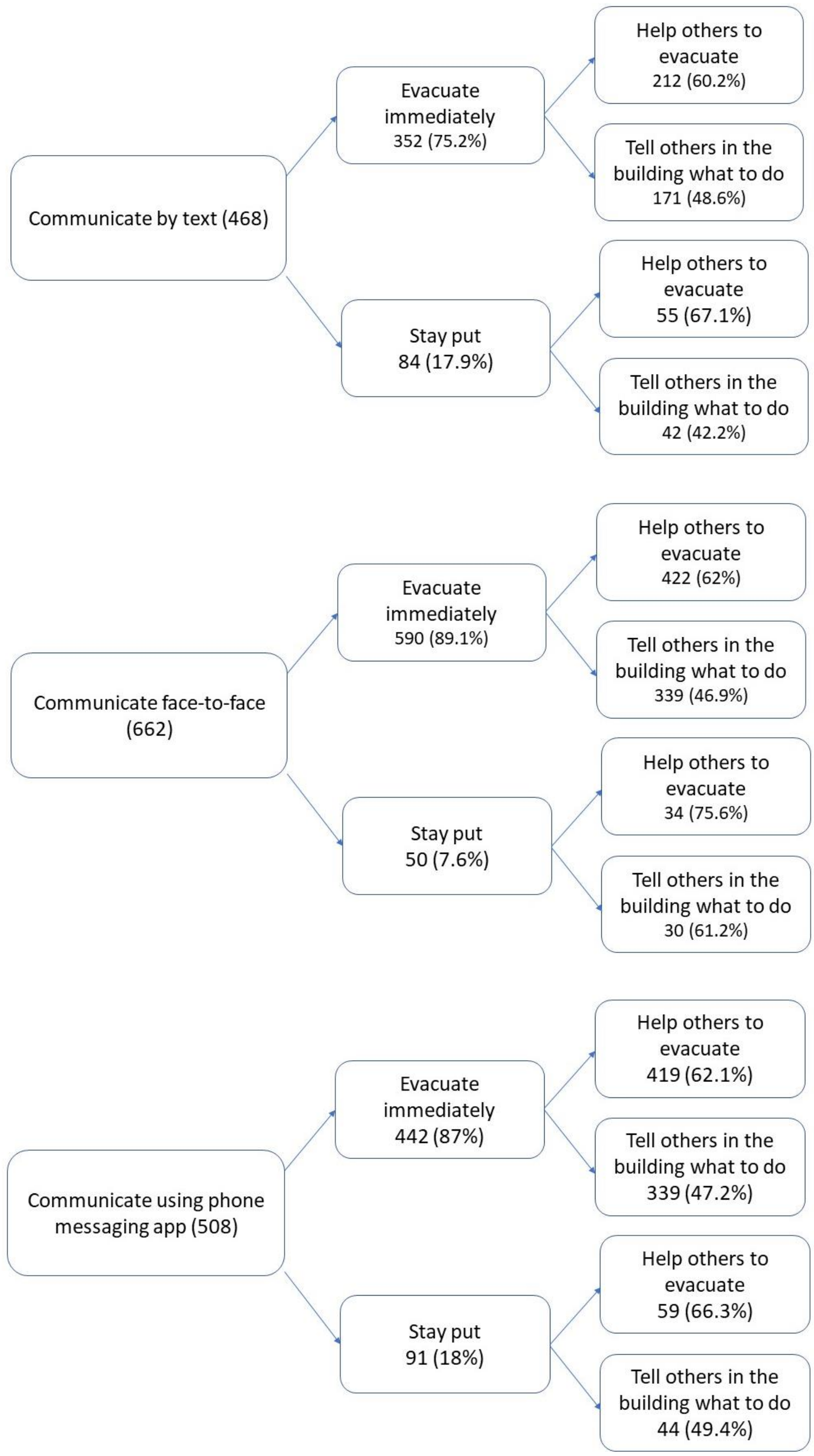


Figure A3-14 Sequence of events from likely mode of communication to likely behaviours

Where Appendix B2 investigated what would a person do on receiving a notification in terms of either immediately evacuating or deciding to stay put the likelihood of these two options was assessed when the notification was provided by four different means: personal text message, face-to-face, some form of social media post or similar, or automatic fire alarm. The results from the survey are shown in Figure A3-14 and Figure A3-15. For certain questions the respondents were able to select more than one option and therefore percentages in sub-branches of the trees do not sum to 100%.

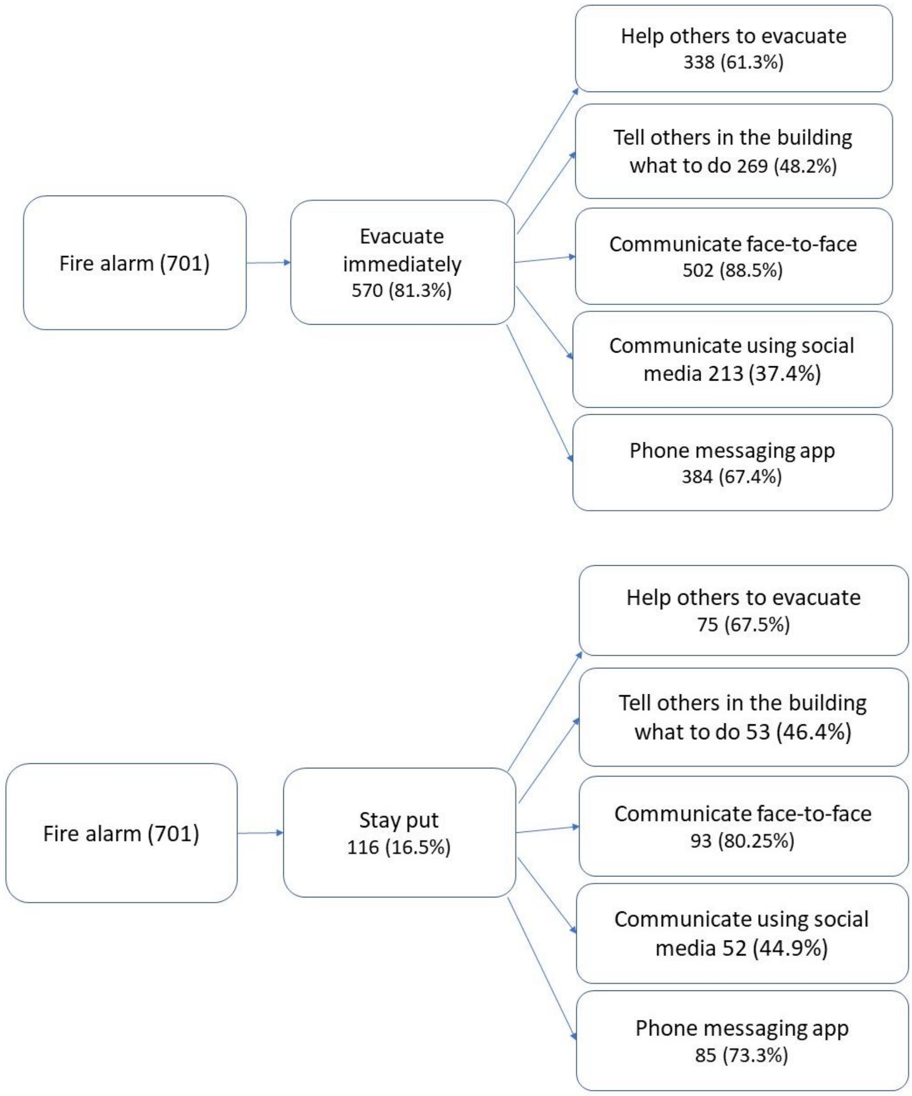


Figure A3-15 Sequence of events from automatic fire alarm notification

Combining results in Figure A3-14 from ‘communicate by text’ and ‘phone messaging app’ suggests that around 80% of people would initiate their evacuation procedure whereas the other 20% would stay put. However, where notification could be face-to-face then the likelihood of evacuating increases to 90%. Furthermore, as indicated in Figure A3-15, approximately 80% of people said they would evacuate on hearing a fire alarm.

Thus, in the simulations an 80% probability is assigned by default to an agent as the likelihood of evacuating the building when remotely notified, where evacuation is not assumed to be start immediately but is still subject to a pre-evacuation delay. This likelihood is independent of the method of notification, i.e., personal text, 'social media' or automatic fire alarm. For face-to-face contact in isolation the resident survey results gives 89.1% in the simulations where an agent is alerted 'face-to-face' then a 90% probability of evacuating the building is used.

A3-4.8.2 Agent-to-agent communication – Social notification

In addition to determining whether an occupant would decide to evacuate or stay put, the resident survey also investigated what a person might do in terms of helping others to evacuate or telling others in their building what to do. It should be noted that a building wide notification system would likely not be present where stay put is the primary strategy. Should residents start to evacuate in such circumstances, then the primary means of notification would have to be social, beyond the flat of fire origin, in the absence of other means. This analysis then might reflect the performance of a population evacuating when the stay put strategy is in place, along with the associated notification systems.

The results shown in Figure A3-14 suggest that around 50% of people would tell others what to do and 50% would help others irrespective of whether they had decided to evacuate or not. Thus, for the purposes of the modelling, a 50% probability might be inferred as the likelihood that an agent would contact other agents remote from their flat. However, in the work of Nagarajan et al. [40] it was suggested from the literature that around 22% to 40% of people would inform their neighbours of an emergency event (albeit this was not for fire incidents in high-rise residential buildings). In the simulations a default uniform distribution between 22% and 50% is assigned to agents when assuming they will contact another agent via a remote means such as a personal text message, etc.

Figure A3-15 shows that the likelihood of contacting other people by different means after being notified by an automatic fire alarm varies. Face-to-face is more likely than using digital communication tools, and of these tools, messaging apps appear to be more likely than social media. For the modelling exercises it is more difficult (although not impossible) to differentiate between the various modes of communication. From Figure A3-15, the average of communicate face-to-face (88.5%), communicate via social media (37.4%) and using a phone messaging app (67.4%) for those residents that will evacuate immediately on hearing a fire alarm is 65%. Similarly, for the case in which residents stay put the average is 66%. Therefore, the probability of an agent contacting another agent after being notified by a fire alarm is set to 65% irrespective of whether the agent doing the contacting proceeds to evacuate or not.

Table A3-9 presents a summary of the default probabilities used in the simulations for the likelihood of agents responding to a notification and also contacting other agents after receiving a notification.

Table A3-9 Agent response and alert probabilities

Responding		
Any agent	Probability of responding to automatic alarm system alert	80%
Any agent not in fire flat (irrelevant to agents in fire flat)	Probability of responding to message alert from another agent	80%
	Probability of responding to in-person alert from another agent	90%
Alerting		
Any agent in fire flat	Probability of alerting other agents via message after becoming aware of the fire	Uniform distribution: Minimum of 22% Maximum of 50%
Any agent in remote flat	Probability of alerting other agents via message after receiving a message	Uniform distribution: Minimum of 22% Maximum of 50%
Any agent in remote flat	Probability of alerting other agents via message after hearing automatic alarm system	65%

A3-4.8.3 Access to social media

The assumptions discussed above regarding the use of social media do not directly account for the likelihood that that not every person will be able to (or choose to) have access to social media. In a report by the Pew Research Center [45] the probability of a person using social media in the UK is given as 87% for the 18-36 age group, 48% for 37+ age group, and 60% overall. Furthermore, the scenarios represented by the simulations are where occupants are asleep and therefore becoming aware of social media posts will be problematic.

It would not be impossible to account for the use of social media (and other associated technologies such as mobile phones) across the building demographic in the simulations but doing so would add another layer of intricacy to an already complex modelling challenge.

A3-5 Selection of representative fire scenario

A3-5.1 Indicative fire and smoke movement

One critical aspect of the simulations is to what extent smoke and toxicity could affect a fire strategy and any subsequent evacuation process. Clearly, if the principles of the stay put strategy are achieved using compartmentation etc., then only the potential impact of smoke on the occupants of the flat of fire origin and possibly those close-by needs to be considered. Similarly, where the separation between the floors of the building and stairs is maintained then it might only be necessary to consider the effects on occupants who use the common spaces should they decide to evacuate from the building.

However, where other evacuation strategies are implemented (or where a portion of the population decides not to stay put irrespective of the strategy in place), or where fire safety systems that are relied upon fail (e.g., where the door to the flat of fire origin remains open, poor maintenance of the systems etc.), then the scope of the impact of smoke spread throughout the building must be better understood. A sequence of events (or 'failures') that could lead to smoke spread throughout a residential building and ultimately lead to trapped occupants is shown diagrammatically in Figure A3-16. The sequence postulates a scenario in which fire and smoke spreads through a building via the stairs. This is not the only route of fire and smoke spread and other internal pathways might include lift shafts, and heating, ventilation and air-conditioning systems (HVAC).

The effect of smoke on occupants is a complex topic. The effect depends on the type of combustion (i.e., smouldering, well-ventilated burning, under-ventilated burning), the material(s) burning, the size (energy release) of the fire and its growth rate, any mixing and dilution of the smoke, the susceptibility of individuals to the smoke characteristics, etc. Many of these factors can be addressed using a fractional effective dose (FED) approach. Here we will use a simplified approach to tenability using smoke visibility as the main factor. Purser and McAllister [46] note that the loss of visibility is typically the first hazard to occupants to occur and thus can be used as a reliable marker for the onset of other occupant hazards related to smoke toxicity.

The extensive literature (e.g., the numerous chapters in the SFPE Handbook) that describe fire development, toxic gas concentrations etc., illustrates that these are highly complex phenomena that are extremely sensitive to the underlying assumptions made (e.g., location, materials involved, air flow/ventilation, etc.). It is therefore impractical for this study to fully simulate the generation and spread of smoke (and heat) around the exemplar buildings given the number of possible fire scenarios that might reasonably exist, and the sensitivity of the smoke spread to these scenarios and the many associated factors. Instead, order of magnitude indications of smoke movement within the buildings to adequately inform the comparative analysis are provided and their potential impact on the evacuation process. This document therefore proposes times that flats, corridors and stairs remain sufficiently clear of smoke that occupants can move normally; when smoke in these areas reaches a point that movement is likely to be hindered; and when conditions mean that occupants will not be willing or able to move through smoke, i.e., the means of escape has become compromised.

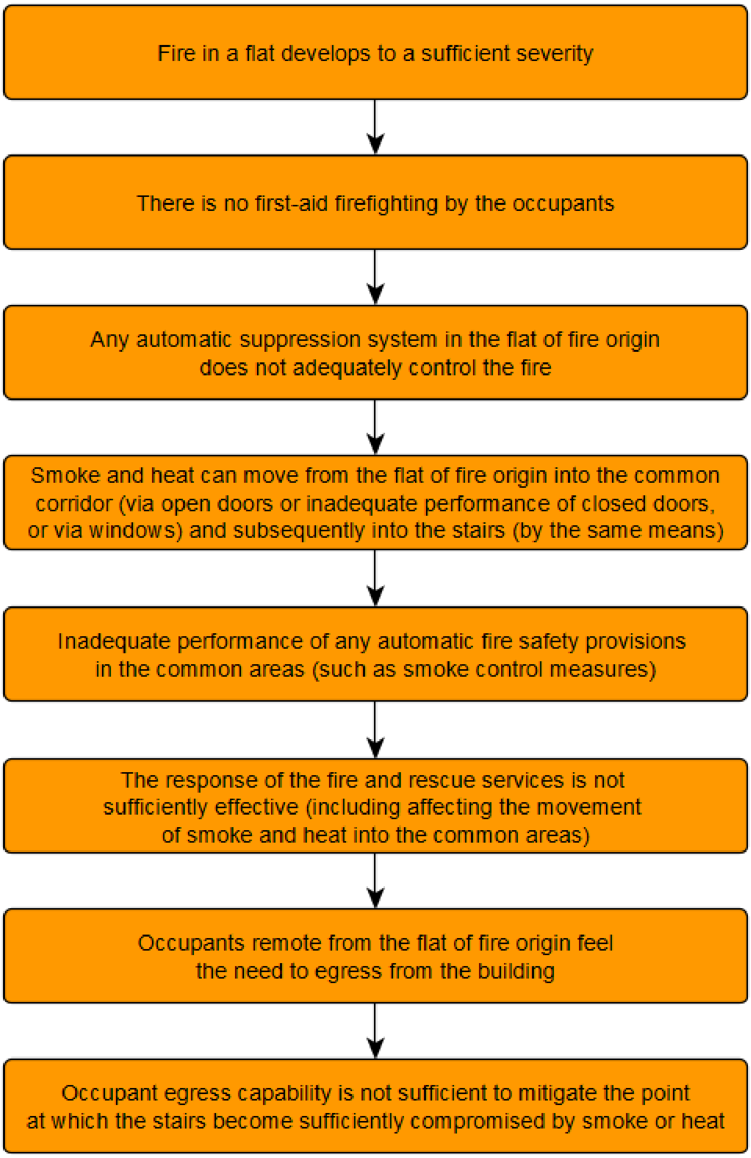


Figure A3-16 Sequence of events that could lead to smoke spread throughout a residential building and the need for occupants remote from the flat of fire to evacuate

Times are proposed that account for the movement of smoke from a flat of fire origin to flats, corridors and stairs that are either closely connected to the fire or those that are more remote. This simple approach does not fully account for situations in which smoke is more likely to affect floors above the fire compared with those floors below and therefore effectively assumes the fire is on the lowest occupied floor. Additionally, the scenarios only consider those cases that exhibit a rapid flaming fire development leading to one of an appreciable magnitude. As such, the scenarios do not include smouldering fires, fires that have a long incipient phase or those fires that remain sufficiently small not to present a hazard to those within the building as a whole or potentially even in the flat of origin. Nor do the scenarios consider the situation in which fire and smoke spread is via the outside of the building either due to spread from window-to-window, from balcony-to-balcony, or via a combustible façade system. Furthermore, there is an assumption that any active fire protection systems present within the building do not perform as expected or are absent, and that firefighting operations are unsuccessful. Therefore, this study assumes the sequence of events described in Figure A3-16 is realised and it has not been within the scope of the work to investigate the likelihood of the movement of smoke to and from flats, corridors and stairs.

As detailed below, the time estimates for smoke to hinder evacuation and compromise routes have been developed from the analysis of previous incidents (investigated by Proulx et al. [47]), the previous work of Malhotra [9], expert witness testimony to the Grenfell Tower inquiry [48], and other relevant resources, as referenced in the appropriate place. These sources were identified as they are broadly reflective of the evacuation scenarios and building types being examined here.

A3-5.1.1 Proulx et al.

Proulx et al. [14] investigated a fire in a 29 storey residential apartment block in 1995 in 2 Forest Laneway, North York, Ontario in which they report the smoke conditions in the apartments, corridors and the two staircases. The fire started around 05:00 in a 5th floor apartment.

Using post-incident surveys, Proulx et al. report on the number of respondents that observed smoke in different parts of the building. It is difficult to generalise the conditions in each part of the building as smoke was first seen in the apartment of fire origin, then observed in a neighbour’s apartment before spreading to the corridor on the 5th floor and thereafter to the staircase in other floors. Proulx et al. noted that all the residents of the 5th floor reported smoke in their unit, the corridor and staircase.

The analysis by Proulx et al. indicates that where smoke was present, it entered apartments before 05:20 in over 60% of cases, and over 80% at around 05:30. Where specifically identified, smoke entered apartments from around the door in

65% of the cases; came through the ventilation system openings in 13% of the cases and there was one instance in which it came through a window.[6] When it came to corridors then over 50% of the occupants saw smoke at or before 05:15 and 86% saw it at or before 05:30. The higher in the building the respondent was, the more likely they saw smoke in the corridor. Around 70% of respondents reported being able to see less than c. 3 m.

Proulx et al. state that 80% of occupants who reported the time at which they saw smoke in the staircases was between 05:10 and 05:30. Attempting to escape the smoke conditions resulted in many evacuees either turning back or seeking refuge in another apartment. More evacuees saw smoke in the 'other' staircase compared with the 'fire' staircase, although a small percentage reported seeing no smoke in the 'other' staircase whereas nobody reported this for the 'fire' staircase. Proulx et al. note that:

> "*Since 65% of the respondents who saw smoke reported that the smoke entered their units around the door, it is likely that the smoke was quite dense in the corridor and that it was partly coming from the staircases, since every time someone tried to use the staircases, they opened the door to the stairs, allowing a substantial quantity of smoke to enter the corridors*."

This would suggest the movement of smoke into apartments was generally via corridors, and from stairs into corridors in a progressive manner. However, plotting the percentage of occupants who stated seeing smoke in each of these three areas as a function of time (Figure A3-17) reveals that it is not possible to simply separate them along a timeline, which might (unrealistically) suggest all three events happened simultaneously.

[6] Presumably this meant smoke travelled from the outside back into the building, although the report by Proulx et al. does not explicitly state this.

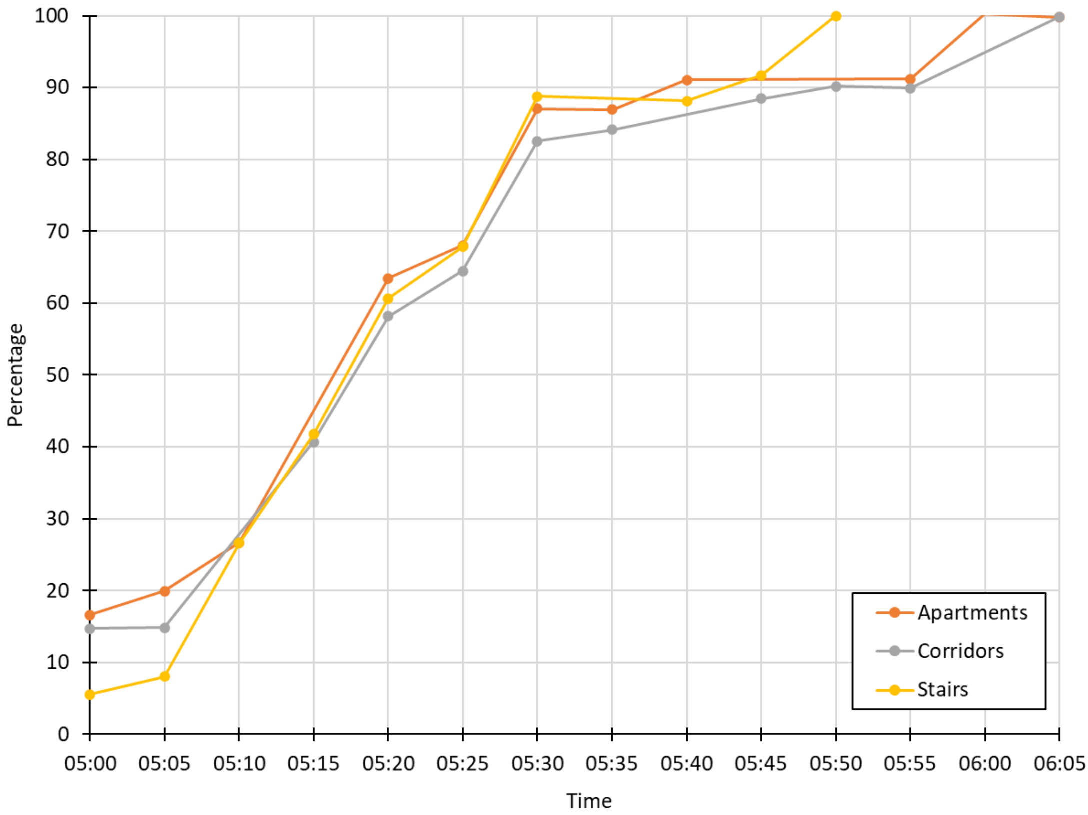


Figure A3-17 Percentage of occupants reporting seeing smoke in apartments, corridors and staircases in the 2 Forest Laneway fire, adapted from Proulx et al. [14]

In a later report by Proulx et al. [47] on the Ambleside fire in Ottawa in 1997 the authors state:

> "*Most fire scenarios predict that a fire that has burned free for 10 minutes emits quantities of smoke, heat and toxic gases that can impede egress. Suite separations will usually provide a means of fire containment for a period of time of typically 10 to 20 minutes. After that, it may be difficult for occupants on the fire floor to leave their apartments. Doors accessing exit stairwells will usually provide 20 to 30 minutes of fire protection to occupants in the stairwells unless occupants' movement and fire suppression activities allow smoke to propagate into them*."

The previous text might suggest the hindrance delay for a corridor be assigned a value of 10 min and hindrance delay to a stair be assigned a value 20 min. Similarly, the compromise time for a corridor be assigned a value of 20 min and the compromise time for a stair be assigned a value 30 min. These times are summarised in Table A3-10, where the hindrance delay time afforded to a corridor is referred to as 'h2', etc.

Table A3-10 Delay times (in minutes) before evacuation might be hindered or compromised by heat / smoke, adapted from Proulx et al. [47]

Enclosure type	Hinder (h)	Compromise (c)
Flat (1)	n/d	n/d
Corridor (2)	10	20
Stair (3)	20	30

n/d = no data

In the Ambleside fire reported by Proulx et al. [47] they found that many occupants who attempted escape around 9 to 10 min after the building alarm was raised were still able to use the common corridor leading to a stairwell even though smoke was present. However, some people decide to turn back at some later stage because of the smoke conditions. Proulx et al. [47] also reported that one of the two occupants of the apartment of fire origin died 2½ months after the incident illustrating the point that a fatality may occur during an incident or as a result of the incident at some later stage.

A3-5.1.2 Malhotra

Malhotra [9] suggests basic design escape times at that are needed prior to conditions becoming critical in buildings, reproduced in Table A3-11. He then provides adjustment factors to the basic design values to account for human nature, reproduced Table A3-12, to derive design escape times.

Table A3-11 Basic design value escape times, taken from Malhotra [9]

<u>A. Unprotected/fire zone</u>

i) normal sized room (=<100 m²)	2 - 2.5 min
ii) Larger compartments/ room height >4 m	4 - 6 "

<u>B. Partially protected zone</u>

i) natural smoke expulsion	5 min
ii) pressurization or extraction system	10 "

<u>C. Fully protected zone</u>

i) natural smoke expulsion, no lobby	30 min
ii) " " " lobby	45 "
iii) pressurization or extraction system	60 "

Table A3-12 Design escape time human behaviour adjustment factors, taken from Malhotra [9]

BUILDING	H_f
a) Domestic buildings	0.8
b) Hotels	0.7
c) Hospitals	0.5
d) Shops	0.8
e) Offices, schools, factories	1.0
f) Assembly buildings	
occupancy level =< 500	0.8
> 500	0.7

Malhotra also gives a table of basic escape times and correction factors, reproduced in Table A3-13. However, it is not clear how the times and factors in this table correspond to those in the two previous tables.

Table A3-13 Basic escape time and correction factors, taken from Malhotra [9]

	Unprotected zone	Partially protected zone
Basic time t_e (minutes)	2.0	4.0
Human factor H_f (see 4.45)	0.5–0.8	0.5–0.8
Compartment size (see 4.44)	1.2	1.2
Smoke control – natural	1.0	1.0
mechanical	1.1	1.1
pressurization	1.15	1.15
Fire detection	1.2	1.25

Applying Table A3-11 and a value of 0.8 for H_f from Table A3-12 for domestic (residential) buildings gives design escape times of:

A. Unprotected/fire zone = 2×0.8 = 1.6 min
B. Partially protected zone (i.e., the common corridor)
   - Natural smoke control = 5×0.8 = 4.0 min
   - Pressurization or mechanical extract = 10×0.8 = 8.0 min
C. Fully protected zone (i.e., stairs)
   - Natural smoke control (no lobby) = 30×0.8 = 24.0 min
   - Natural smoke control (with lobby) = 45×0.8 = 36.0 min
   - Pressurization or mechanical extract = 60×0.8 = 48.0 min

A3-5.1.3 Grenfell Tower

The following paragraphs have been extracted from the expert witness testimony of Dr Barbara Lane to the Grenfell Tower Inquiry [48] regarding the smoke conditions within areas of the building as a function of time.

2.8.3 *On the 14th June 2017, a fire started in the kitchen of Flat 16, on Level 4 of the tower.*

2.8.4 *The first call to London Fire Brigade is recorded at 00:54. By 01:14, the internal kitchen fire broke out of the top portion of the kitchen window,*

2.13.13 *The fire in the building impacted the stairs on all levels between 4 to the top Level 23. There is substantial evidence of early smoke spread in multiple lobbies at Levels 05 & 06, 15 & 16 before 01:18 and subsequently lobbies deteriorated on upper levels after this time.*

2.13.14 *Based on the available witness statements, it appears that between 01:40 and 01:58 the conditions worsened within the stairs and lobbies. Thick smoke with low to zero visibility is described as filling the stair. It is described as becoming increasingly hot below Level 20. Additionally, lobbies on levels 6 -10, 14, 19, and 20 are all described as being smoke filled. Lobbies on Levels 6-10 are described as containing smoke hotter than the stair.*

2.13.15 *Between 01:59 and 02:58, some lobbies, in particular at Level 10, are described in the witness statements as 'incredibly hot'. The stair at Level 10 is also described as 'boiling hot' at this level with thick heavy smoke between Levels 7 to 12.*

2.13.19 *In general, from 00:55 to 01:30 the stairs appear to have been free of smoke and therefore tenable for escape.*

2.14.8 *Between 01:39 and 01:58 the evacuation rate slowed significantly from 5.5 people/minute to 1 person/minute. In this time period, 01:39 and 01:58, some LFB crews accessing the tower were still advising residents to stay in their flats or in another flat on that floor, consistent with the Stay Put policy. Only 20 people escaped. The highest floor escaped from in that time period was Level 20. 18 residents that escaped in this time period were from Level 11 or below.*

2.14.9 *Between 01:59 and 02:58 the rate of evacuation slowed even further, a total of 24 people which is 0.4 persons/min: this is now only 10% of the flow rate in the first 40 minutes of the fire event. At this time, some lobbies, in particular Level 10 are described as 'incredibly hot'. The stair at Level 10 is also described as 'boiling* *hot' at this level with thick heavy smoke between Levels 7 to 12. The people who were able to evacuate, and importantly willing to evacuate in such conditions, came from multiple floors, from Level 3 to 23. In that hour the same numbers of people escape from above or in the hot zone (12 people), has did from below the hot zone, a total of 24 people.*

Paragraph 2.8.4 records that the first call to the London Fire Brigade (LFB) was at 00:54 and therefore this can be assumed to be the 'zero time'. Paragraph 2.13.13 notes smoke spread into specific lobbies by 01:18 (i.e., 24 min) after the call to the LFB. Paragraph 2.13.19 of Dr Lane's evidence also noted that the stairs remained clear up to 01:30 (i.e., 36 min) after the call to the LFB. Finally, Paragraph 2.14.9 states that the lobbies and stairs around 01:59 were 'hot', suggesting both were compromised at 65 min. However, it is further informative to note that residents willing and able to evacuate from Grenfell Tower were still using the stairs around 2 hr after the initial call to the LFB. Thus, representative times at which residents were likely hindered or blocked by heat / smoke during the Grenfell Tower fire are given in Table A3-14.

Table A3-14 Times (in minutes) from the start of the fire at which evacuation was hindered or compromised by heat / smoke at Grenfell Tower, adapted from Lane [48]

Enclosure type	Hinder	Compromise
Flat (1)	n/d	n/d
Corridor (2)	24	65
Stair (3)	36	65

n/d = no data

In addition to the expert witness statements of Dr Lane, there are also the comments made by Prof. David Purser as part of his verbal testimony on 29 June 2022 in which he notes that

"– *there was a clear considerable delay in smoke filling the lobby, particularly on the – these are mainly on the lower floors, but not all of them. The 18th floor, for example, was one where there was a good 20 minutes or so before the lobby became filled with smoke*."

This 20-minute delay in smoke filling is similar to the findings of Dr Lane, albeit Prof. Purser's comment infers that smoke filling may have been initiated at some point prior to the 20-minite mark. When Table A3-14 is compared to Table A3-10 it is clear that the times given by Proulx et al. are less than the findings from Dr Lane although the margin of difference between the corridor and stair hinderance times are similar.

A3-5.1.4 Approved Document B

Approved Document B (AD B) provides recommended minimum periods of fire resistance for flat, corridor and stair fire-rated enclosures as a function of trigger height. From the discussion in Section A3-2.4 it is suggested that it is reasonable to assume that the characteristics of a fire in a flat are independent of building height. This principle is followed by AD B since it gives 30 min ratings to doors (flat entrance doors, cross-corridor doors and stair doors) irrespective of enclosure type and building height unless in the case of a firefighting stair where the door into the stair enclosure is to be rated to 60 min. Firefighting stairs are recommended for buildings above 18 m, noting that in a building with multiple stairs, they may not necessarily all be firefighting stairs, but it is common to have 60 min stair doors in buildings above 18 m tall from a design perspective.

As a building gets taller, a greater number of occupants are likely to be present and therefore understandably consideration should be made from a risk perspective to an increased level of fire resistance. AD B specifies minimum periods of fire resistance for structural and separating elements in blocks of flats that increase as a building height increases. These increasing minimum periods impact on the required separation protection between the floor and stairs. Thus, minimum periods of fire resistance can be inferred as those given in Table A3-15. Caution must be exercised in treating fire resistance times as times to the onset of hazards as this is generally not a recommended practice. Fire resistance ratings are achieved through a standard test under a specific time-temperature curve that may under- or over-estimate the conditions depending on factors such as ventilation, boundary conditions, etc.

Table A3-15 Minimum periods of fire resistance (min) from Approved Document B for specified trigger heights

Enclosure type	Up to 18 m	18 m to 30 m	>30 m
Flat	60	60	60
Corridor	60	60	60
Stair	60	90	120

In addition to mitigating the spread of fire through the provision of fire resistance it is also necessary to mitigate smoke propagation. This is addressed by the requirement to restrict smoke leakage using smoke seals via an ‘S’ classification to the performance of doors. The testing regime applied to the ability of a fire door to mitigate smoke movement would suggest it is independent of its fire resistance rating.

It is unclear whether the expectations expressed by Proulx et al. [47] between corridor and stair doors are relative to their fire resistance rating, e.g., a 30 min rating for the corridor and 60 min for a stair (i.e., assumes the smoke performance is a third of the fire resistance rating). Alternatively, the difference might be a function of location where an apartment door is likely to be directly exposed to a fire whereas a stair door will be remote. Either way, this does suggest that stair doors may have a better relative performance over other doors and this is reflected in the work of Proulx et al. [47] as expressed in Table A3-10 and somewhat the findings from Dr Lane expressed in Table A3-14.

A3-5.1.5 Analysis

The times as to when occupants are hindered from escaping and then when the paths become compromised are derived from Table A3-10, however the table does not give a times for ‘h1’ and ‘c1’. In the case of the flat of fire origin, p. 2394 of the SFPE Handbook [46] suggests that "...*even the most rapidly growing flaming fires take approximately 3 min to reach levels of heat and gases hazardous to life*…" which might point towards ‘h1’ in Table A3-10 as being 3 min. For simplicity the value for ‘c1’ is taken as twice the hindrance time. It is important to note though that there is not necessarily an expectation that occupants in the flat of fire origin will have sufficient time to escape. For example, C/VM2 [18] states that

> “…*the fire engineer does not have to demonstrate that tenability is maintained for occupants within the enclosure of fire origin.*”

The times shown in Table A3-16 represent the movement times of smoke from the fire flat to connected and remote spaces within the building. The time to affect the remote stair assumes there is separation between the corridor on the fire floor. There is an assumption that there is no effective smoke control in the common corridors or the stair/s. The times do not account for any impact that the FRS may have on smoke movement during their operations which might include opening doors, using portable smoke curtains, or interacting with a smoke control system. Furthermore, there is no consideration for effective firefighting by the FRS.

The critical design escape times derived from Malhotra provide more challenging values than obtained from Table A3-16 and this is where Malhotra also includes the contribution from natural or mechanical smoke control measures in the partially and fully protected zones. However, this analysis assumes failure of such systems (see Section A3-5.1). Compared to the Forest Laneway fire, Table A3-16 gives a hinderance time for stairs between 33 min (t4) and 53 min (t9), i.e., when between 80% to 90% of occupants saw smoke on the stairs (from Figure A3-17).

Dr Lane's Grenfell Tower Inquiry evidence (Table A3-14) suggests that there was early smoke spread into some of the lobbies around 24 min into the fire and the stairs remained clear for 36 min. In comparison, Table A3-16 suggests hindrance times after 13 min for the corridor on the fire floor (t2), 53 min for other corridors (t5) and 33 min for the stairs (t4). It was further expressed by Dr Lane that conditions within the corridors and stairs probably became untenable after 65 min. Table A3-16 gives compromise times for corridors as between 26 min on the fire floor (t2) and 86 min on other floors (t5). For the stairs, the compromise time in Table A3-16 is 56 min (t4). Thus, the times in Table A3-16 provide times that bracket those from the findings in Dr Lane's evidence in which hindrance and compromise times in the corridor on the fire floor occur prior to that at Grenfell Tower, hindrance and compromise times in the stairs are 3 min and 9 min shorter, whereas hindrance and compromise times in the remote corridors are around 20 min to 30 min longer.

It is therefore proposed that the values given in Table A3-16 be used in the evacuation simulations as indicative times at which agents are slowed by smoke (i.e., when the smoke hinders movement) and agents are no longer able to use an escape path (i.e., when a route becomes compromised). Given the discussion in Section A3-5.1.4 on smoke mitigation, these times are to be applied to buildings of any height or dimensions. One exception to Table A3-16 in the simulations is when the flat of fire origin is compromised after 6 min. For the simulations it is assumed the flat of fire origin remains in a hindered state, otherwise agents in the flat of fire origin almost always cannot evacuate the space where any form of pre-evacuation delay is applied. There is debate within the literature on whether it is reasonable to anticipate that occupants 'intimate' with the fire will be able to successfully reach a place of safety. For example, the International Fire Engineering Guidelines [49] note that they do not "*apply to those situations where a person is, either accidentally or intentionally, intimate with the fire ignition or early stages of development of a fire; building fire safety systems are not generally able to protect such persons*." The expectation of building design for the occupants of the compartment of fire origin is beyond the scope of this project.

Table A3-16 Selected for times (in minutes) at which evacuation is hindered or compromised by heat / smoke accounting for movement within the building

	Hinder (H)	Compromise (C)
t1: Fire flat	3	6
t2: Corridor on fire floor Fire in flat (t1) Smoke to enter corridor (h2, c2)	 3 10 = 13	 6 20 = 26
t3: Flats on fire floor Smoke to go from flat to corridor (t2) Smoke to go from corridor to flat (h2, c2)	 13 10 = 23	 26 20 = 46
t4: Stair connected to corridor on fire floor Smoke to go from flat to corridor (t2) Smoke to go from corridor to stair (h3, c3)	 13 20 = 33	 26 30 = 56
t5: Corridors remote from fire floor Smoke to go from corridor to stair (t4) Smoke to go from stair into corridor (h3, c3)	 33 20 = 53	 56 30 = 86
t6: Flats remote from fire floor Smoke to get into corridors remote from fire floor (t5) Smoke to enter flats (h2, c2)	 53 10 = 63	 86 20 = 106
t7: Separated corridor on fire floor* Smoke to go from flat to corridor (t2) Smoke to go from corridor to separated corridor (h3, c3)	 13 20 = 33	 26 30 = 56
t8: Corridor separated flat on fire floor Smoke to separated corridor (t7) Smoke to go from corridor to flat (h2, c2)	 33 10 = 43	 56 20 = 76
t9: Stairs separated by a corridor on fire floor Smoke to separated corridor (t7) Smoke to go from corridor to stair (h3, c3)	 33 20 = 53	 56 30 = 86

*Cross-corridor doors are assumed to have performance equivalent to stair doors, based on these having no direct fire load in the vicinity (compared to flat doors), and being within the landlord demise with respect to maintenance.

Although the comparison made here is between the fire that largely spread over the outside of Grenfell Tower versus an assumed internal fire, the effect on the smoke conditions within the building are similar. Therefore, even if the smoke spread pathways are different between Grenfell Tower and the assumed smoke movement used in this work, the outcome is a challenging scenario for occupant evacuation. As a result, it is assumed herein that investigating a separate external fire is not a key scenario to consider. Given that the changes to Regulation 7 of the Building Regulation for England mean only materials meeting Class A1 or Class A2-s 1,d0 in accordance with BS EN 13501-1:2007+A1:2009 are acceptable then an incident such as Grenfell Tower should not occur in future new high-rise residential buildings.

A3-5.2 Automatic detection and alarm systems

Although the analysis presented in Section A3-5.1 is focused on the movement and effect of smoke on occupants it can also serve other purposes, namely the activation of fire protection systems and any effects on fire and rescue service (FRS) personnel. It is not generally within the scope of this study to simulate the specific interactions between the fire, the residents and FRS personnel as this is the subject of the parallel work being undertaken by the University of Central Lancashire (UCLan). However, the time at which smoke is deemed to hinder residents can serve as a (likely conservative) proxy for the time of smoke detector activation. The 3 min (180 s) hinderance time in the flat given by Table A3-16 corresponds to the upper range of times from Tan et al. [31]. Similarly, the compromise time of 6 min can serve as a proxy for the time of heat detection systems. Likewise, the hinderance time of 13 min and the compromise time of 26 min for the common corridor are used for smoke and heat detection times respectively outside the flat.

Since the smoke development and movement scenarios exclude smouldering fires and those in which fires have a long incipient phase then it could be argued that the benefits of automatic smoke detection and alarm systems are not represented to their full potential. In such situations it is probable that detection and alarm will occur well in advance of there being a hazard to occupants. For example, the work by Spearpoint et al. [50] illustrates how detectors can detect smoke from smouldering polyurethane foam well ahead of the onset of hazardous conditions. It is also important to note that the performance of automatic detection has been considerably simplified in this analysis by only considering heat or smoke indicators. Modern automatic detections systems include multi-sensor detectors and sophisticated algorithms that can enable reliable, fast detection whilst minimising nuisance activations. However, simulating such systems is a complex undertaking particularly where the algorithms are often proprietary. Finally, it has been assumed in this analysis that an automatic detection and alarm system is fully operational in the event of a fire and therefore no failure likelihood has been included. Yashiro et al. [51] used a reliability of 0.945 in their study based on data from the Tokyo Fire

Department (1987-1996). Whether this reliability reflects the current situation has not been investigated further herein.

When considering how automatic smoke and heat detection systems can be used to raise an alarm within the building there are various factors – the type of detectors (i.e., smoke or heat), where the detection is located (i.e., in the flats and/or placed in common areas such as the corridor outside the flats), and where the alarm is raised. In some scenarios the expectation is that the alarm is restricted to the flat of fire origin whereas a detection system could initiate an alarm to other parts of the building, the whole building and also to notify building management and/or the fire and rescue services. Figure A3-18 illustrates these combinations.

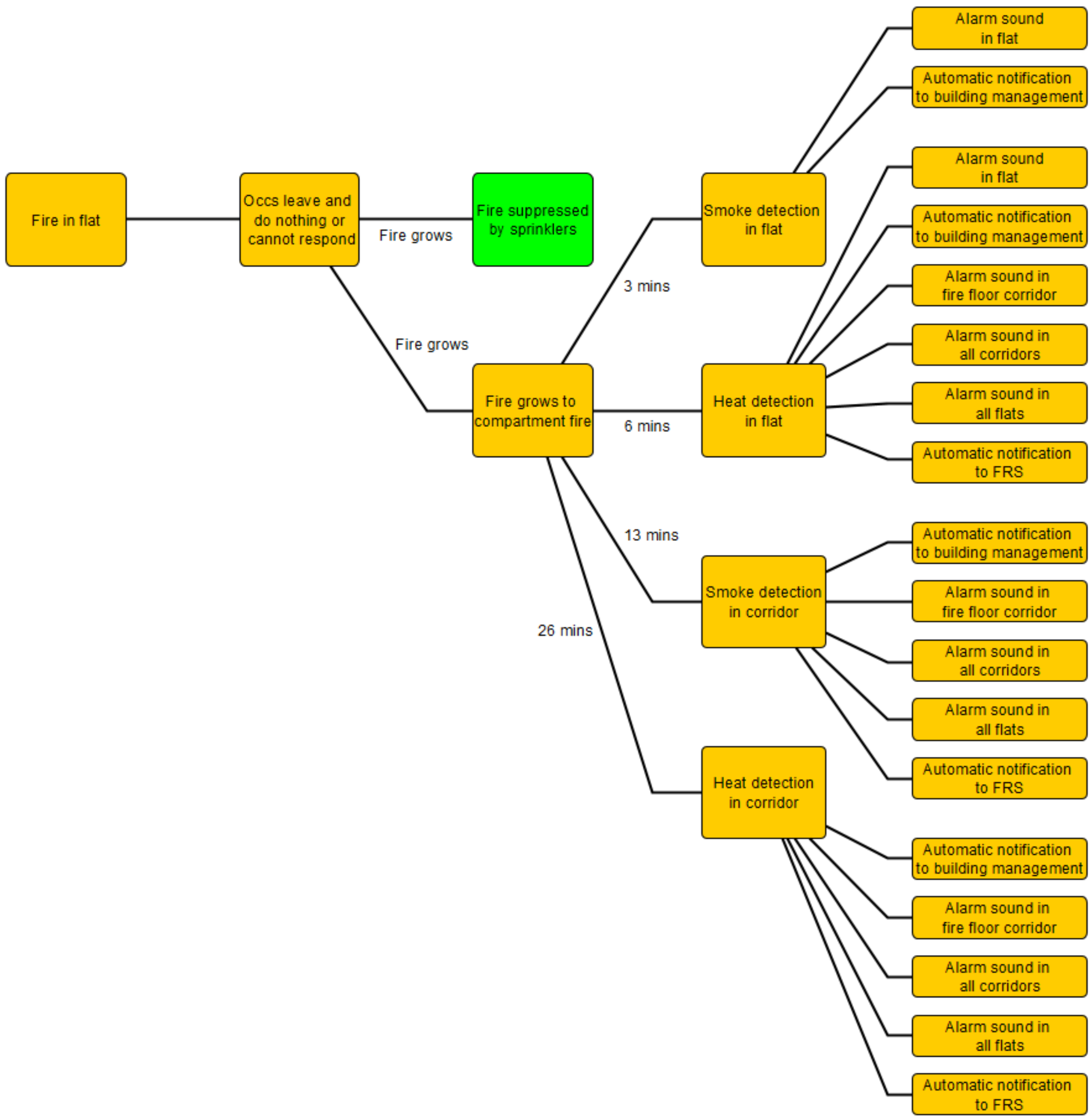


Figure A3-18 Automatic fire detection and alarm system configurations

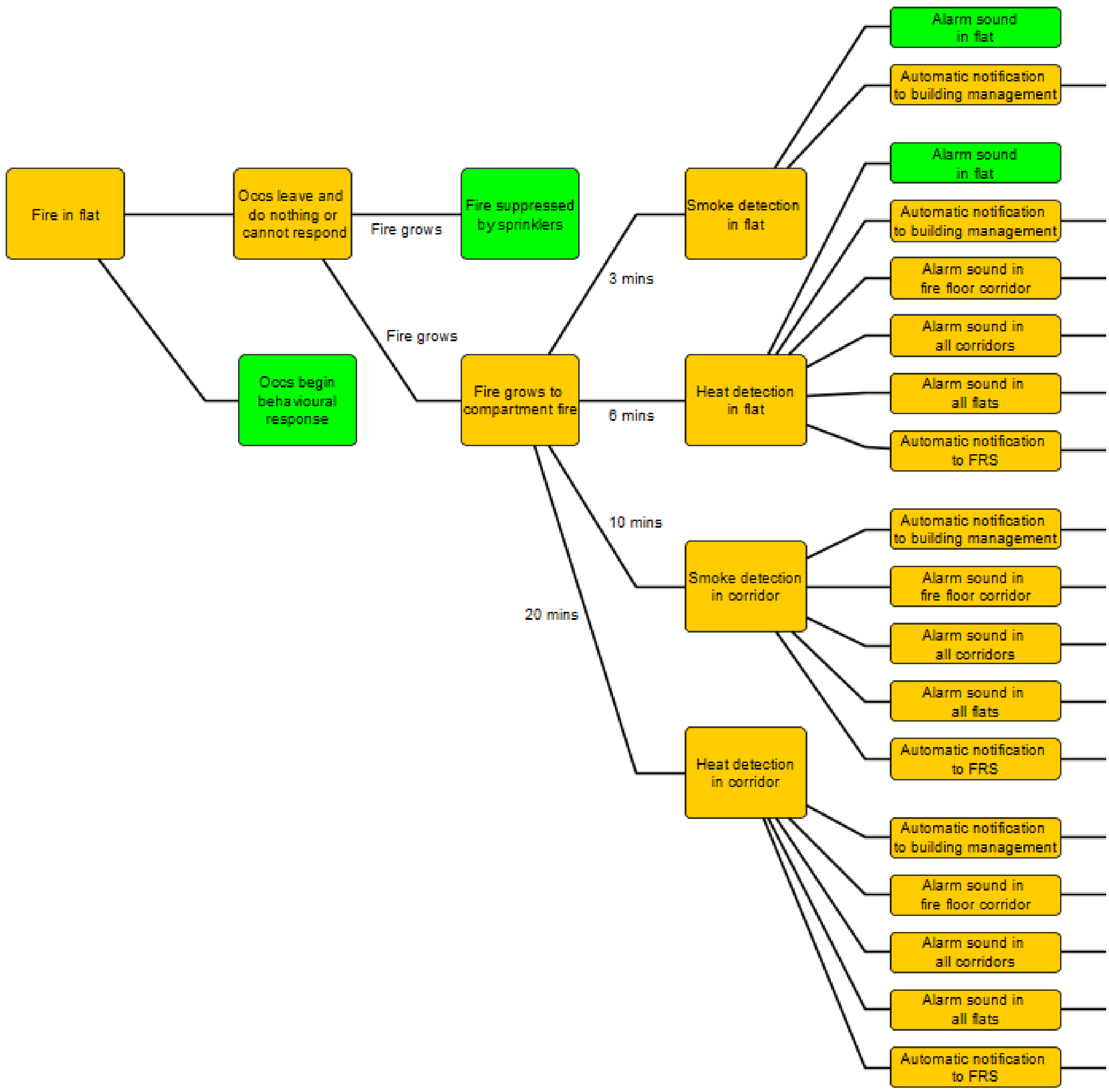
An example of a detection and alarm system configuration might be that given in Technical Guidance Document [52] published in Ireland which states:

> “*In addition to alarms within individual dwellings, in a building containing flats where the flats are accessed by common protected corridors / lobbies / stairways, a common fire detection and alarm system should be provided. It should be designed to provide adequate warning in the case of fire. This system should not be connected to any alarms within individual dwellings provided in accordance with 1.5.5 or 1.6.3(d).*
>
> *It should consist of:*
>
> > *(i) a heat detector in each flat, located adjacent to the entrance door to the flat,*
> >
> > *(ii) a sounder in each flat, meeting the requirements of EN 54-3, located in the circulation area, not more than 5 m from any bedroom door,*
> >
> > *(iii) smoke detectors and sounders in all common escape routes*…”

and also

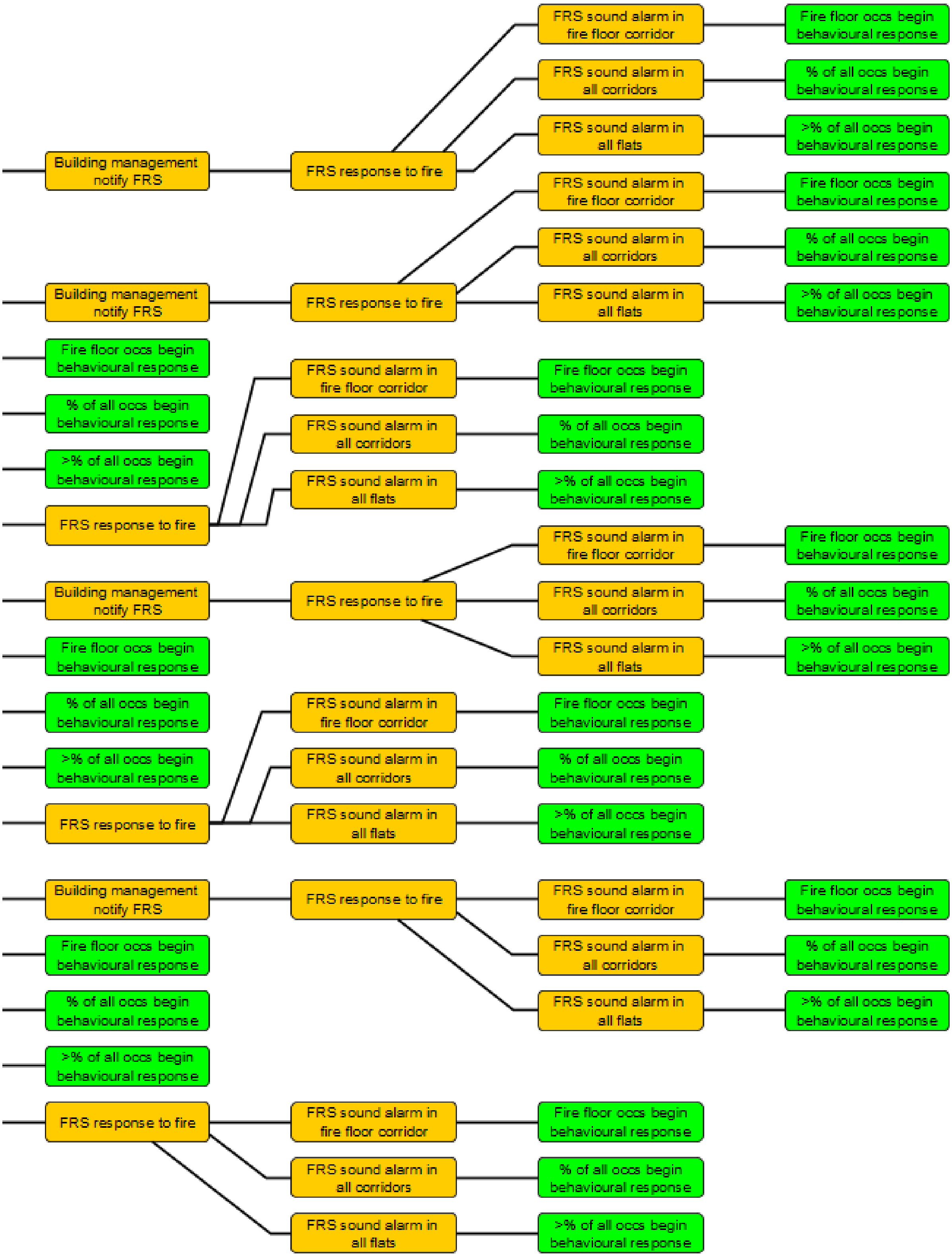
> “…*provide for a means of control so that a pre-determined response leading to the evacuation of the building can be initiated*.”

Once some form of alert is raised then recipients may then decide to initiate additional alerts through face-to-face interactions, via some form of message (social media / text message / telephone call) or by activating a system provided in the building. Figure A3-19 shows how Figure A3-18 can be extended to illustrate the alerting process, and it is clear the process can potentially become fairly complex.



Fire in flat
Occs leave and do nothing or cannot respond
Fire grows
Fire suppressed by sprinklers
Occs begin behavioural response
Fire grows
Fire grows to compartment fire
3 mins
6 mins
10 mins
20 mins
Smoke detection in flat
Heat detection in flat
Smoke detection in corridor
Heat detection in corridor
Alarm sound in flat
Automatic notification to building management
Alarm sound in flat
Automatic notification to building management
Alarm sound in fire floor corridor
Alarm sound in all corridors
Alarm sound in all flats
Automatic notification to FRS
Automatic notification to building management
Alarm sound in fire floor corridor
Alarm sound in all corridors
Alarm sound in all flats
Automatic notification to FRS
Automatic notification to building management
Alarm sound in fire floor corridor
Alarm sound in all corridors
Alarm sound in all flats
Automatic notification to FRS

(a)



(b)

Figure A3-19 Extending the automatic fire detection and alarm alert process to include further notification processes; (a) left half of the tree (b) right half of the tree

A3-6 Modelling approach

A3-6.1 Overview

The goal of the modelling work is to provide insights into the respective impact of different building designs, fire protection measures and occupant movement on the outcome of an emergency evacuation. The scenario space – the potential scenarios that might reasonably occur in residential properties – is vast and is beyond the scope of this (or any) modelling analysis. It is therefore impractical to model every parameter combination given the number of scenarios produced and the functionality of the two modelling tools (i.e., that some scenarios would have been beyond the capabilities of the models employed).

Two computational egress modelling tools are employed in this work, namely Evacuationz and Pathfinder. The basis for the selection of these tools was previously discussed in Appendix A2. Given the different modelling approaches adopted, Evacuationz is primarily employed to scope out the differences around many of the scenarios, while Pathfinder is used to (1) benchmark the Evacuationz simulations, (b) provide specific diagnostic insights into the underlying dynamics of a scenario, and (c) examine scenarios outside the capability of Evacuationz (e.g., the use of evacuation lifts). Similarly, Evacuationz is used to examine scenarios that are outside the capability of Pathfinder when it comes to the interaction between agents and certain fire protection measures. In this section, the parameters listed in Appendix A2 are extended and a representative set of scenarios have been selected to be simulated in the Evacuationz network model. Based on the analysis of the parametric outputs of the Evacuationz model and the known limitations of the model, a sub-set of scenarios to be simulated in Pathfinder and Evacuationz are identified.

The following work process is employed:

- Recognise the extent of the total scenario space – the potential combinations of all options of all parameters,
- Examine baseline cases – the combinations of options identified as baseline cases reflecting basic building designs are stress-tested with simplified evacuee response. The objective is also to better understand where any similarities and differences exist between the output of the two models applied given the relative simplicity of these scenarios,
- Sensitivity analysis – using the baseline cases to assess where there are likely to be scenarios of further interest or where scenarios would not provide significant

further insights. Findings from the sensitivity analysis are used to inform the parametric analysis phase,

- Parametric analysis – conduct a comprehensive study of a combination of building and behavioural factors to identify where certain conditions lead to potentially beneficial outcomes. The analysis is primarily undertaken in Evacuationz with selected scenarios benchmarked against Pathfinder, and

- Diagnostic analysis - further investigation of specific scenarios by conducting a diagnostic analysis of a reduced set of scenarios of interest using the specific capabilities of Pathfinder or Evacuationz where appropriate.

A3-6.2 Modelling phases

The modelling is broken down into four stages (see Figure A3-20). These employ the Evacuationz and Pathfinder models to generate insights according to the objectives set for each stage – be it stress-testing the building designs, exploring parameter changes on evacuation performance, a broad analysis of representative conditions or a deep-dive into the underlying conditions. Each of these stages is now described in the following sections.

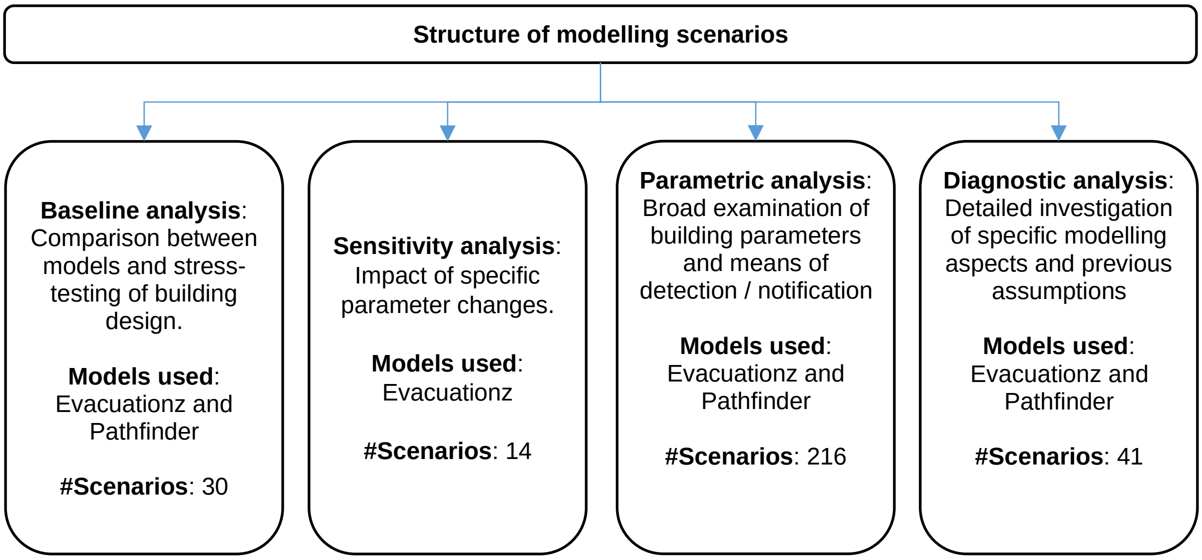


Figure A3-20 Overview of modelling process

A3-6.2.1 Baseline analysis and scoping

As the Pathfinder and Evacuationz models simulate the evacuation process from different perspectives, i.e., flow-based evacuee movement and individual evacuee movement, the models are first compared using a series of Baseline scenarios before they are employed in the proceeding stages of analysis. **The objective is to better understand any differences that exist between the simulated output, the impact of introducing data on these results and explore how the two models**

might be most effectively deployed on the scenarios of interest. This is similar to the approach taken by Ronchi and Nilsson [53]. **In addition, assuming suitable confidence in model equivalence has been created (as explored in the Baseline scenarios), these scenarios stress-test the capacity of the building designs examined given that the occupant population is assumed to respond simultaneously / move uniformly and therefore place maximum demand on the egress capacity present.** These scenarios are not realistic per se, in that the occupant population will respond so uniformly or immediately; however, the conditions represented likely generate the maximum levels of congestion – showing potential demand issues and allowing comparison congestion levels produced where initial responses are more distributed. Although not realistic, the simplicity of these scenarios allows specific factors to be examined in isolation with a reduced set of assumptions being made.

The Baseline scenarios (B1–B30) are outlined in Table A3-17. Evacuationz and Pathfinder are used to simulate all these scenarios and the results are presented in Section A3-7.

A3-6.2.2 Sensitivity analysis

Following on from the Baseline scenarios, Evacuationz has been employed to examine the sensitivity of the simulated results to changes to the underlying scenario conditions and the stability of the results produced given the number of simulations conducted. Given there are so many scenarios that could be modelled there is a need to determine which are most valuable to include in the Parametric scenario analysis, i.e., which represent sufficiently different scenario conditions such that they provide useful insights. **The objective of this Sensitivity scenario analysis is to analyse selected scenarios exclusively using Evacuationz to investigate the sensitivity of inputs and to therefore identify the scope of the parametric simulation phase.** Table A3-18 summarises the Sensitivity scenarios. For this objective, the building design is held constant to reduce the ‘scenario space’ examined - limited to the ground floor plus six storeys (18 m high), single stair configuration with the 15 m corridor and seven flats per floor (see Floorplate 1 in Section A3-2.1) with two agents per bedroom (196 occupants). It is assumed that the agents always follow the desired behaviour conditions, e.g., they always respond to an automatic alarm system. Such cases would be similar to the expectations of AD B as the guidance does not consider situations in which occupants do not follow the expected fire strategy. The impact of having agents either evacuating or not is investigated in the Diagnostic scenario simulations (see Section A3-6.2.4).

Table A3-17 Baseline scenarios (B1–B30) and associated attributes

Baseline scenario	Building parameters					Occupancy level	
	Building height (m)	No. of stairs	Stair width (m)	Corridor length (m)	Amenity spaces	No. of residents	No. of visitors
B1	11	1	1	15	-	140	0
B2	18	1	1	15	-	196	0
B3	30	1	1.1	15	-	308	0
B4	140	1	1.1	15	-	1456	0
B5	18	1	1.5	15	-	196	0
B6	18	1	2	15	-	196	0
B7	11	2	1	15	-	140	0
B8	18	2	1	15	-	196	0
B9	30	2	1.1	15	-	308	0
B10	140	2	1.1	15	-	1456	0
B11	11	1	1	30	-	420	0
B12	18	1	1	30	-	588	0
B13	30	1	1.1	30	-	924	0
B14	140	1	1.1	30	-	4368	0
B15	11	2	1	30	-	420	0
B16	18	2	1	30	-	588	0
B17	30	2	1.1	30	-	924	0
B18	140	2	1.1	30	-	4368	0
B19	18	1	1	15	Low (F1)	196	60
B20	18	1	1	15	Mid (F3)	196	60
B21	18	1	1	15	High (F6)	196	60
B22	18	2	1	15	Low (F1)	196	60
B23	18	2	1	15	Mid (F3)	196	60
B24	18	2	1	15	High (F6)	196	60
B25	18	1	1	30	Low (F1)	588	180
B26	18	1	1	30	Mid (F3)	588	180
B27	18	1	1	30	High (F6)	588	180
B28	18	2	1	30	Low (F1)	588	180
B29	18	2	1	30	Mid (F3)	588	180
B30	18	2	1	30	High (F6)	588	180

Table A3-18 Sensitivity scenarios (S1–S14) and associated attributes

Sensitivity scenario	Parameter assessed	Variations	Report section
S1	Number of simulations	5, 10, 20, 50, 100, 200, 300 and 500 repeated simulations	A3-8.2
S2 – S3	Output metric (mean vs 80th percentile)	Corridor detection, flat detection	A3-8.3
S4	Presence of smoke	No smoke in building, smoke hindrance effect from t = 0 s	A3-8.4
S5 – S7	Location of smoke	Fire at ground, third floor, sixth floor with smoke hindrance effect on fire floor and above	A3-8.4
S8 – S11	Location of detection and alerting mechanism	Smoke detection in corridor; heat detection in flat. Global building-wide tone and voice alert *	A3-8.5
S12 – S14	Effect of inter-agent communication: fire location	Fire at ground, third floor, sixth floor with floor-by-floor agent communication	A3-8.6

* Additional scenarios of smoke detection in flat and heat detection in the corridor will be considered, noting that both are likely to be impractical in reality.

A3-6.2.3 Parametric analysis

The objective of the Parametric analysis is to give a comprehensive set of results for the key scenarios of interest in which the impact of the building parameters (e.g., building height, number of stairs) and the means of detection / notification are assessed in representative conditions. Scenarios have been developed for the different floorplate variations given in Section A3-2.1 and building heights given in Section A3-2.2. This phase also considers the different means of detection and alerting that have been discussed in Sections A3-4.8.2 and A3-5.2. As with the Sensitivity analysis, it is assumed that the agents always follow the expected behaviour conditions. Smoke spread throughout the buildings has been modelled in the scenarios in line with Section A3-5.1.5 such that different areas in the buildings become hindered and compromised at the corresponding times given in Table A3-16.

Table A3-19 sets out the building parameters that have been varied in each scenario. For each scenario (e.g., P1), the same set of detection and notification conditions have been considered, resulting in six sub-scenarios (e.g., P1A, P1B, etc.). This produces a total of 144 scenarios generated by the combination of the variables examined. The notification and detection variables are described in Table A3-20. The inclusion of amenity spaces as discussed in Section A3-2.1 has also been considered in this analysis, resulting in a further 24 scenarios. The design of this part of the parametric analysis was informed by the Baseline analysis regarding amenity spaces, as discussed in Section A3-7.2.4, where it was shown that the location of the amenity space (e.g., low, middle or high) does not have great bearing on the total evacuation time. However, the total evacuation times marginally increase when the amenity space is higher up the building. Therefore, the Parametric analysis considers scenarios where the amenity space(s) are located on the top storey of the building.

Table A3-19 Parametric scenarios (P1A–P28F) examined and associated attributes

Parametric scenario	Building parameters					Occupancy level	
	Building height (m)	No. of stairs	Stair width (m)	Corridor length (m)	Amenity spaces	No. of residents	No. of visitors
P1A–P1F	11	1	1.0	15	-	140	0
P2A–P2F	11	1	1.5	15	-	140	0
P3A–P3F	11	1	2.0	15	-	140	0
P4A–P4F	11	1	1.0	30	-	420	0
P5A–P5F	11	2	1.0	15	-	140	0
P6A–P6F	11	2	1.0	30	-	420	0
P7A–P7F	18	1	1.0	15	-	196	0
P8A–P8F	18	1	1.5	15	-	196	0
P9A–P9F	18	1	2.0	15	-	196	0
P10A–P10F	18	1	1.0	30	-	588	0
P11A–P11F	18	2	1.0	15	-	196	0
P12A–P12F	18	2	1.0	30	-	588	0
P13A–P13F	30	1	1.1	15	-	308	0
P14A–P14F	30	1	1.6	15	-	308	0
P15A–P15F	30	1	2.2	15	-	308	0
P16A–P16F	30	1	1.1	30	-	924	0
P17A–P17F	30	2	1.1	15	-	308	0
P18A–P18F	30	2	1.1	30	-	924	0
P19A–P19F	140	1	1.1	15	-	1456	0
P20A–P20F	140	1	1.6	15	-	1456	0
P21A–P21F	140	1	2.2	15	-	1456	0
P22A–P22F	140	1	1.1	30	-	4368	0
P23A–P23F	140	2	1.1	15	-	1456	0
P24A–P24F	140	2	1.1	30	-	4368	0
P25A–P25F	18	1	1.0	15	High (F6)	196	60
P26A–P26F	18	1	1.0	30	High (F6)	588	60
P27A–P27F	18	2	1.0	15	High (F6)	196	180
P28A–P28F	18	2	1.0	30	High (F6)	588	180

Table A3-20 Means of notification investigated in the Parametric scenarios

Parametric sub-scenarios	Description of means of detection and notification
A	'Tone' pre-evacuation* distribution instigated at t = 0 min
B	'Agent' pre-evacuation* distribution instigated from inter-agent (floor to floor) social communication starting with fire flat occupants (see Section A3-4.8.2 for response probabilities and Section A3-8.6 for further discussion on the method)
C	'Tone' pre-evacuation* distribution instigated from corridor smoke detection at t = 13 min (see Section A3-5.1.5)
D	'Voice pre-evacuation* distribution instigated from corridor smoke detection at t = 13 min (see Section A3-5.1.5)
E	'Tone' pre-evacuation* distribution instigated from flat heat detection at t = 6 min (see Section A3-5.1.5)
F	'Voice' pre-evacuation* distribution instigated from flat heat detection at t = 6 min (see Section A3-5.1.5)

* The pre-evacuation distribution adopts either the component or implied values, subject to the model that is used (i.e., component in Evacuationz and implied in Pathfinder).

A3-6.2.4 Diagnostic analysis

The objective of the Diagnostic scenario modelling is to examine in more detail some of the evacuation procedure effects and the underlying factors that influence them, based on the findings from previous simulations. For example, the Sensitivity scenarios assume that agents always respond to notification from automatic alarms or other agents; the Parametric scenarios assume the response outlined in Section A3-4.8. In the Diagnostic analysis the effect of this assumption is investigated. In cases where not all agents are willing or able to fully evacuate then the percentage of agents remaining in the building is discussed. The Diagnostic modelling also demonstrates how various levels of complexity can be introduced using some of the specific capabilities of Evacuationz such as where the effect of an automatic detection and alarm system can be combined with agent interaction. For this phase the building has generally been held constant – limited to the ground floor plus six storeys (18 m tall), single stair configuration with the 15 m corridor and seven flats per floor (see Floorplate 1 in Section A3-2.1). However, different occupant loadings are considered across some scenarios, and other building configuration have been assessed in Scenarios D32–D40.

Table A3-21 summarises the Diagnostic scenarios investigated, however the specific building configurations etc. are discussed in the relevant report sections. As result of their specific capabilities Scenarios D1 to D26 used Evacuationz and Scenarios D24 to D40 used Pathfinder.

Table A3-21 Diagnostic scenarios

Diagnostic scenario	Parameter assessed	Variations	Report section
D1–D4	Body size and stair width	1.0 m and 1.5 m wide stairs. Body size is varied according to the assumed nature of the impairment	A3-10.2.1
D5–D8	Presence of MIP (formed from MDP and MRP)	Presence or not of Movement Dependant Persons (MDP) and Movement Reduced Persons (MRP) where smoke detection is in the common corridor	A3-10.2.2
D9–D11	Pre-evacuation delay and MIPs	Implied, component and no pre-evacuation delay; presence of MIPs (see Sections A3-4.5 and A3-4.6)	A3-10.3
D12–D14	Notification response and proportion of population choosing to evacuate	Limiting to an 80% alert response probability to tone and voice alarms. Alert response coupled with inter-agent communication	A3-10.4
D15–D17	Occupant numbers and inter-agent response	Modified occupant numbers	A3-10.5.2
D18	Inter-agent response / Social notification	Reduced likelihood of agent response to communication from other agents	A3-10.5.3
D19	Combined alerting mechanisms	Combined automatic notification and inter-agent communication	A3-10.5.4
D20	Building-wide tone activated by FRS	Variation in FRS arrival time	A3-10.6.2
D21	FRS interaction with building residents	Variation in FRS arrival time	A3-10.6.3
D22–D23	Phased evacuation procedures	Type of notification and floor alert order	A3-10.7
D24–D25	Occupant state in amenity scenarios	Flat occupants awake or asleep, amenity occupants awake	A3-10.8
D26–D31	Lift use and MDP	MDPs have access to no lift, one lift and two lifts	A3-10.9
D32–D40	Floor clearance times	Detection and notification, corridor length, number of stairs	A3-10.10
D41A–F	One or two stairs	One 2.2 m wide stair or two 1.1 m wide stairs	A3-10.11

A3-6.3 Metrics

In general, the metric applied to compare the scenarios is the **total building evacuation time**. This metric is useful where all the occupants have the opportunity to evacuate from the building and the occupants choose to take that action. Total evacuation times are reported in minutes (and fractions thereof) but when doing comparisons between certain scenarios it is sometimes more useful to report times in seconds where the differences are small (especially in the graphs presented). Where occupants choose not to evacuate a building then a metric such **as the percentage of occupants that do evacuate** and at what times provides additional insight into the performance of the evacuation scenario.

In scenarios in which occupants choose to evacuate but are unable to due to the hazard presented by a fire then **the expected number of trapped occupants** may be a relevant metric in combination with the proportion of occupants that do successfully evacuate at different times. To determine the relative benefit of a proposed set of building fire safety measures, the analysis has assessed the number of agents that remain within the building at the critical hazard times as defined by the compromise times discussion in Section A3-5.1. Thus, the total number of trapped agents is the sum of agents remaining in the flats, plus the number of agents in the corridors and stair(s) at times at which each of the areas become compromised by smoke. Care needs to be taken in interpreting the results of the study as the purpose has been to provide a comparative analysis and not to determine absolute numbers. Thus, the numbers of trapped agents are not necessarily assumed to be taken as injuries or fatalities as individuals exhibit different responses to the exposure of smoke and heat. More medically vulnerable occupants are likely less able to withstand the effects of fire than those less vulnerable. Inevitably there is an inherent risk from fires posed to residents in current buildings regardless of the fire safety precautions are provided. This study does not aim to address the level of acceptable risk that exists in current high-rise residential buildings designed to AD B (or older guidance) and the outcomes herein should not be confused with that kind of study. In particular, as discussed in Section A3-5, the test scenarios assume that many of the fire safety features provide no benefit and there is no intervention from the fire and rescue services leading to the fire eventually involving the whole building.

Where scenarios incorporate stochastic inputs, then building clearance times, successfully evacuated occupant proportions and the number of trapped agents will vary for each simulation and so results are expressed as a mean, minimum and maximum values. Section A3-8.3 discusses the applicability of these as metrics.

It is recognised that other metrics could be applied such as corridor clearance times (i.e., when all occupants enter the protected stairs), or congestion levels within the stair. Corridor clearance times are investigated for some specific scenarios in Section A3-7.2.2. Where more refined insights are required, the constituent parts of the evacuation process are reported; for instance, the distances travelled, and the time spent in congestion. Further, in the presence of smoke, the building evacuation performance could be represented as a threshold time to identify the number/proportion of occupants that still might be in danger.

A3-7 Baseline analysis – Scenarios B1 to B30

In this section, the outputs of the two models from running several selected Baseline scenarios are compared to demonstrate the consistency of model predictions under the examined conditions, i.e., the configurations of the simulation cases. The difference between the two models may be used to justify what further analysis (by running Pathfinder simulations) is needed. In addition, once the results are deemed acceptable, the scenarios examined allow the designs to be stress-tested – based on the assumption that the maximum simultaneous demand is placed on the egress components used (e.g., simultaneous response). The findings of these cases also feed into later analysis, supporting decisions regarding the impact of certain factors under the conditions examined.

A3-7.1 Overview

A total of 30 Baseline scenarios are defined in Section A3-6.2.1, varying the five building parameters (building height, number of stairs, stair width, corridor length and amenity spaces) and the corresponding occupancy level. These scenarios are divided into four groups, with each group of scenarios examining the impact of one building parameter: building height, stair width, number of stairs and corridor length, and presence of amenity spaces. Some of these parameter changes are paired given their design (and performance) implications, e.g., number of stairs and corridor length. For each scenario (noting the exception discussed in Section A3-7.2.1 where a single agent is simulated), the occupancy of the building is taken as two occupants per bedroom. The corresponding occupancy levels are given in Section A3-6.2.1 for each scenario, which includes the number of visitors for those scenarios with amenity spaces).

The Baseline scenarios give insight into how varying building parameters (and the corresponding occupancy level) affect the total time to clear the buildings without considering the complex interaction with the other parameters (i.e., fire event, procedural measures, FRS activities, occupant, and response parameters), which are left to the later phases of analysis. Therefore, it is assumed in these scenarios that the occupants immediately and simultaneously start the evacuation procedure and that all occupants move at a fixed walking speed of 1.2 m/s. Clearly the Baseline scenarios are not intended to represent reality; rather, they provide a means to benchmark the predicted times made by Evacuationz and Pathfinder in which a limited number of variables are examined separately, through stress-testing the building design given maximum demand. Given the simplification made in designing the Baseline scenarios (i.e., fixed initial occupant location and unimpeded movement speed, instant evacuation response), there is little variation generated from repeat runs, especially considering that Pathfinder is a deterministic model. Thus, one simulation is conducted for each Baseline scenario in Evacuationz and Pathfinder. The detailed comparison of the simulation results produced by both tools for these scenarios is presented in Section A3-7.2.

The results from the Baseline scenarios have been used to inform the analysis carried out in the subsequent Sensitivity, Parametric and Diagnostic analyses (see Sections A3-8 to A3-10).

A3-7.2 Impact of varying building parameters

A3-7.2.1 Building height

The first group of Baseline scenarios, Scenarios B1–B4, have been designed to examine the impact of varying building height (and the corresponding occupancy level) on the total evacuation time (see Section A3-2.2). These four scenarios are based on Floorplate 1 (see Section A3-2.1), which is comprised of seven flats and a single, 1.0 m wide staircase. The floorplate is duplicated multiple times, separated by a representative storey height of approximately 2.75 m, to give rise to the number of storeys. Four buildings of different number of storeys are modelled in this way in both Evacuationz and Pathfinder (corresponding to the maximum building heights of 11 m, 18 m, 30 m and 140 m).

To examine the consistency of representing the four buildings in both models, the maximum travel distance from the furthest room at the top floor to the final exit on the ground floor is estimated (see Table A3-22). The evacuation time of single occupant travelling at an unimpeded speed of 1.2 m/s along the maximum distance path is also simulated (see Table A3-22 and Figure A3-21). It was found that Evacuationz overestimated the distance travelled by agents on the stairs. Section A3-2.4.3 discusses the reason for and resolution of this in the analysis.

Due to the inherent difference in representing the physical spaces between the two models (e.g., a room is represented as two-dimensional space in Pathfinder while it is represented as a node in Evacuationz), the travel distance estimated in Pathfinder is longer than that in Evacuationz across the two shorter buildings and shorter in the 140 m tall building. There is a maximum 11% difference in travel distances produced for the 140 m tall building represented in the two models. The difference is smaller with the other three building heights. Despite the difference in maximum travel distance, the evacuation times produced by the two models are consistent, with a maximum difference of 14.6% for the 140 m tall building and a minimum difference of 6.8 % for the 11 m tall building. It is unclear why the evacuation times given by Pathfinder are always less than Evacuationz, even though the relative difference in maximum travel distances alters with building height.

Table A3-22 Maximum travel distance and evacuation time of single occupant in Scenarios B1–B4

Scenario*	Building height (m) / Number of levels	Evacuation time (s / min)		Maximum travel distance (m)	
		Evacuationz	Pathfinder	Evacuationz	Pathfinder
B1	11 / G+4	69 / 1.2	64 / 1.1	59	64
B2	18 / G+6	93 / 1.6	82 / 1.4	77	80
B3	30 / G+10	129 / 2.2	118 / 2.0	111	111
B4	140 / G+51	562 / 9.4	480 / 8.0	477	425

* These scenarios are comparable to Scenarios B1–B4; however, with a single agent.

The four buildings were then populated with two agents per bedroom within the buildings (in line with the scenarios described in Section A3-6.2.1). Under the assumptions that the occupants immediately start the evacuation procedure and move with a fixed unimpeded walking speed, both models predict a similar and linear relationship between the total evacuation time and the building height (see Figure A3-21 and Table A3-22). The maximum difference in total evacuation time is 17.8% for the 11 m tall building and the minimum difference is 1.4% for the 140 m tall building where the difference decreases with building height.

Table A3-23 Total evacuation time of Scenarios B1–B4

Scenario	Building height (m) / Number of levels	Total evacuation time (s / min)		Difference (%)
		Evacuationz	Pathfinder	
B1	11 / G+4	238 / 4.0	202 / 3.4	17.8
B2	18 / G+6	329 / 5.5	284 / 4.7	15.8
B3	30 / G+10	448 / 7.5	427 / 7.1	4.9
B4	140 / G+51	2137 / 35.6	2107 / 35.1	1.4

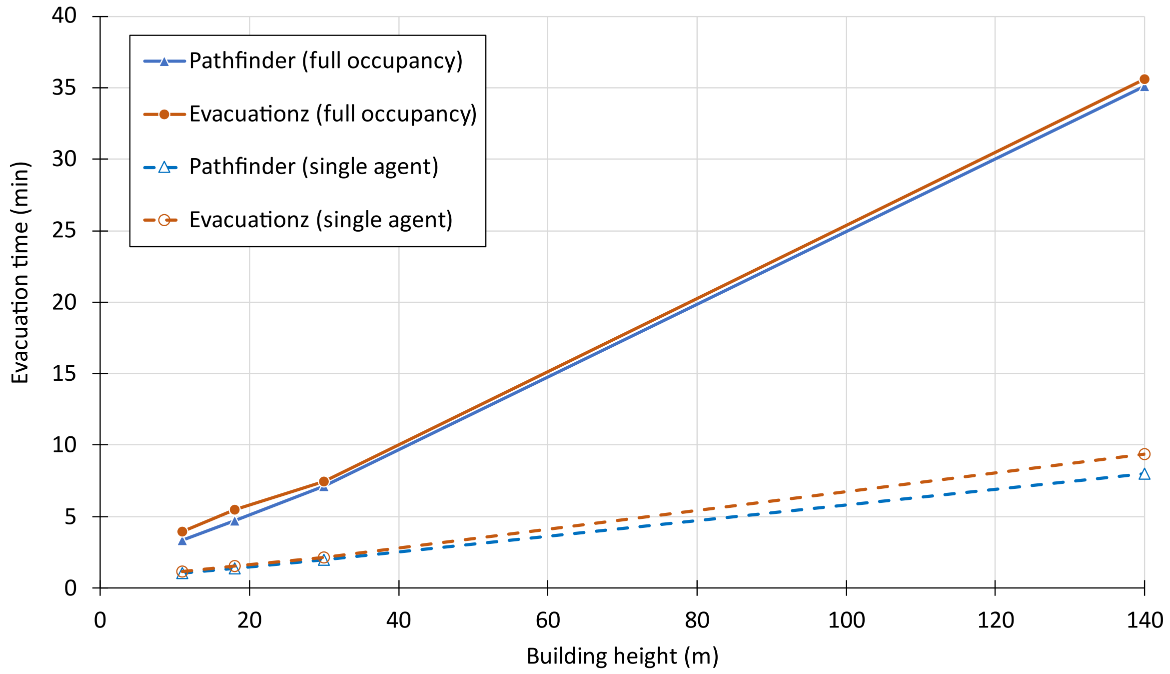


Figure A3-21 The impact of varying building height on total evacuation time

Figure A3-21 shows the comparison of the total evacuation times of the four buildings predicted by the two models. In both loading conditions (i.e., single agent and full occupancy), the total evacuation times produced by Evacuationz are slightly larger for all building heights except the single agent of low buildings. However, the difference is consistent across all four buildings of different height and the general trend lines are largely comparable. When the buildings are at full occupancy the constant of proportionality between total evacuation time and building height is around 0.25.

These results show that the representation of the four building heights in both models produce similar and consistent evacuation performance for individual occupant and a population of the same density – an important basis for further analysis of high-rise residential building evacuation performance when more factors are considered.

A3-7.2.2 Stair width

Scenarios B2, B5 and B6 have been designed to examine the impact of varying the width of the single available staircase on the total evacuation time and corridor clearance time. The impact of stair width would be particularly relevant if demand exceeded stair capacity driving the overall total evacuation time. These three scenarios are based on Floorplate 1, which is composed of seven flats and a single staircase (see Section A3-2). The three buildings in these scenarios have the same height of 18 m and are populated with the same number of 196 occupants (i.e., two occupants per bedroom). The only difference among the buildings is the width of the single staircase, which is increased by 0.5 m from 1.0 m to 2.0 m in these three scenarios.

Figure A3-23 shows the total evacuation time predicted by the two models for the three scenarios, with the times given in Table A3-24. With the increase of the stair width, both models produce a similar trend of improvement in total evacuation time: the improvement when the stair width increases from 1.0 m to 1.5 m is larger than that when the stair width increases further from 1.5 m to 2.0 m. In the Evacuationz simulations, the total evacuation time decreases by 44% when the stair width increases from 1.0 m to 1.5 m and by 23% when the width increases from 1.5 m to 2.0 m. Similarly, in Pathfinder simulations, the total evacuation time decreases by 60% when the stair width increases from 1.0 m to 1.5 m and by 18% when the width increases from 1.5 m to 2.0 m. On 1.0 m wide stairs agents form one lane of free movement (which could form into two lanes when congested), and they can slow down when merging on landings (see Figure A3-22(a)); while on wider stairs agents form two lanes of free movement. Therefore, wider stairs increase flow capacity and reduce congestion due to merging flows on landings, hence reducing total evacuation time. When the width of stairs increases from 1.5 m (see Figure A3-22(b)) to 2.0 m the flow capacity on stairs is no longer the cap on evacuation performance, but it is the time taken to enter the stairs, i.e., the width of corridor exit doors opening into the stairwell.

(a) 1.0 m wide stair **(b) 1.5 m wide stair**

Figure A3-22 Agent movement on stairs in Pathfinder

These results from Evacuationz and Pathfinder show that the benefit of increasing the stair width in terms of reducing the total evacuation time under the assumptions diminishes when the stair width is more than 1.5 m.

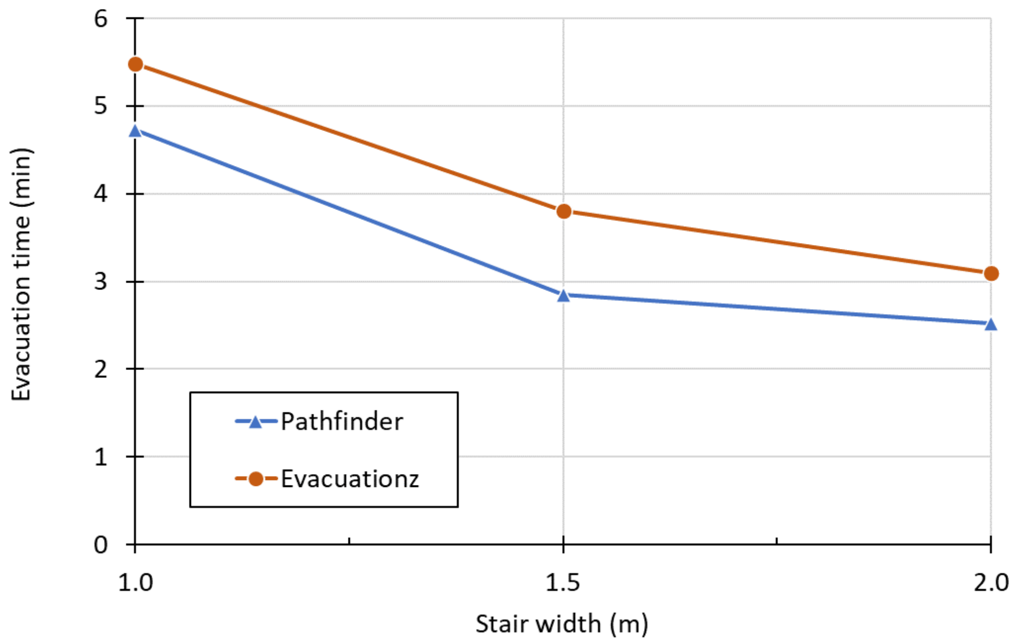


Figure A3-23 The impact of varying single stair width on total evacuation time

Table A3-24 Total evacuation time of Scenarios B2, B5 and B6

Scenario	Stair width (m)	Total evacuation time (s / min)	
		Evacuationz	Pathfinder
B2	1.0	329 / 5.5	284 / 4.7
B5	1.5	228 / 3.8	171 / 2.9
B6	2.0	186 / 3.1	151 / 2.5

The impact of varying the width of the single available staircase on the evacuation is also examined through the corridor and hence the floor clearance time. Figure A3-24 and Figure A3-25 show the floor clearance times of all seven floors of the three buildings with different stair width produced by Evacuationz and Pathfinder, respectively. In Evacuationz, the clearance times of the seven floors connecting the flats to the stairs in Scenario B2 vary widely between 58 s to 76 s with an average value of 66 s, while the floor clearance times in Scenarios B5 and B6 are within a much smaller range between 58 s to 61 s (see Table A3-25). Similar results are also obtained from Pathfinder simulations. The clearance times of the seven floors in B2 vary between 48 s to 88 s with an average value of 73 s, the clearance times in B5 and B6 are within a relatively smaller range between 36 s and 53 s (see Table A3-25).

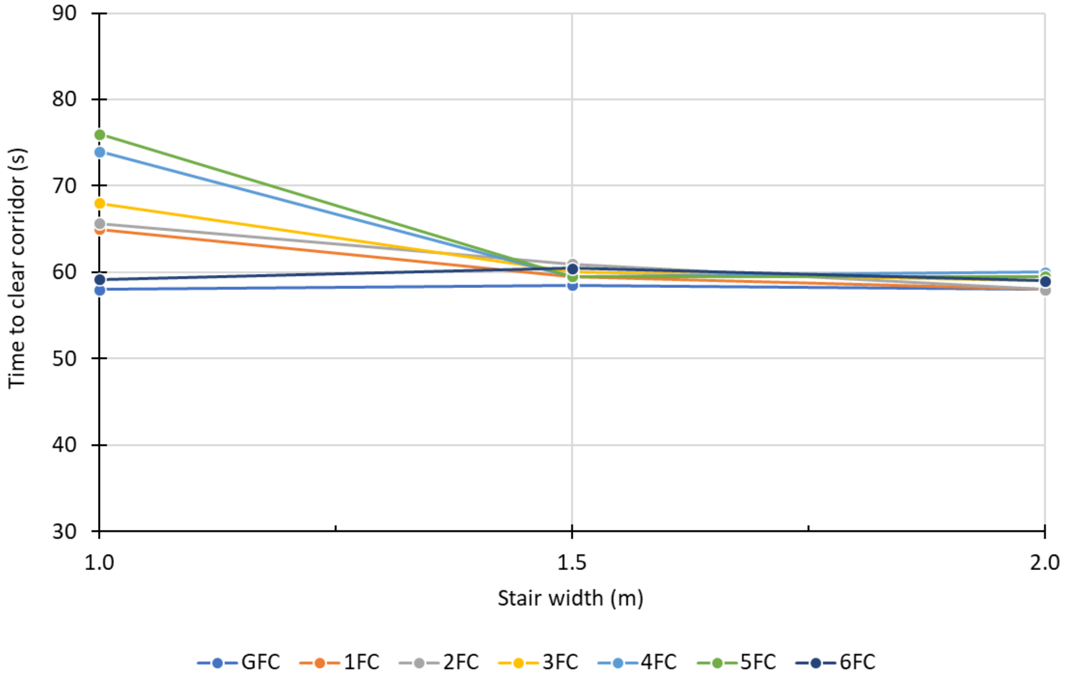


Figure A3-24 Impact of varying single stair width on floor clearance time in Evacuationz (GFC = ground floor corridor etc.)

In the results produced by both models, the floor clearance times of different levels in Scenarios B5 and B6 are broadly similar and are lower than that of Scenario B2. In Scenario B2, the process of clearing the floors between the top floor and the ground floor are hindered by occupants travelling down the stairs at the same time due to the comparatively limited capacity of the 1.0 m wide stair and landing space.

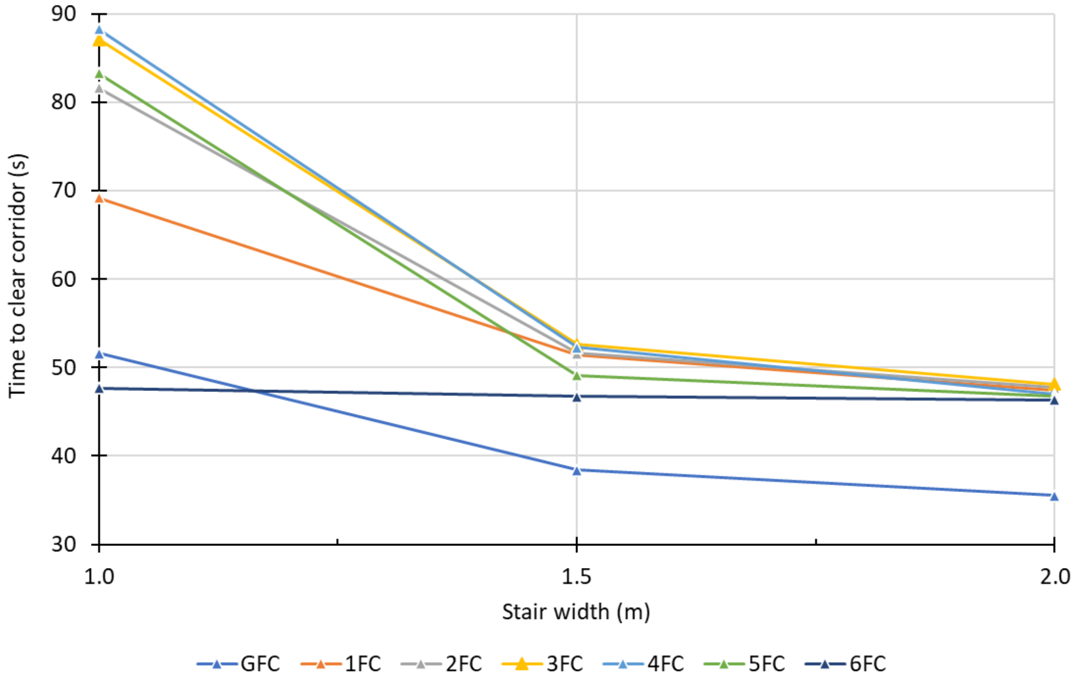


Figure A3-25 Impact of varying single stair width on floor clearance time in Pathfinder (GFC = ground floor corridor etc.)

In B5 and B6, the clearing process for these floors is no longer negatively impacted by the evacuating flow from upper floors since there is enough space to accommodate the occupants joining from each floor. However, the increase of stair width from 1.5 m to 2.0 m produces no more (significant) improvement in terms of floor clearance times compared with the increase of stair width from 1.0 m to 1.5 m. This provides some confidence that the two models are capturing comparable underlying evacuee dynamics in addition to the overall clearance and evacuation times. The variation in the maximum floor clearance times between Evacuationz and Pathfinder with the 1.0 m wide door are thought to be as a result of the different simulation mechanics employed by the two tools. As expected, given that Pathfinder simulates agent interactions in more detail, and requires them to resolve local geometrical conditions, Pathfinder results are more conservative.

Table A3-25 Floor clearance times (in seconds) for different stair widths in Scenarios B2, B5 and B6

Floor number	Scenario B2 (1.0 m)		Scenario B5 (1.5 m)		Scenario B6 (2.0 m)	
	ENZ	PF	ENZ	PF	ENZ	PF
Ground floor corridor (GFC)	58	52	59	38	58	36
1FC	65	69	60	52	58	48
2FC	66	82	61	52	58	48
3FC	68	87	60	53	59	48
4FC	74	88	60	52	60	47
5FC	76	83	60	49	60	47
6FC	59	48	61	47	60	46
Average	67	73	60	49	59	46

ENZ – Evacuationz; PF - Pathfinder

Table A3-25 reiterates the marginal benefits evident by increasing stair widths beyond 1.5 m to 2.0 m, in line with the impact on overall evacuation times.

Stair width not only has the potential to impact the evacuation time but also the stair capacity, as discussed in Section A3-2.4.1. The stair capacity allows the occupants on each floor to fill a stair/landing configuration (while seeking refuge) on the proviso that there is sufficient space with no expectation that the occupants need to have the necessity to move any further. Table A3-26 determines the occupant density in the stairs on each floor for the various building heights, number of stairs etc. as previously shown in Table A3-19. In these calculations it is assumed that boundary layers are not applicable, and the full area is available to the occupants. For the Evacuationz simulations the stair length between each landing and half-landing is fixed at 2.43 m and landings are 1 m long with a width the same as the stair width.

The last four rows include occupants in amenity spaces in which it is assumed these occupants are averaged across all the floors.

Research has shown that in extreme circumstances, occupant densities of 6-8 pers/m^2 might be achievable for short periods of time – although this assumes people are stationary, and often constrains them to be so [54]. However, where movement is required, research suggests densities of approximately 4-5 pers/m^2 to be the maximum sustainable whilst maintaining tolerable conditions. For instance, for the hydraulic model approach discussed by Gwynne and Rosenbaum [6] the maximum density is 3.8 pers/m^2. Table A3-26 can be used to check where the occupant density is problematic for evacuee movement (e.g., exceeds 5 pers/m^2) and to indicate which of the building configurations may not provide sufficient stair capacity for the occupants on that level. As might be expected, those configurations with the 30 m long corridors and a single stair have the highest occupant loads, with the building with two stairs and the amenity space also included in this group.

A hand calculation has been carried out to assess whether some level of congestion occurs when compared to Figure A3-24 and Figure A3-25 obtained from the Evacuationz and Pathfinder simulations. The number of agents per floor on Floorplate 1 is 28, with the corridor travel distance set to 11 m and the width of the door from the corridor to the stairs as 0.85 m. Using the unimpeded walking speed of 1.2 m/s then it would take around 9 s to travel from the furthest flat entrance door to the stair door. The time to flow through the door assuming an effective width of 0.55 m for a 0.15 m boundary layer, and a flow rate of 1.33 pers/s per m effective width is around 38 s, giving a total time of 47 s. This result is similar to the modelling in which the stairs are 1.5 m or 2.0 m wide but the where the stair is 1.0 m then the floor clearance times suggest some congestion between the corridor and stair occurs. Table A3-26 shows that the stair capacity occupant density would be 3.2 pers/m^2 (i.e., close to the 3.8 pers/m^2 limit for the hydraulic model, and also above the default node occupant density of 2.75 agents/m^2 used by Evacuationz).

Table A3-26 Calculated occupant density in the stairs for the different building configurations

Building height (m)	No. of stories	No. of stairs	Stair width (m)	Corridor length (m)	Landing area (m^2)	Stair floor area per storey (m^2)	No. of residents	No. of visitors	Occupants per storey	Occupant density ($pers/m^2$)
11	5	1	1	15	2	8.9	140	0	28	3.2
11	5	1	1.5	15	3	16.3	140	0	28	1.7
11	5	1	2	15	4	25.7	140	0	28	1.1
11	5	1	1	30	2	8.9	420	0	84	9.5
11	5	2	1	15	2	17.7	140	0	28	1.6
11	5	2	1	30	2	17.7	420	0	84	4.7
18	7	1	1	15	2	8.9	196	0	28	3.2
18	7	1	1.5	15	3	16.3	196	0	28	1.7
18	7	1	2	15	4	25.7	196	0	28	1.1
18	7	1	1	30	2	8.9	588	0	84	9.5
18	7	2	1	15	2	17.7	196	0	28	1.6
18	7	2	1	30	2	17.7	588	0	84	4.7
30	11	1	1.1	15	2.2	10.2	308	0	28	2.7
30	11	1	1.6	15	3.2	18.0	308	0	28	1.6
30	11	1	2.2	15	4.4	30.1	308	0	28	0.9
30	11	1	1.1	30	2.2	10.2	924	0	84	8.2
30	11	2	1.1	15	2.2	20.4	308	0	28	1.4
30	11	2	1.1	30	2.2	20.4	924	0	84	4.1
140	52	1	1.1	15	2.2	10.2	1456	0	28	2.7
140	52	1	1.6	15	3.2	18.0	1456	0	28	1.6
140	52	1	2.2	15	4.4	30.1	1456	0	28	0.9
140	52	1	1.1	30	2.2	10.2	4368	0	84	8.2
140	52	2	1.1	15	2.2	20.4	1456	0	28	1.4
140	52	2	1.1	30	2.2	20.4	4368	0	84	4.1
18	7	1	1	15	2	8.9	196	60	37	4.1
18	7	1	1	30	2	8.9	588	60	93	10.4
18	7	2	1	15	2	17.7	196	180	54	3.0
18	7	2	1	30	2	17.7	588	180	110	6.2

A3-7.2.3 Number of stairs and corridor length

The third group of Baseline scenarios investigates the impact of varying the number of stairs and the corridor length (and the corresponding occupancy level) on the total evacuation time. Scenarios have been developed for the four different floorplate variations given in Section A3-2.1 and four building heights given in Section A3-2.2, resulting in 16 scenarios in this group.

Table A3-27 Total evacuation time for different number of stairs and corridor length

Scenario	Building height (m) / Number of levels	Number of stairs	Corridor length (m)	Total evacuation time (s / min)	
				Evacuationz	Pathfinder
B1	11 / G+4	1	15	238 / 4.0	202 / 3.4
B2	18 / G+6	1	15	329 / 5.5	284 / 4.7
B3	30 / G+10	1	15	448 / 7.5	427 / 7.1
B4	140 / G+51	1	15	2094 / 34.9	2107 / 35.1
B7	11 / G+4	2	15	155 / 2.6	121 / 2.0
B8	18 / G+6	2	15	211 / 3.5	175 / 2.9
B9	30 / G+10	2	15	294 / 4.9	251 / 4.2
B10	140 / G+51	2	15	1320 / 22.0	1192 / 19.9
B11	11 / G+4	1	30	588 / 9.8	556 / 9.3
B12	18 / G+6	1	30	858 / 14.3	825 / 13.8
B13	30 / G+10	1	30	1215 / 20.3	1237 / 20.6
B14	140 / G+51	1	30	6232 / 103.9	6251 / 104.2
B15	11 / G+4	2	30	328 / 5.5	306 / 5.1
B16	18 / G+6	2	30	466 / 7.8	436 / 7.3
B17	30 / G+10	2	30	664 / 11.1	671 / 11.2
B18	140 / G+51	2	30	3269 / 54.5	3321 / 55.4

Table A3-27 presents the simulated results from the Evacuationz and Pathfinder models. Providing two stairs decreases the total evacuation time in each scenario due to the availability of another route decreasing congestion in the stairs, compared to the equivalent single stair scenario. Conversely, when the occupant loading is increased as a result of the longer corridor floorplate, the total evacuation time increases in both the single and two stair scenarios due to increased demand on the stair(s). It is useful to compare the total evacuation times from Scenarios B6 and B8 in which the building height and floorplate are the same, but Scenario B6 has one 2 m wide stair versus Scenario B8 having two 1 m wide stairs. The times for Scenario B6 are lower in both Evacuationz and Pathfinder by 13% and 16% respectively and this might be as expected given the effective width of two separate 1 m wide stairs is around 20% less than a single 2 m wide stair (1.4 m versus 1.7 m).

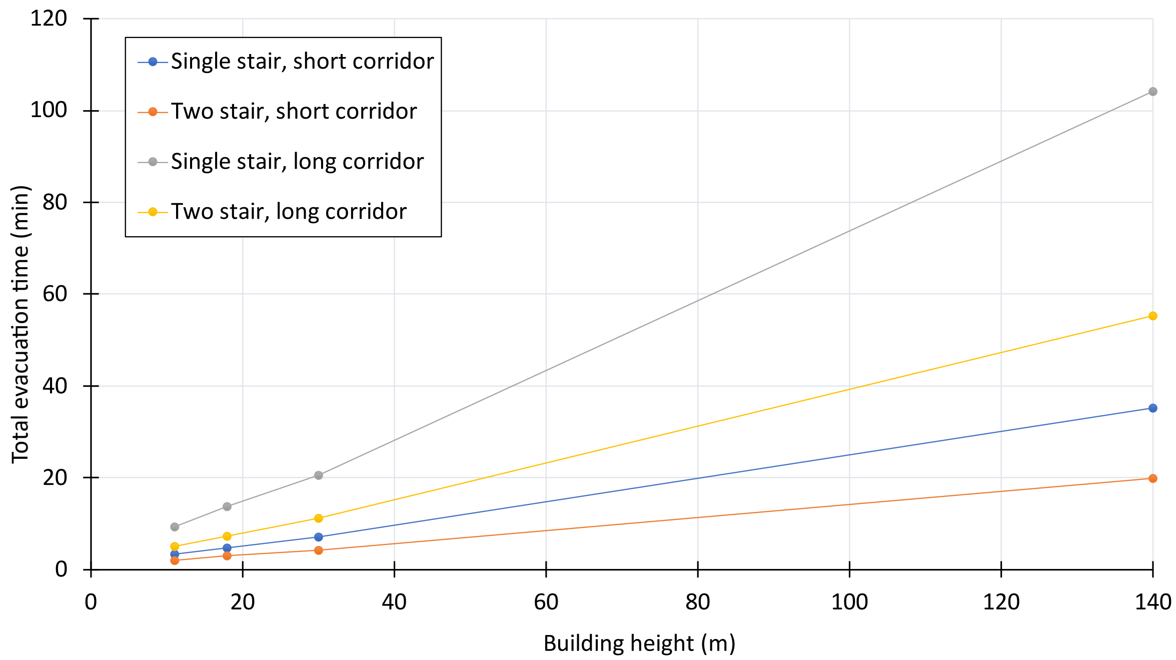


Figure A3-26 Pathfinder results showing the impact of number of stairs and corridor length on total evacuation time

Figure A3-26 plots the Pathfinder results extracted from Table A3-27. This shows the general expected trend of increased total evacuation time vs building height, as well as the trends due to the number of stairs (decreased total evacuation time) and the corridor length (increase in total evacuation time).

In the scenarios with two stairs, the agents do not use the staircases evenly given the location of the flats in relation to the stairs and the manner in which the models allocate residents to their nearest stair. The split in occupancy results in c. 57% of agents using one stair and the remainder the other in both Evacuationz and Pathfinder simulations. Comparing the normalised benefit of two stairs over one (in both the short and long corridor scenarios) yields a comparable decrease in total evacuation time. **The average reduction in total evacuation time through the availability of two stairs over one stair for the short corridor is 65% and 57% for Evacuationz and Pathfinder, respectively, across all building heights. For the long corridor, the average reduction in evacuation time is 55% and 54% for Evacuationz and Pathfinder, respectively.**

A3-7.2.4 Amenity spaces

The fourth and final group of Baseline scenarios considers the inclusion of amenity space (and the corresponding occupancy level) at different locations within the building to understand the impact of this variable on the total evacuation time. Scenarios have been developed for the four different floorplate variations given in Section A3-2.1; however, only for a single building height of 18 m / G+6 storeys. The three different amenity locations considered for each floorplate results in

12 scenarios in this group. The scenario in which a fire starts in the amenity space has not been included in the simulations.

Table A3-28 presents the results of the 12 Baseline scenarios, as well as the respective scenarios with no amenity spaces. As expected, the inclusion of amenity spaces somewhere in the building increases the total evacuation time, when compared to the cases without. This is due to the assumed increase in building occupancy in each of the amenity scenarios. From the results in Table A3-28, it can be concluded that the location of the amenity space does not have great bearing on the total evacuation time, with the time marginally increasing when the amenity space is higher up the building. For example, in Scenarios B25–B27, the change in total evacuation time increases by 3% and 4% from the low-level location to the mid and high-level locations, respectively.

To gauge whether the amenity location impacts corridor clearance times, further investigation has been carried out. Figure A3-27 shows the total evacuation time against the number of agents exited for Scenarios B19–B24. This graph reinforces the conclusion that the amenity location within the building has little bearing on the total evacuation time. Also included in Figure A3-27 are markers noting the time at which the corridor adjoining to the amenity space clears in each scenario. These markers indicate that the corridors generally clear at comparable times, noting that the longer times are when the amenity space is located in the middle of the building (i.e., Scenarios B20 and B23), albeit only marginally.

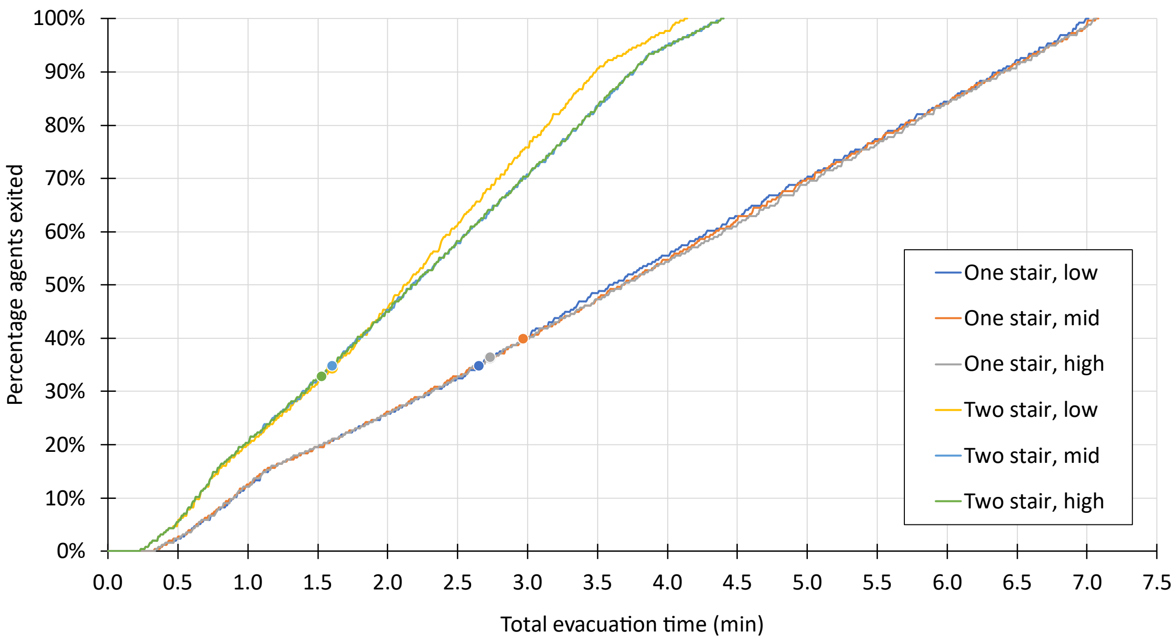


Figure A3-27 Comparison of total evacuation time across Scenarios B19 to B24 with markers identifying the time at which the corridor adjoining to the amenity space clears in the respective scenario

Table A3-28 Total evacuation times for different amenity locations and corridor lengths

Scenario	Number of stairs	Corridor length (m)	Amenity location / number of visitors	Total evacuation time (s / min)	
				Evacuationz	Pathfinder
B2	1	15	None	329 / 5.5	284 / 4.7
B8	2	15	None	211 / 3.5	175 / 2.9
B12	1	30	None	858 / 14.3	825 / 13.8
B16	2	30	None	466 / 7.8	436 / 7.3
B19	1	15	Low (L1) / 60	424 / 7.1	381 / 6.4
B20	1	15	Mid (L3) / 60	423 / 7.1	384 / 6.4
B21	1	15	High (L6) / 60	424 / 7.1	383 / 6.4
B22	2	15	Low (L1) / 60	249 / 4.2	202 / 3.4
B23	2	15	Mid (L3) / 60	264 / 4.4	210 / 3.5
B24	2	15	High (L6) / 60	264 /4.4	223 / 3.7
B25	1	30	Low (L1) / 180	1107 / 18.5	1090 / 18.2
B26	1	30	Mid (L3) / 180	1135 / 18.9	1110 / 18.5
B27	1	30	High (L6) / 180	1150 / 19.2	1105 / 18.4
B28	2	30	Low (L1) / 180	598 / 10.0	592 / 9.9
B29	2	30	Mid (L3) / 180	608 / 10.1	603 / 10.1
B30	2	30	High (L6) / 180	611 / 10.2	576 9.6

A3-7.3 Analysis

Pathfinder and Evacuationz show similar trends when certain geometrical elements are compared (see Figure A3-28). Evacuation times for both models are plotted to show their respective estimates for the Baseline scenarios (B1–B30). The ideal outcome would be where all the plotted points fall on the dashed line – indicating parity. It is apparent that although not ideal, the results show a level of similarity that provides confidence in the performance of the suitably configured and calibrated models.

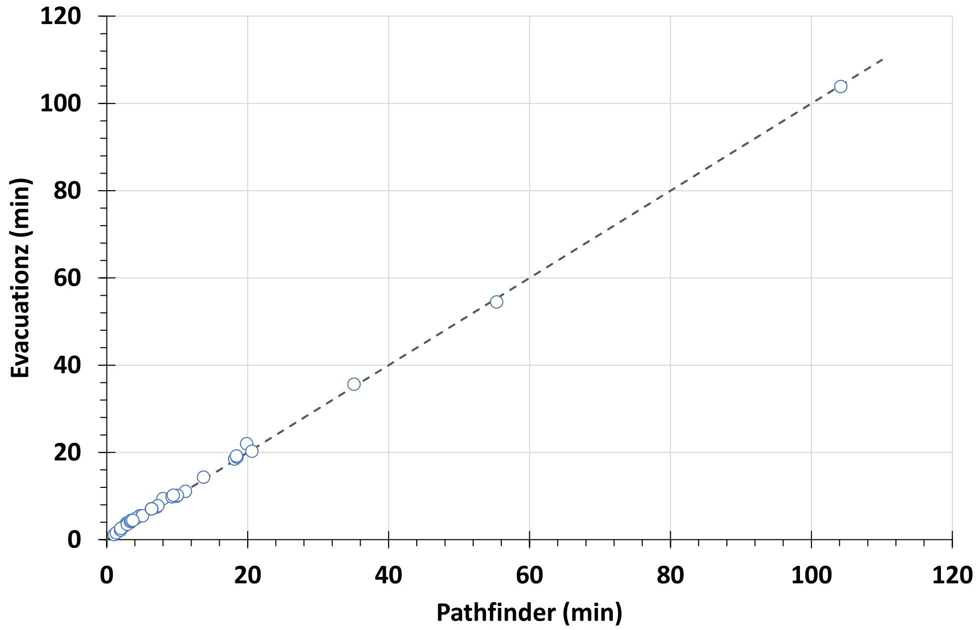


Figure A3-28 Comparison between evacuation times produced by Pathfinder and Evacuationz for Scenarios B1–B30

General findings from the Baseline analysis show that:

- As would be expected with all other things being equal, the taller the building the longer the total evacuation time – moving from approximately 3.5 min (11 m) to 35 min (140 m) for a fully occupied building in which agents respond immediately.
- The occupied building designs produce total evacuation times 3–4 times greater than when an individual is simulated travelling from the most remote location. This indicates that the demands placed on the egress components (and the interactions between evacuees) extend the evacuation time.
- Increasing the stair width from 1.0 m to 1.5 m reduces the total evacuation time by between 30–40%; however, this benefit falls to under 20% when the stair width is further increased from 1.5 m to 2.0 m.
- Assuming that agents use the nearest stair to their flat, the average reduction in total evacuation time through the availability of two stairs over one stair for the short corridor is approximately 60% and 55% for long corridor design, across all building heights**.**
- The inclusion of an amenity space (and the increase in population size) increases overall total evacuation time as the additional number of occupants increases. However, the location of the amenity does not have a clear impact on the results produced.

The Baseline scenarios do not include pre-evacuation delays and therefore exclude a key factor from the actual evacuation performance. These results should be considered optimistic estimates of evacuation performance – although situations which promote the generation of congestion on the egress components employed given the simultaneous demand increasing occupant loading. Whether the total evacuation times are actually the fastest that might be achieved will depend on whether having all the agents simultaneously using the stairs generates sufficient congestion compared with the delay that might be incurred by the inclusion of pre-evacuation delays. There is likely to be an ideal tipping point at which the agent presentation rate to doors to the stairs or the final exit door at which evacuation achieves greatest efficiency.

The evacuation performance given the building height (from Scenarios B1–B4 averaged across model types) is shown in Table A3-29 and Table A3-30. Relative performance is given as the ratio of the total evacuation time for each building height against the 11 m tall building.

Table A3-29Total evacuation times of individual and full population evacuation for building heights across comparable scenarios (B1–B4)

Building height (m)	11	18	30	140
Individual (s / min)	67 / 1.1	87 / 1.5	124 / 2.1	521 / 8.7
Population (s / min)	220 / 3.7	307 / 5.1	438 / 7.3	2122 / 35.4

Table A3-30 Relative performance of individual and full population evacuation for building heights across comparable scenarios (B1–B4)

Building height (m)	11	18	30	140
Individual (min)	1.0	1.3	1.9	7.8
Population (min)	1.0	1.4	2.0	9.6

The full population results are expanded across a wider array of Baseline conditions (beyond those allowing direct comparison with the individual results), including Scenarios B1–B4, B7–B18. It is apparent from Table A3-31 that the results are broadly equivalent with those shown in Table A3-29 and Table A3-30 for the full population evacuations.

Table A3-31 Total evacuation times and relative performance of full population evacuation for building heights across comparable scenarios (B1–B4, B7–B18)

Building height (m)	11	18	30	140
Evacuation time (s / min)	312 / 5.2	448 / 7.5	651 / 10.9	3223 / 53.7
Relative performance	1.0	1.4	2.1	10.3

It should be noted that (a) the full unimpaired population extends the evacuation time indicating that evacuee interaction and the aggregate conditions generated (e.g., congestion) affect arrival time and (b) the population times here might be combined with a pre-evacuation delay representative of the overall population to provide a conservative estimate of the evacuation time for this scenario (e.g., 360 s for a population asleep, without movement impairments assuming a tone alarm system). The evacuation times and relative evacuation performance given stair width is shown in Table A3-32. Evacuation times have been averaged across Evacuationz and Pathfinder results and then compared against the evacuation results generated with a 1.0 m wide stair. It is apparent that there is a 30% reduction in total evacuation times when a 1.5 m wide stair is introduced. The introduction of the 2.0 m wide stair produces only a further 10% reduction in total evacuation time.

Table A3-32 Evacuation times given stair width derived from Scenarios B2, B5 and B6 and relative evacuation performance (normalised to 1.0 m width)

Stair width (m)	1.0	1.5	2.0
Evacuation time (s / min)	307 / 5.1	200 / 3.3	168 / 2.8
Relative performance	1.0	0.7	0.6

As already noted in Section A3-7.2.3, the impact of the number and width of stairs can be examined across Scenarios B2, B6 and B8. This assumes immediate response and unimpaired movement across the population. The results show that without taking into account risk analysis or loss of one stair, two 1.0 m wide stairs (Scenario B8) show similar results to a single 2.0 m wide stair. The 2.0 m width is a little better than two stairs of 1.0 m due to the width efficiency when considering the number of boundary layers.

Table A3-33 Evacuation times and relative evacuation performance given number of stairs and width of stairs derived from Scenarios B2, B6 and B8

Number of stairs (stair width (m)	B2: 1 (1.0)	B8: 2 (1.0)	B6: 1 (2.0)

Evacuation time (min)	5.5	3.5	3.1
Relative performance	1.00	0.64	0.56

A3-8 Sensitivity analysis – Scenarios S1 to S14

A3-8.1 Overview

The purpose of the sensitivity modelling exercise is discussed in Section A3-6. The specific objectives of this section are to:

- Determine the minimum number of simulations needed in the parametric analysis to get representative results given that Monte Carlo sampling is necessary,
- Decide how smoke spread around the building will have the greatest effect on agent movement and how that impacts on floor-to-floor agent interaction,
- Investigate the impact of the location of automatic detection (heat or smoke) and alarm systems (tone or voice alarm notification), and
- Examine the impact of inter-agent communication.

A3-8.2 Number of simulations – Scenario S1

To test convergence of the Monte Carlo simulation runs, Scenario S1 comprises of the 18 m, single stair building with two agents per bed, 80% of which are able bodied and the remaining 20% movement impaired (15% movement reduced persons, MRP, and 5% movement dependent persons, MDP, see Section A3-3). For the test scenario, 100% of agents will respond to a building wide voice alarm following detection in the corridor, with the corresponding component pre-evacuation delay given in Section A3-4.6. The number of simulations has been varied from 5 to 500.

When employing a Monte Carlo approach, generally, the higher number of simulations will give a more representative result, i.e., better reflecting any distributions employed. However, there is a trade-off with computational power and time – the point being that additional resources spent on additional runs may, at some point, not affect the outcome or its stability. For example, the larger buildings (i.e., the 140 m tall building scenarios) have approximate simulation times of 20 minutes. As is shown in Figure A3-29, there is little variance in the result when more than 20 simulations are run for both the mean evacuation time and the 80th percentile evacuation time, indicating that the result has converged from this point.

The outcome of Scenario S1 demonstrates that 20 simulations per scenario should provide a reasonably stable indication of performance and could be considered sufficient for the analysis. However, where practical, 50 simulations are run for each of the Evacuationz scenarios unless otherwise noted. More sophisticated means of comparison are available in the literature such as the work pioneered by Ronchi et al. [55] and then extended by Grandison [56], or the more recent work from Tinaburri [57]. These methods employ various statistical techniques to examine simulation convergence criteria and evaluate the uncertainty resulting from the number of iterations for the same scenario in evacuation model predictions. These techniques are useful in studies where a predefined set of scenarios exists prior to conducting the simulations. However, considering the sequential nature of scenario development in this study, starting from Baseline scenarios and progressing to Diagnostic scenarios, with later scenarios determined only after completing the previous ones, these techniques were likely less applicable. Furthermore, the techniques are not directly implemented in Evacuationz or Pathfinder but could be revisited were additional resources made available.

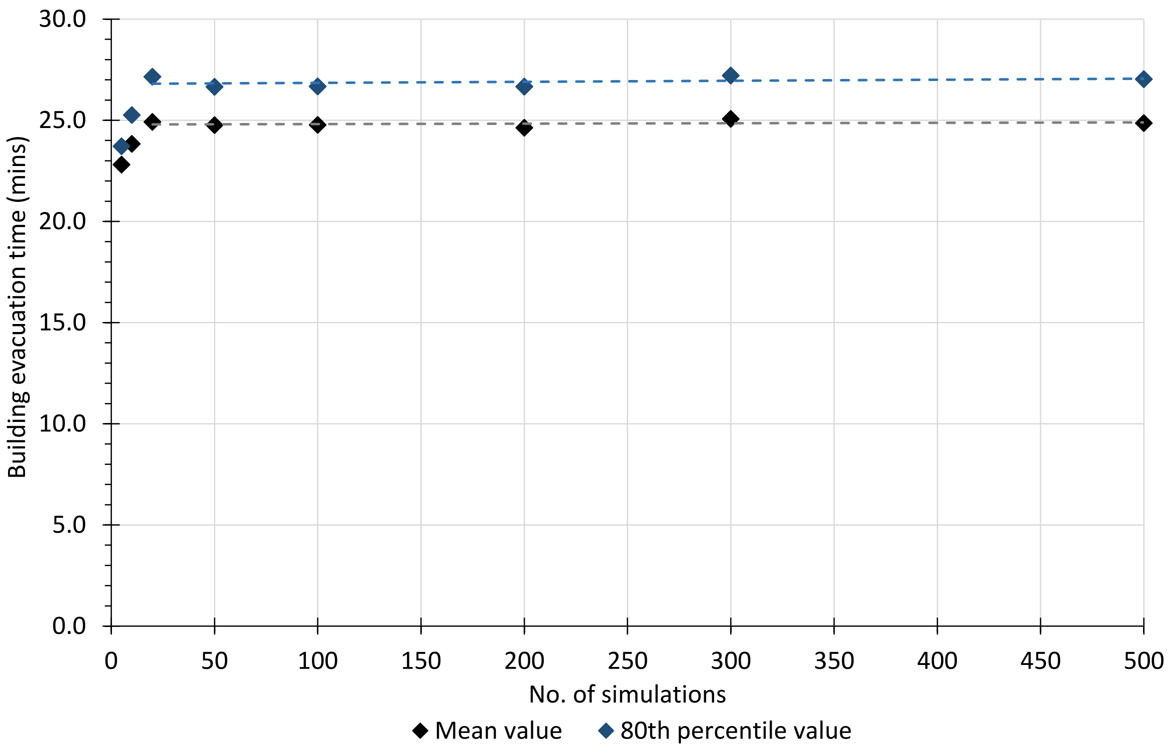


Figure A3-29 Test to show convergence of result for given number of Monte Carlo simulation runs

A3-8.3 Output metric – Scenario S2 to S3

The aim of this sensitivity analysis is to show that assessing the mean value of the total evacuation time of the 50 simulations is a suitable metric when compared to a higher percentile value of the simulations, in this case, the 80th percentile.

Scenario S2 comprises the same building and population definition as Scenario S1, given in Section A3-8.2. Scenario S3 is broadly the same, with the location of the fire detection changing from within the corridor to within a flat. In both scenarios, agents respond with the component pre-evacuation delay for a voice alarm given in Section A3-4.6.

Figure A3-30 shows both the mean and 80th percentile values for Scenarios S2 and S3 for 50 simulations. This shows that the difference between the means of both scenarios and the difference between the 80th percentile values are comparable, suggesting that adopting the mean value of 50 simulations as the basis of the comparative analysis is appropriate, on the premise that the purpose of this work has been to provide a comparative analysis and not to just determine absolute numbers.

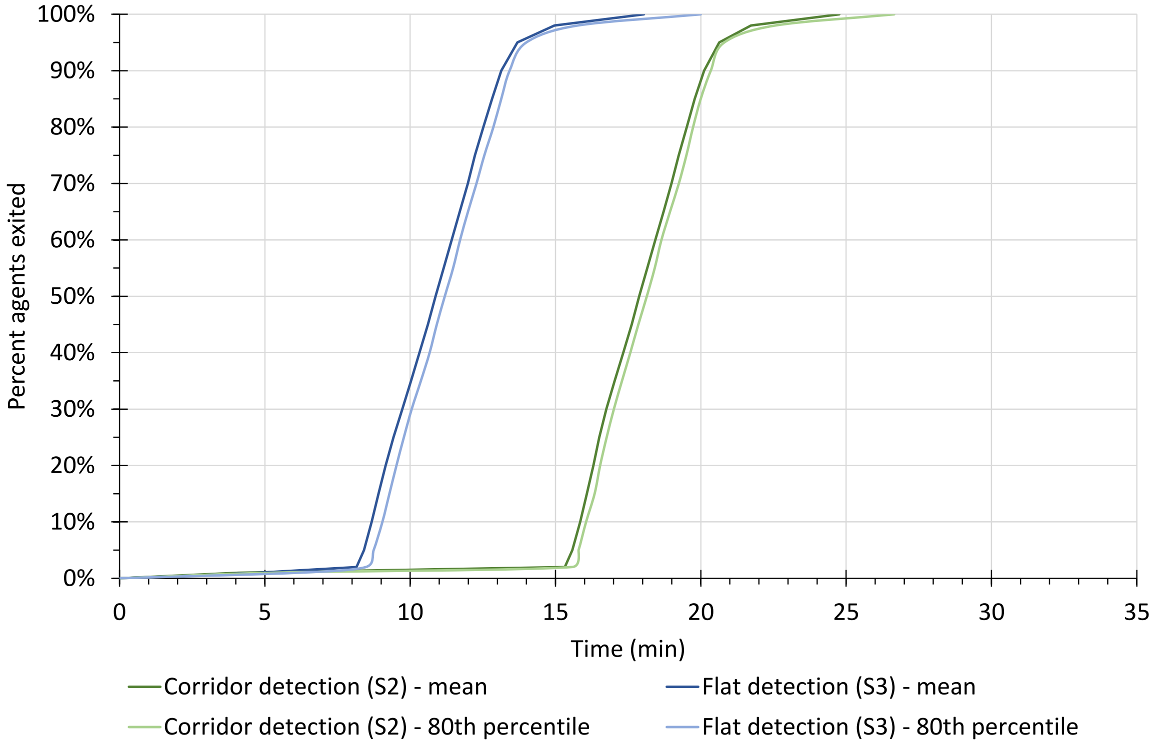


Figure A3-30 Comparison between the mean and 80th percentile values across two scenarios

A3-8.4 Effect of smoke – Scenarios S4 to S7

Scenarios S4 to S7 have been carried out to verify that including the effect of smoke onto evacuee performance into the simulations has the desired effect of slowing agent movement and to define at which floor the flat of fire origin should be assumed to be located. Since the influence of smoke does not have an effect on the corridor adjacent to the flat of fire origin until 13 min, for these simulations smoke at a level that is equivalent to the hinderance criterion discussed in Section A3-5.1 has been introduced throughout the building at time t = 0 s for the 'no pre-evacuation delay' scenario later described in Section A3-10.3 (i.e., effectively shifting the event along the timeline).

Figure A3-31 shows the comparison between the inclusion or omission of the effect of smoke on movement where the presence of the smoke has slowed the agent movement and also introduced a greater level of uncertainty particularly at the tail of the curve. The simulations assume that the fire is on the ground floor so that every node in the Evacuationz building representation has smoke present.

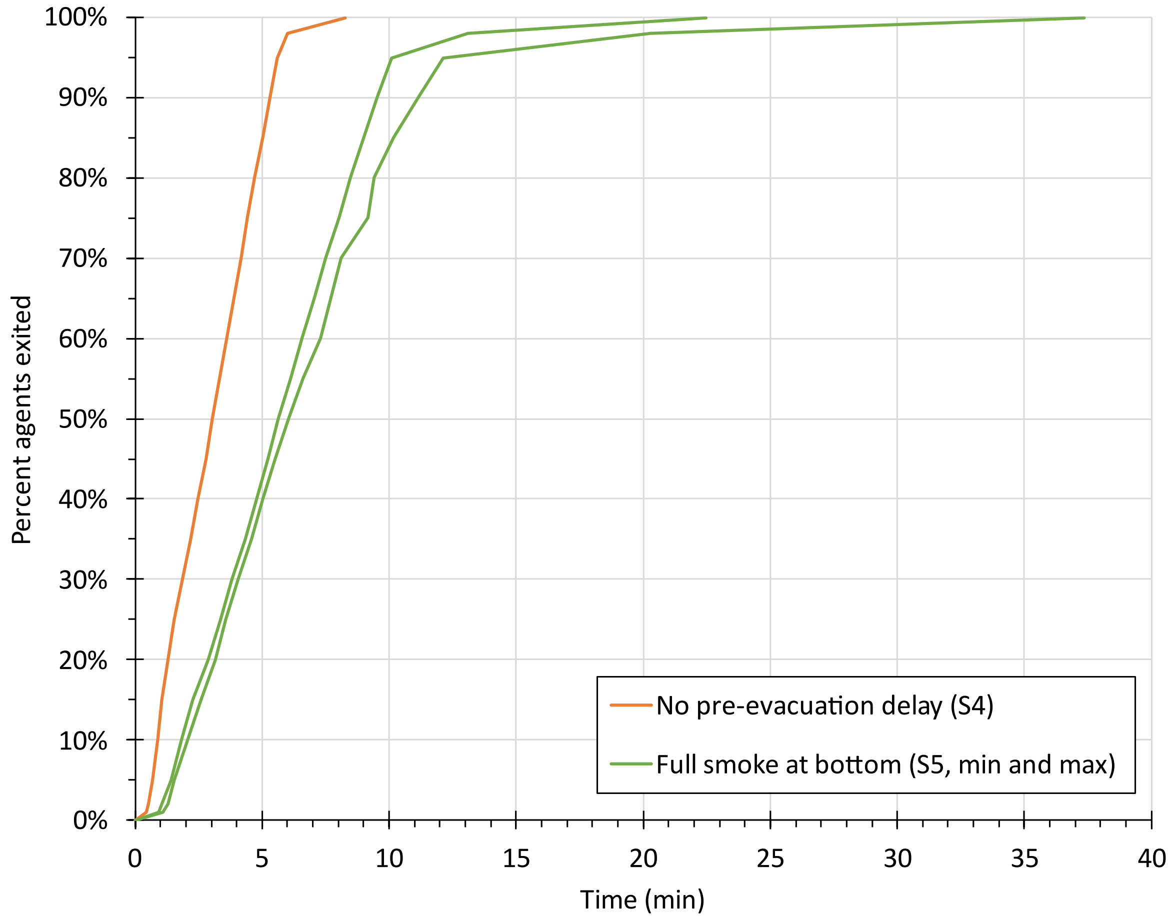


Figure A3-31 Comparison of simulations with no agent pre-evacuation delay, with and without smoke hinderance throughout the building for the whole duration

To examine the effect of fire location it has been assumed in Scenarios S5 to S7 that the location could be at the bottom of the building (as above), on the third (middle) floor, or the sixth (top) floor. To represent the natural buoyancy of smoke should it enter a stairwell the smoke is only located in the nodes on the fire floor and the floors above. The results of 50 simulations for each of the three scenarios is shown in Figure A3-32. As expected, where the fire is assumed to be located lower in the building then the evacuation times are longer as more agents are slowed by the smoke as they move from their flats and into the corridors and stairs.

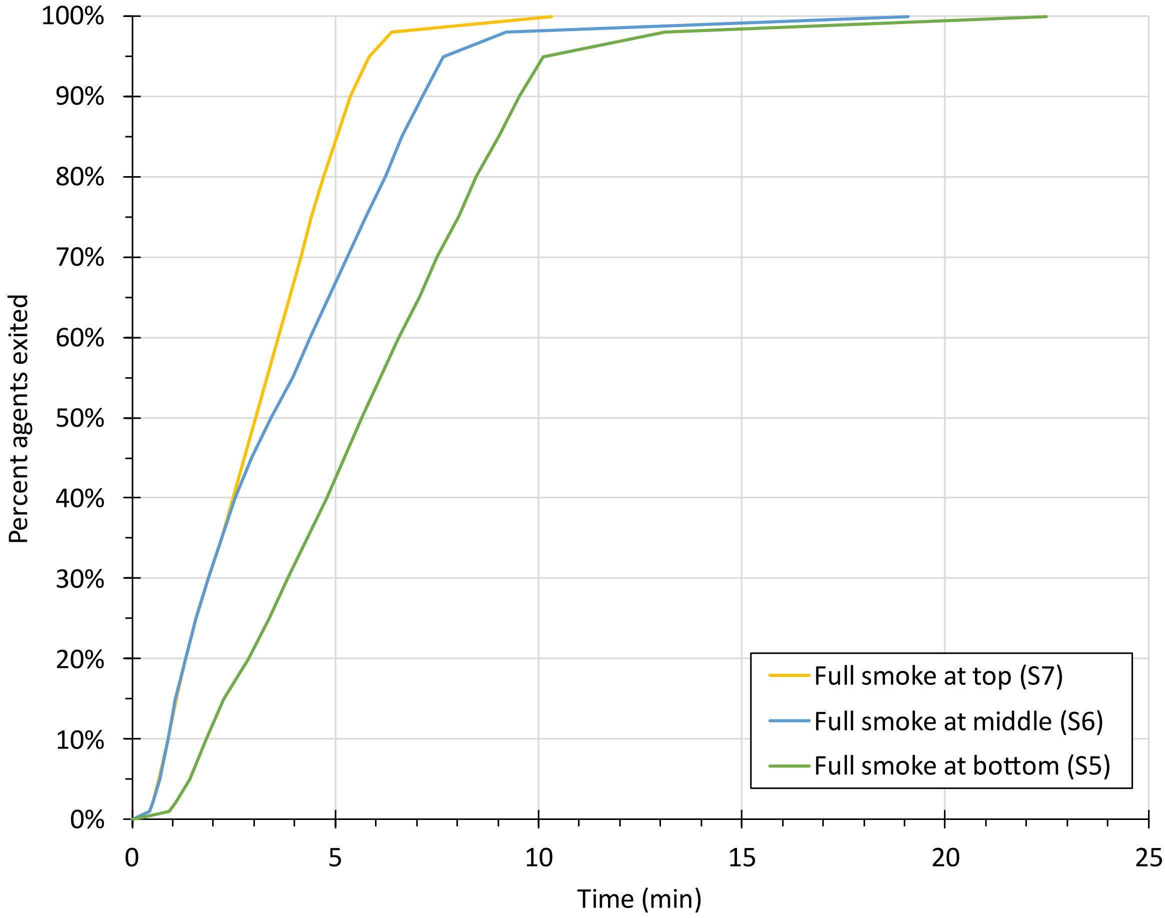


Figure A3-32 Comparison of simulations with no agent pre-evacuation delay, assuming the fire and smoke is located in different parts of the building for the whole duration

The results of the above simulations demonstrate that the introduction of smoke into the building will slow agent movement and so extend evacuation times. Locating the fire on the lower floor causes more agents to be affected by the smoke (leading to longer total evacuation times) than was the case when the fire was on the upper or middle floors. Therefore, it is assumed hereafter in the sensitivity and parametric simulations (Section A3-9) that the fire is located on the ground floor.

Assuming the smoke is the result of a fire on the ground floor also considers circumstances where the movement of smoke in a stairwell is not only due to buoyancy. However, it is recognised that from a fire and rescue service perspective that a fire on a lower floor might be less operationally challenging than a fire on an upper floor even if less of the building could potentially be affected by smoke. Although it would be possible to simulate such scenarios, they are beyond the scope of this research.

A3-8.5 Building-wide automatic fire detection and alarm notification – Scenarios S8 to S11

Scenarios S8 to S11 examine the impact of having different notification systems when detection is located in the common corridor or within the flat of fire origin. Figure A3-33 shows the impact of locating the detection in the common corridor where the alarm is sounded at 13 min. Here the difference between the tone and voice systems is clearly distinguishable – with a difference of over 15 min between the average final evacuation times. This outcome is not surprising given the result largely depends on the alert delays inferred through Table A3-5 for the simulations discussed in Section A3-4.

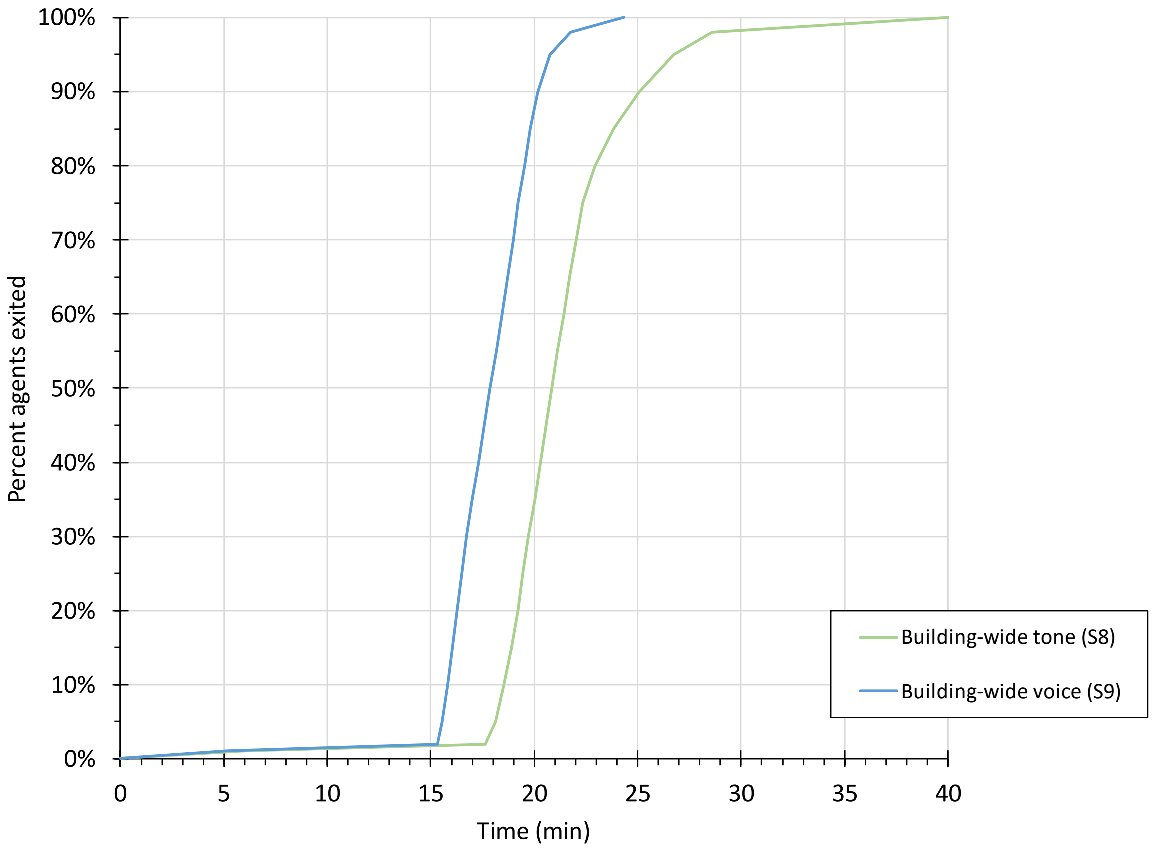


Figure A3-33 Comparison of building-wide alarm activation on smoke detection in the adjacent corridor with results for agents that exit the building without any trapped agents

Results from the simulations show that the use of the tone alarm where smoke is detected in the adjacent corridor to the flat of fire origin results in a small number of agents effectively becoming trapped when the corridor adjacent to the fire flat is taken to be compromised. This is because some agents exhibit extended pre-evacuation delay times that are longer than the assumed time for the corridor to become compromised. Of the 50 simulations, instances of trapped agents occurred in 29 with an average of 1.6 trapped agents per simulation in which at least one occurred, with the maximum being 4 agents in 2 of 29 simulations. No trapped agents occur when the voice alarm is utilised.

An alternative scenario has been run in which the time to heat detection in the fire flat is used to initiate the building-wide alarm, varying the notification type as in the previous S8 and S9 scenarios. As with the use of smoke detection in the common corridor, this matches part of the Technical Guidance Document [52] in Ireland. As discussed in Section A3-5, it is assumed that the flat of fire origin becomes compromised after 6 min and so this is used as the time of heat detection.
Figure A3-34 shows the results of the Scenario S10 and S11 simulations assuming all agents respond to the notification by initiating a building evacuation. All agents manage to exit irrespective of the alarm type in all the simulations conducted.

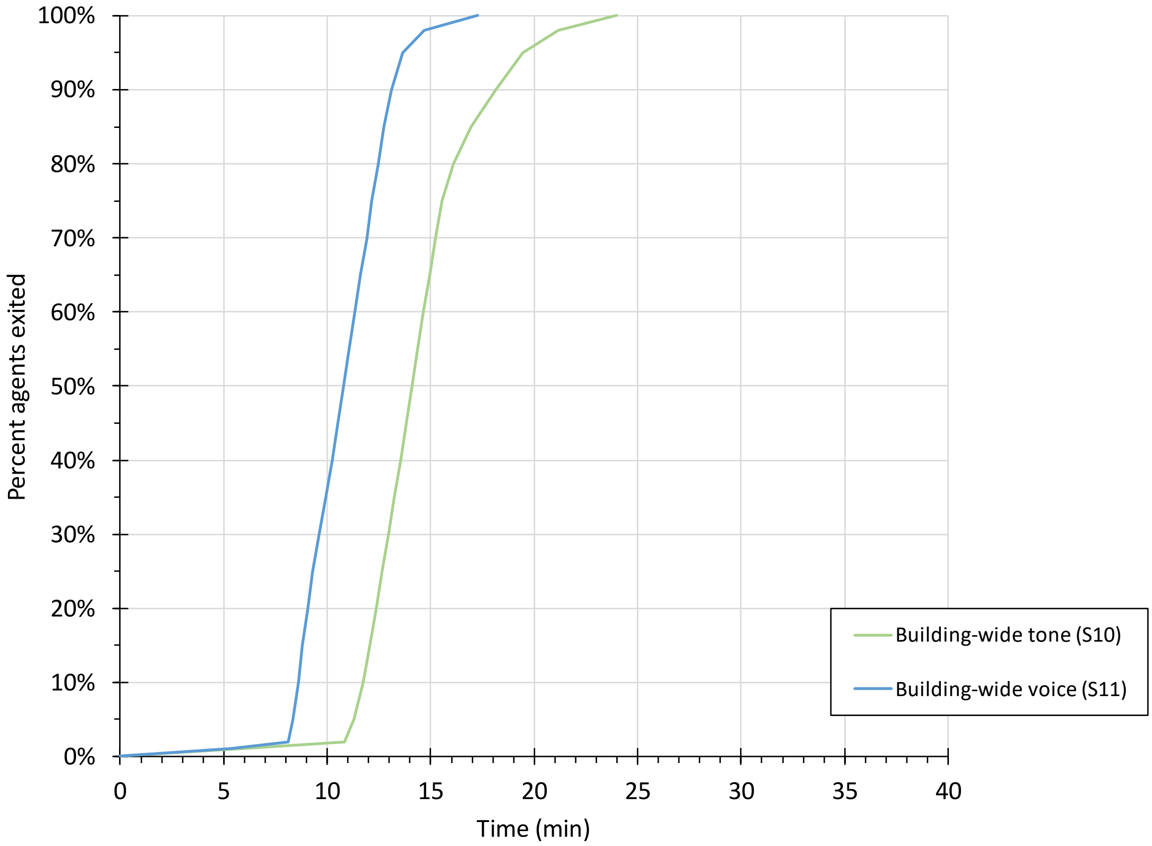


Figure A3-34 Comparison of automatic alert system evacuations assuming all agents respond to cue. Building-wide alarm activation on heat detection in the fire flat

The results therefore suggest that heat detection in the flat of fire origin initiating a building-wide alert is likely to be more effective than having smoke detection in the adjacent common corridor. Furthermore, the impact on the potential for trapped agents using a tone alarm is only relevant to the detection in the corridor scenario.

The impact of these options is investigated more thoroughly in the Parametric analysis.

It would be possible to conduct further simulations to assess the combination of heat detection in the corridor and smoke detection in the flat of fire origin. However, the former will result in more trapped agents that smoke detection in the corridor. The latter will result in a marginally quicker overall evacuation time but the likelihood of false alarms would need to be factored in to applying this option.

A3-8.6 Inter-agent communication – Scenarios S12 to S14

The objective of these scenarios is to examine the impact on evacuation performance of not having a building-wide notification system (or where a system fails to operate). This assumes that the occupants will have the means and willingness to communicate to other occupants to varying degrees (and that there is no building-wide means of communication present in the building). Scenarios S12 to S14 assume that agent(s) in the flat of fire origin may, after being notified by a local detection and alarm, then alert the remainder of the agents on their floor and also the floor above and floor below using a message of some sort (text, telephone, etc.). If the fire is on the top floor, it is just the top floor and the floor below that gets alerted, and similarly if the fire is on the bottom floor, it is only the bottom floor and the floor above that gets alerted.

The scenarios assume the fire occurs in a flat that contains two agents and these agents independently decide to notify other remote agents. The more agents there are in the flat of fire origin then the greater chance that a remote agent will receive multiple notifications. The two-agent flat assumption balances between the possibility that in a more populated flat a greater number of occupants may send separate messages to remote occupants versus the likelihood that not every occupant will do so. In a flat with two occupants, only one of them may send a message because only they have access to a phone or the relevant messaging contacts, etc. Further sensitivity analysis of this assumption has not been addressed herein although could be, should any future analysis be deemed appropriate.

Agents that receive an alert may respond or ignore it. An agent that reacts to the recipient of an alert responds by potentially alerting their neighbouring floors with a message as part of their evacuation procedure. The process is repeated across the building involving those agents that have not yet decided to respond to the recipient of an alert. As a result, this leads to a cascade of alerts and responses away from the fire floor to the remaining floors in the building. The probabilities of alerting and responding are given in Table A3-9 and agents may receive multiple alerts before they respond depending on the outcome of each probability assessment.

As with the automatic detection and alert scenario, the likelihood of all agents eventually evacuating from the building is reliant on the probabilities of agent response and, in this scenario, agents alerting other agents on neighbouring floors.

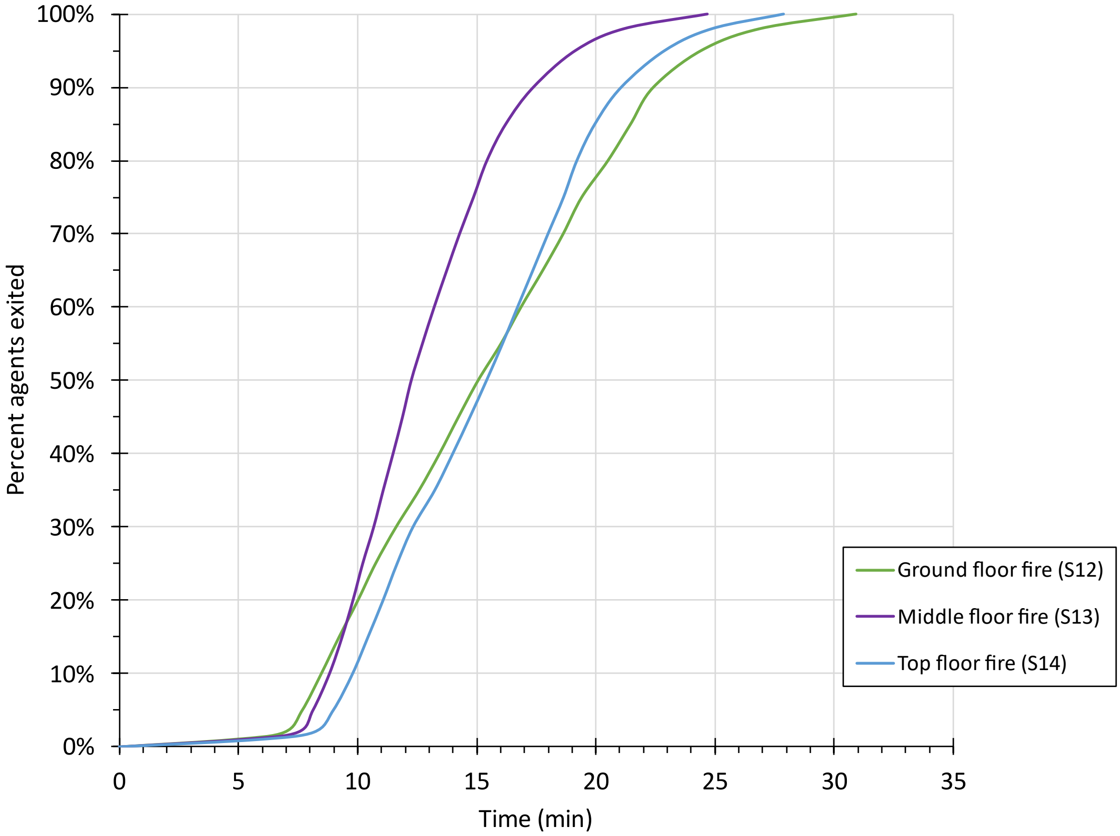


Figure A3-35 Comparison of floor-by-floor agent communication simulations starting at different floors in the building

Simulations have been run to examine what happens if the agents in the flat of fire origin always contact the neighbouring floors. Furthermore, similar to Section A3-8.3, this analysis has been carried out for cases in which the fire is assumed to start on the top floor, on the middle floor and on the ground floor (see Figure A3-35). Where the fire starts in a flat on the ground floor, the overall evacuation time is longer for a given pre-evacuation delay as the last agents to get an alert are furthest from the exit and agents that start moving on the lower floors may impede those leaving from higher floors. Where the fire starts in the middle of the building, the evacuation time is reduced as the cascade of notifications to agents occurs both up and down the building, as opposed to only in one direction for the other fire locations. In the case of the fire starting on the top floor the result is similar to the bottom floor in that the cascade is unidirectional, but agents will move from the top floor first.

Therefore, for the Parametric analysis discussed in Section A3-9 it has been assumed that the floor-to-floor agent interaction scenarios consider the fire starting on the ground floor (the more conservative of the three fire locations in terms of its impact on evacuation performance). This matches the assumption that the fire starts here when considering agent movement speed in smoke.

A3-9 Parametric analysis – Scenarios P1A to P28F

A3-9.1 Overview

Section A3-6.2.3 defines the list of scenarios that are undertaken in the Parametric analysis. Scenarios have been developed for the different floorplate variations given in Section A3-2.1 and building heights given in Section A3-2.2. This analysis also considers the different means of detection and alerting that have been discussed in Sections A3-4.8.2 and A3-5.2. The result is a total of 216 scenarios produced by the combination of variables examined, with 50 Monte Carlo simulations performed for each scenario owing to the distribution of some input variables. Table A3-19 and Table A3-20 show the associated attributes for each scenario.

A3-9.2 Results

Table A3-34 to Table A3-38 present the simulation results of the parametric study for each building height in terms of the mean total building evacuation time and the mean number of occupants left in the building when the escape routes are assumed compromised, where applicable. Also provided are the minimum and maximum values for each metric in parentheses. In some scenarios where the evacuation time approaches the time at which corridors or stairs become compromised due to smoke, a percentage of the simulations will show full building evacuation, with the remainder showing occupants becoming trapped. Scenarios in which occupants become trapped are highlighted in Table A3-34 to Table A3-38 with a grey background. For these cases, the total evacuation time is taken as the average time of only the simulations that show full building evacuation. Where no simulations result in a full building evacuation (i.e., there are always trapped agents), no total evacuation time is reported (indicated by '-').

Where the means of notification is via an alarm throughout the building (tone or voice), all agents respond to the alert notification to start their evacuation. With the agent communication, agents have an 80% likelihood of responding to the communication attempt and a uniformly distributed chance of between 22–50% of alerting the neighbouring floors, based on the discussion in Section A3-4.8.2. The agent communication is modelled akin to the method described in Section A3-8.6. In all the Parametric scenarios, the fire is simulated at the ground floor resulting in the agent communication cascading up through the building (shown to be the more conservative case in Section A3-8.6).

For the single stair scenarios in the 140 m building (Scenarios P19–P22), due to the greater travel distance, there are no instances where 100% of the building occupants evacuate. This is a result of the stair becoming compromised at 56 min, as discussed in Section A3-5.1.5, and the evacuation not being completed in sufficient time. This is generally true of the two stair scenarios as well (P23 and P24); however, in a handful (2–10%) of the simulations in Scenario P23 (low number of occupants), all the agents evacuate.

For the scenarios that include amenity spaces (i.e., Scenarios P25–P28), in an effort to characterise what may be considered to be a representative scenario conditions, the agents throughout the building (both within flats and in the amenity spaces), are assumed to be awake with the corresponding pre-evacuation times from Section A3-4.6. This assumption is investigated in greater detail in Section A3-10.8. In these scenarios, the amenity space is considered at the top of the building, as discussed in Section A3-6.2.3.

Table A3-34 Comparison of total evacuation times (in minutes) and number of trapped agents for the 11 m tall building (Scenarios P1A–P6F)

Parametric scenario		Means of warning					
		Immediate	Social notification	Corridor smoke detection		Flat heat detection	
				Tone	Voice	Tone	Voice
P1	Time (min)	16.9 (13.3, 22.8)	24.5 (19.1, 29.6)	29.5 (27.1, -)	23.2 (19.8, 29.3)	22.3 (18.9, 27.9)	16.8 (12.9, 22)
	Trapped	0	0	1.5 (0, 5)	0	0	0
P2	Time (min)	17.5 (13.7, 23.2)	24.9 (19.9, 32.6)	29.9 (26.8, -)	23.6 (20.4, 27.5)	22.7 (19.7, 26.8)	16.2 (12.7, 20.5)
	Trapped	0	0	1.3 (0, 3)	0	0	0
P3	Time (min)	16.6 (12.5, 20.1)	24.7 (21.3, 34.1)	29.3 (26.4, -)	23.6 (19.8, 28.5)	23.1 (19.2, 30.3)	16.6 (13.4, 20.6)
	Trapped	0	0	1.8 (0, 7)	0	0	0
P4	Time (min)	20.4 (16.9, 24.8)	27.1 (22.3, -)	-	26.6 (24.9, -)	25.4 (21.7, -)	19.8 (17.9, 23.4)
	Trapped	0	0.02 (0, 1)	7 (0, 18)	0.2 (0, 1)	0.2 (0, 2)	0
P5	Time (min)	15.7 (12.6, 20.4)	23.2 (19.7, 26.7)	28.9 (26, -)	22.5 (19.8, 26.5)	21.4 (18.5, 23.8)	15.5 (12.5, 19.1)
	Trapped	0	0	0.4 (0, 2)	0	0	0
P6	Time (min)	18.7 (15.5, 21.9)	22.7 (20.1, 26.3)	32.2 (29.6, -)	24.8 (22.6, -)	24.3 (20.8, -)	16.9 (14.5, 19.5)
	Trapped	0	0	3.1 (0, 8)	0.04 (0, 1)	0.08 (0, 2)	0

Table A3-35 Comparison of total evacuation times (In minutes) and number of trapped agents for the 18 m tall building (Scenarios P7A–P12F)

Parametric scenario		Means of warning					
		Immediate	Social notification	Corridor smoke detection		Flat heat detection	
				Tone	Voice	Tone	Voice
P7	Time (min)	18.4 (14.3, 24.4)	30.4 (25.8, 43.6)	31.5 (26.2, -)	24.7 (21.1, 30.3)	24 (20.1, 27.6)	17.7 (13.8, 23.8)
	Trapped	0	0	1.4 (0, 5)	0	0	0
P8	Time (min)	18.8 (14.3, 24.4)	31.6 (25.4, 43.1)	31.3 (26.3, -)	24.6 (20.8, 30.6)	24.9 (21.4, 30.6)	17.9 (13.5, 23.8)
	Trapped	0	0	1.3 (0, 7)	0	0	0
P9	Time (min)	18.9 (14.4, 24)	31.1 (25.7, 42.8)	30.9 (27.4, -)	24.6 (20.5, 32)	24.7 (21, 29.9)	18.5 (14.4, 23.9)
	Trapped	0	0	1.7 (0, 8)	0	0	0
P10	Time (min)	22.1 (18.6, 27.5)	33.4 (25.5, -)	-	30.7 (27.5, -)	27.4 (23.5, -)	23.5 (20.7, 28.4)
	Trapped	0	0.1 (0, 1)	6 (1, 15)	0.3 (0, 2)	0.2 (0, 2)	0
P11	Time (min)	17.6 (13.5, 22.2)	29.6 (23.8, 43.7)	29.8 (26.7, -)	23.9 (20.1, 28.9)	23.5 (19.6, 28.8)	16.6 13.6, 20.9)
	Trapped	0	0	0.5 (0, 3)	0	0	0
P12	Time (min)	19.8 (16.2, 23.7)	28 (24.3, 31)	30.5 (29.6, -)	26.6 (23, -)	25.7 (22.2, -)	19.3 (15.9, 23.7)
	Trapped	0	0	3.2 (0, 8)	0.1 (0, 2)	0.1 (0, 1)	0

Table A3-36 Comparison of total evacuation times (in minutes) and number of trapped agents for the 30 m tall building (Scenarios P13A–P18F)

Parametric scenario		Means of warning					
		Immediate	Social notification	Corridor smoke detection		Flat heat detection	
				Tone	Voice	Tone	Voice
P13	Time (min)	21.9 (16.1, 31.2)	41.8 (30.8, 51.5)	36.4 (29, -)	28.4 (17, 40.2)	27.4 (21.9, -)	21.9 (16.5, 29.4)
	Trapped	0	0	1.4 (0, 5)	0	0.02 (0, 1)	0
P14	Time (min)	22.3 (15.4, 29.8)	42 (33.2, 50.5)	36.6 (29.8, -)	28.3 (16.3, 28.1)	28.1 (21.6, 40.8)	21.6 (16.3, 28.1)
	Trapped	0	0	1.6 (0, 5)	0	0	0
P15	Time (min)	22.3 (15.4, 31.8)	42.6 (31.8, 48)	37.6 (30.9, -)	29.3 (22.9, 37.6)	28.4 (22.4, 40.1)	22.4 (16.4, 27.5)
	Trapped	0	0	1.3 (0, 7)	0	0	0
P16	Time (min)	28.5 (24.7, 34.2)	42.6 (31.2, 48.3)	52.9 (52.9, -)	48.8 (37.9, -)	36.1 (31.4, -)	32.5 (28.8, 39.7)
	Trapped	0	0	7.8 (0, 24)	0.4 (0, 4)	0.2 (0, 3)	0
P17	Time (min)	20.6 (15.9, 26.1)	42.8 (34.1, 48.8)	37.9 (28.8, -)	28 (22.9, 33.9)	26.4 (20.7, 34.6)	21.1 (15.7, 26.7)
	Trapped	0	0	0.4 (0, 2)	0	0	0
P18	Time (min)	24.4 (19.8, 29.6)	40.3 (32.3, 48.1)	37.9 (31.1, -)	32.4 (26.4, -)	30.2 (25, -)	24.3 (20.2, 28.8)
	Trapped	0	0	3 (0, 8)	0.1 (0, 1)	0.1 (0, 1)	0

Table A3-37 Comparison of total evacuation times (in minutes) and number of trapped agents for the 140 m tall building (Scenarios P19A–P24F)

Parametric scenario		Means of warning: Immediate	Social notification	Corridor smoke detection: Tone	Corridor smoke detection: Voice	Flat heat detection: Tone	Flat heat detection: Voice
P19	Time (min)	-	-	-	-	-	-
	Trapped	17.3 (3, 44)	956.5 (912, 1002)	318.8 (263, 387)	220 (177, 385)	55.5 (16, 212)	18.2 (6, 117)
P20	Time (min)	-	-	-	-	-	-
	Trapped	19.7 (6, 99)	206.7 (162, 260)	324.4 (272, 396)	220.2 (168, 388)	64.7 (17, 206)	15.6 (6, 26)
P21	Time (min)	-	-	-	-	-	-
	Trapped	18 (6, 38)	208.6 (145, 268)	327.7 (277, 454)	218.2 (168, 336)	63.1 (19, 202)	19.9 (7, 90)
P22	Time (min)	-	-	-	-	-	-
	Trapped	2595 (2539, 2672)	3004.2 (2929, 3083)	3117.4 (3059, 3168)	3025 (2988, 3124)	2834 (2783, 2929)	2747.6 (2715, 2795)
P23	Time (min)	58.3* (47.4, -)	-	-	67.9* (-, -)	71.8* (52.8, -)	67.4* (49.3, -)
	Trapped	2.7 (0, 8)	664.4 (627, 722)	9.5 (2, 22)	4.7 (0, 14)	4.5 (0, 15)	2.8 (0, 11)
P24	Time (min)	-	-	-	-	-	-
	Trapped	54.4 (19, 176)	2149 (2028, 2275)	1031.7 (910, 1270)	813.4 (722, 908)	492.6 (361, 665)	299 (184, 488)

* Results are from a limited proportion of simulations where all agents evacuated. Generally, there is at least one trapped agent.

Table A3-38 Comparison of total evacuation times (in minutes) and number of trapped agents with amenity spaces (Scenarios P25A–P28F)

Parametric scenario		Means of warning					
		Immediate	Social notification	Corridor smoke detection		Flat heat detection	
				Tone	Voice	Tone	Voice
P25	Time (min)	14.2 (11.1, 19.8)	26.9 (22.9, 34.7)	27.5 (23.9, -)	24.6 (21.4, 31.8)	20.9 (16.9, 27.9)	17.5 (14.3, 25.2)
	Trapped	0	0	0.1 (0, 1)	0	0	0
P26	Time (min)	23.5 (22, 27.5)	33.2 (25.7, 52.2)	42.2 (36.6, -)	38.1 (34, -)	29.9 (27.8, -)	28.6 (26.5, 32.2)
	Trapped	0	0	0.5 (0, 3)	0.2 (0, 1)	0.1 (0, 1)	0
P27	Time (min)	14.2 (10.6, 19.9)	26.7 (22.4, 34)	27.3 (23.4, 35.3)	24.4 (20.1, 31)	20 (16.4, 24)	16.5 (13.1, 21.5)
	Trapped	0	0	0	0	0	0
P28	Time (min)	17.4 (13.4, 22.4)	30.5 (24.4, 45.4)	30.5 (26.5, -)	27.5 (24.7, 31.4)	23.7 (19.7, 28.3)	20.4 (17.3, 24)
	Trapped	0	0	0.2 (0, 1)	0	0	0

A3-9.3 Normalised parametric results

Compiling the results across the notification systems examined (e.g., across all building heights), it is possible to extract a relative performance (using only evacuation times) for the combination of various detection and notification methods examined.[7] These are derived from all the comparable scenarios in Scenarios P1A to P28F and then normalised to the results produced in the 'B' scenarios (involving no notification system but relying on inter-agent communication (social notification), as described in Section A3-6.2.3). The results are shown in Table A3-39.

[7] Results were excluded from scenarios where residents were trapped in each simulation.

Table A3-39 Performance of detection and alerting systems across comparable scenarios (P1–P24).

Method of notification / detection	Social notification	Corridor smoke detection		Flat heat detection	
		Tone	Voice	Tone	Voice
Evacuation time (min)	32.4	34.0	27.5	25.9	19.9
Normalised value	1.00	1.05	0.85	0.80	0.62

Compiling the results across the conditions for each building height produces the results shown in Table A3-40.[8] As expected, it is apparent there is an increase in the evacuation times required with increasing building height. The constant of proportionality between total evacuation time and building height is around 0.52, compared to 0.25 in the Baseline scenarios (see Section A3-7.2.1)

Table A3-40 Evacuation performance according to building height across comparable scenarios (P1–P6 vs P7–P12 vs P13–P18 vs P19–P24)[9]

Building height (m)	11	18	30	140
Evacuation time (min)	22.5	24.9	31.9	66.4*
Normalised value	1.00	1.11	1.42	2.95

* From a limited number of simulations in a restricted number of scenarios (i.e., Scenario P23, see Table A3-37)

The impact of the notification approach can also be broken down according to building height (see Table A3-41). It is apparent that the benefits of introducing more effective notification and detection become increasing beneficial as the building increases in height.

[8] These results reflect the range of pre-evacuation delays considered on the basis that most situations will involve a distributed response (according to the notification system employed), while other situations might involve residents delaying their response but arriving at the stair in a narrow time window (placing additional demand on the stair).

[9] Results were excluded from scenarios where residents were trapped in each simulation.

Table A3-41 Relative performance according to detection and alerting systems by building height (P1–P6 vs P7–P12 vs P13–P18 vs P19–P24)

Building height (m)	Social notification	Corridor smoke detection		Flat heat detection	
		Tone	Voice	Tone	Voice
11	1.00	1.22	0.98	0.95	0.69
18	1.00	1.00	0.84	0.82	0.62
30	1.00	0.95	0.77	0.70	0.60
140*	-	-	-	-	-

* The 140 m tall building only results in a very few simulations for Scenarios P23A and P23D–P23F in which there are full building evacuations.

Following on from the Sensitivity analysis, the impact of stair width is also examined here in the Parametric simulations. Although the total evacuation time increases with building height (as already shown in Table A3-40) and there is no change in the relative impact of having a wider stair. For example, with the 18 m tall building the relative performance of having a 1.5 m wide or 2.0 m wide stair does not vary for each of the six detection and notification combinations (e.g., P7A vs P8A and P9A, etc). Similar results are found for the 11 m and 30 m tall buildings. For the 140 m tall building the relative change in the number of agents become trapped generally varies between no material change and a 10% difference. However, there is an outlier set of Scenarios (P19B to P21B) in which evacuation is instigated from inter-agent (floor to floor) social notification in which increasing the stair width from 1.0 m to either 1.5 m or 2.0 m reduces the average number of trapped agents by a quarter (from around 960 to 210). It is unclear why this is the case and further investigation would be needed to examine the reason, although it may be due to such communication producing local demand given the clustering effect of social notification.

The number of agents unable to evacuate without interacting with deteriorating environmental conditions is shown in Table A3-42. It is apparent that social communication, tone notification combined with flat heat detection and voice notification combined with corridor smoke detection produce very few trapped agents for buildings between 11 m and 30 m in height, while voice notification traps no agents when flat detection was used. Tone notification produces an average of just over two agents who are trapped when coupled with corridor smoke detection. When a 140 m tall building is examined, all approaches produce significant numbers of trapped agents (ranging from 517 (voice notification / flat detection) to nearly 1200 (social notification).

Table A3-42 Average number of trapped agents according to detection and alerting systems by building height (P1–P24)

Building height (m)	Social notification	Corridor smoke detection		Flat heat detection	
		Tone	Voice	Tone	Voice
11	0.00	2.52	0.04	0.05	0.00
18	0.02	2.35	0.07	0.05	0.00
30	0.00	2.58	0.08	0.08	0.00
140	1198.23	854.92	750.25	585.73	517.18

Compiling the results across the conditions with scenarios grouped according to the number of stairs present produces the results shown in Table A3-43 and Table A3-44. It is apparent that including an extra stair reduces evacuation times by an average of 8% across the scenarios examined.

Table A3-43 Evacuation performance according to number of stairs across directly comparable scenarios (P1, P4, P7, P10, P13, P16 vs P5, P6, P11–P12, P17–P18)[10]

Number of stairs	Single stair	Two stairs
Evacuation time (min)	27.9	25.7
Normalised value	1.0	0.92

Table A3-44 Evacuation performance (in minutes) according to number of stairs given building height across comparable scenarios (P1, P4, P7, P10, P13, P16 vs P5, P6, P11–P12, P17–P18)[10,11]

Building height (m)	Number of stairs		Relative performance
	1	2	
11	23.0	22.2	0.97
18	25.8	24.2	0.94
30	34.9	30.5	0.87
140	-	-	-

The number of agents unable to evacuate without interacting with deteriorating environmental conditions is shown in Table A3-45. There is little difference in the performance of one or two stairs for buildings ranging between 11–30 m in height with the number of trapped agents being one or less.

Table A3-45 Number of trapped agents according to number of stairs by building height (Scenarios P1, P4–P6, P7, P10–P12, P13, P16–P18, P19, P22–P24)

Building height (m)	Number of stairs		Reduction in number of trapped agents with two stairs (%)
	1	2	
11	0.74	0.30	60
18	0.67	0.33	49
30	0.83	0.30	64
140	1575.79	460.73	70

[10] Results from a reduced set of scenarios are included to (1) exclude 140 m buildings, given the severely compromised evacuation, and (2) to ensure directly comparable scenario conditions.

[11] It should be noted that if ‘A’ sub-scenarios are also excluded (where evacuees respond simultaneously), then the overall results are broadly comparable: with evacuation times for two stairs (23.3, 25.4, 32.1 min) still on average 8% shorter than those produced on a single stair (23.9, 27.0, 36.9 min) across 11/18/30 m tall buildings respectively.

For 140 m tall buildings, having two stairs produces a considerable number of trapped agents (461) even when two stairs are available. However, in relative terms having two stairs results in a reduction of between 50–70% trapped agents across the building heights examined. The differences between the building heights are likely due to the uncertainty in the inputs and running a larger number of simulations may lead to closer outcomes.

A3-10 Diagnostic analysis – Scenarios D1 to D41

A3-10.1 Overview

The objective of the diagnostic analysis phase is to separately assess:

- **The delay that MDPs have on agent movement,**
- **The effect of notification response likelihood,**
- **The potential impact of the fire and rescue services, and**
- **How the provision of lifts affects evacuation performance.**

These aspects have been selected based on findings from the previous three modelling phases. As with the sensitivity analysis phase, Floorplate 1 (see Section A3-2) is predominantly used as the common configuration for an 18 m high, single stair building with 15 m long common corridors. Evacuationz and Pathfinder are used for the diagnostic simulations although no comparative benchmarking has been carried out mainly due to certain modelling elements being unique to each tool.

As discussed in Section A3-8.2, each scenario is run 50 times in Evacuationz. Although Pathfinder is more computationally demanding than Evacuationz, typically 50 simulations have also been run for the respective scenarios.

A3-10.2 Effects of Movement Dependent Persons – Scenarios D1 to D8

A3-10.2.1 Agent blocking

Scenarios D1 to D4 have been simulated to determine whether including Movement Dependent Persons (MDPs) slows the movement of other agents as they move along egress components (e.g., stairs). Previously, several of the Baseline simulations described in Section A3-7 included a single agent located at the most remote flat from the exit to get their travel time (Scenarios B1–B4). In those simulations the agent had an unimpeded movement speed of 1.20 m/s and was not assigned a pre-evacuation delay.

To investigate the impact of adding an MDP to the evacuation, a second agent has been inserted into the building and placed in the stairs on Level 6 at the start of the simulation. The goal here is to establish whether the interaction between unimpaired and impaired individuals might have a local impact on performance. For each iteration the movement speed and body size of the MDP has been selected as per Section A3-3. To assess the modelling uncertainty 100 simulations rather than the typical 50 simulations of the two cases have been run, and these have been repeated for a 1.0 m wide stair and a 1.5 m wide stair. Additional simulations were included as it was assumed that the precise characteristics and location of each evacuating individual might affect the overall outcome.

Without the MDP, the average times in Scenarios D1 and D2 for single agent to exit the building are 97 ± 6 s and 92 ± 6 s for the 1.0 m and 1.5 m wide stair, respectively (i.e., around 1.5 min). This is comparable to the results produced by Evacuationz for Scenario B2 where an individual agent was simulated. For Scenario D3 with the MDP agent, in the 1.0 m stair building the average time for the non-MIP agent to exit is 156 ± 27 s (2.6 ± 0.5 min) and the average time for both agents is 234 ± 104 s (3.9 ± 1.7 min). **The introduction of the MDP produces a 62% increase in the time for the non-MIP agent to reach safety over the time produced when they evacuated alone (97 s, 1.6 min).[12]** The detailed log (reflecting the experience of the evacuating individual during the simulation) of the non-MDP agent shows the agent being blocked by the MDP agent at some point in the stairs given their relative movement speeds.

For the Scenario D4 with the 1.5 m wide stair, the average time for the non-MIP agent is 93 ± 6 s (1.6 min) which is equivalent to the single non-MIP agent cases. This demonstrates that the agent is not blocked by the MDP agent, i.e., is able to pass on the wider stair. The average time for both agents is 240 ± 115 s (4.0 ± 1.9 min), i.e., as with the 1.0 m wide stair, it is the speed of the MDP agent that dictates to final building clearance time, irrespective of the blocking of the non-MIP agent. A stair that is wide enough to allow for overtaking may provide a benefit to overall building evacuation where slow moving occupants are present who have the potential to block the movement of other users – assuming that lifts are not available, and the additional width is sufficient to allow passing.

It is apparent that Scenario D3 (with a 1.0 m wide stair) produces an average evacuation time of 234 s while Scenario D4 (with a 1.5 m wide stair) produces an average evacuation time of 240 s. In both cases, the total evacuation time is dictated by the slowest persons evacuating (MDP residents). Therefore, the total evacuation times of the two scenarios, i.e., 234 ± 104 s and 240 ± 115 s are effectively the same and dictated by travel speeds rather that flow constraints produced by the stair. It should also be noted that Scenario D4 produces shorter evacuation times than

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[12] i.e., without assumed intervention from additional residents or emergency services.

Scenario D3 for non-MDPs, who can pass slower-moving MDPs and achieve the same level of evacuation time as in the baseline scenario without MDPs.

This analysis provides insights into the potential impact of slower moving individuals that have the potential to delay others on the movement of other evacuees should additional provisions not be provided. In addition, this analysis focuses on the physical capacity to pass a slower moving evacuee and does not address any social inhibition at doing so – which might prolong (or at least complicate) the evacuation process still further. This may have implications for the inclusion of other means of egress for those with significant movement impairments, i.e., the use of evacuation lifts.

A3-10.2.2 Alarm activation

The previous sensitivity analysis (see Section A3-8.5) noted that even with smoke detection in the corridor there is a possibility that agents may become trapped (i.e., not be able to evacuate before conditions became untenable) where they have an extended pre-evacuation delay. The likelihood of the extended pre-evacuation delay is partly due to the presence of Movement Dependent Persons (MDP) and more generally Movement Impaired Persons (MIP). To further investigate the impact on the number of trapped agents due to the pre-evacuation delay, Scenario D5 and D6 simulations have been conducted in which the 5% of MDPs have not been included but are instead treated as Movement Reduced Persons (MRP) – meaning that they should be able to use stairs unassisted, albeit at a reduced movement rate and do not block other agents as MDP agents do as a result of their assumed wider body size. However, even when the response to the tone alarm is 100%, 24 of 50 (i.e., approximately a half) of the simulations that include a mixture of 20% MRP and 80% non-MRP (i.e., non-MIP) agents do not result in a full building evacuation.

Table A3-46 Average total evacuation times for Diagnostic scenarios D5–D8

Scenario	Total evacuation time (min)
S8 – Building-wide tone alarm with MIPs	40.2
S9 – Building-wide voice alarm with MIPs	25.4
D5 – Building-wide tone alarm with no MDPs	37.6
D6 – Building-wide voice alarm with no MDPs	21.2
D7 – Building-wide tone alarm with no MIPs	23.2
D8 – Building-wide voice alarm with no MIPs	20.3

The average number of trapped agents is 1.4 per simulation of those where at least one occurred with one simulation generating 4 trapped agents. This is because by the time these agents start their movement, they enter the corridor adjacent to the flat of fire origin at the point it becomes compromised (taken as 26 min from Table A3-16). In Scenarios D7 and D8 all agents are assumed to be non-MIP, such that other than in Scenario D5, there are no trapped agents. Figure A3-36 shows the results from the Scenario D5 to D8 simulations when compared to the previous S7 and S8 simulations, and average total evacuation times are shown in Table A3-46.

The presence of MDPs increases the total evacuation time by around 17 min when the tone alarm is used and around 5 min when the voice alarm is used. As already noted in Section A3-8.5, this suggests that **a building-wide tone alarm on detection of smoke in the corridor adjacent to the flat of fire origin may lead to some occupants being exposed to deteriorating conditions under the specific circumstances of the scenario presented – implying a qualitative benefit of employing building-wide voice alarms.**

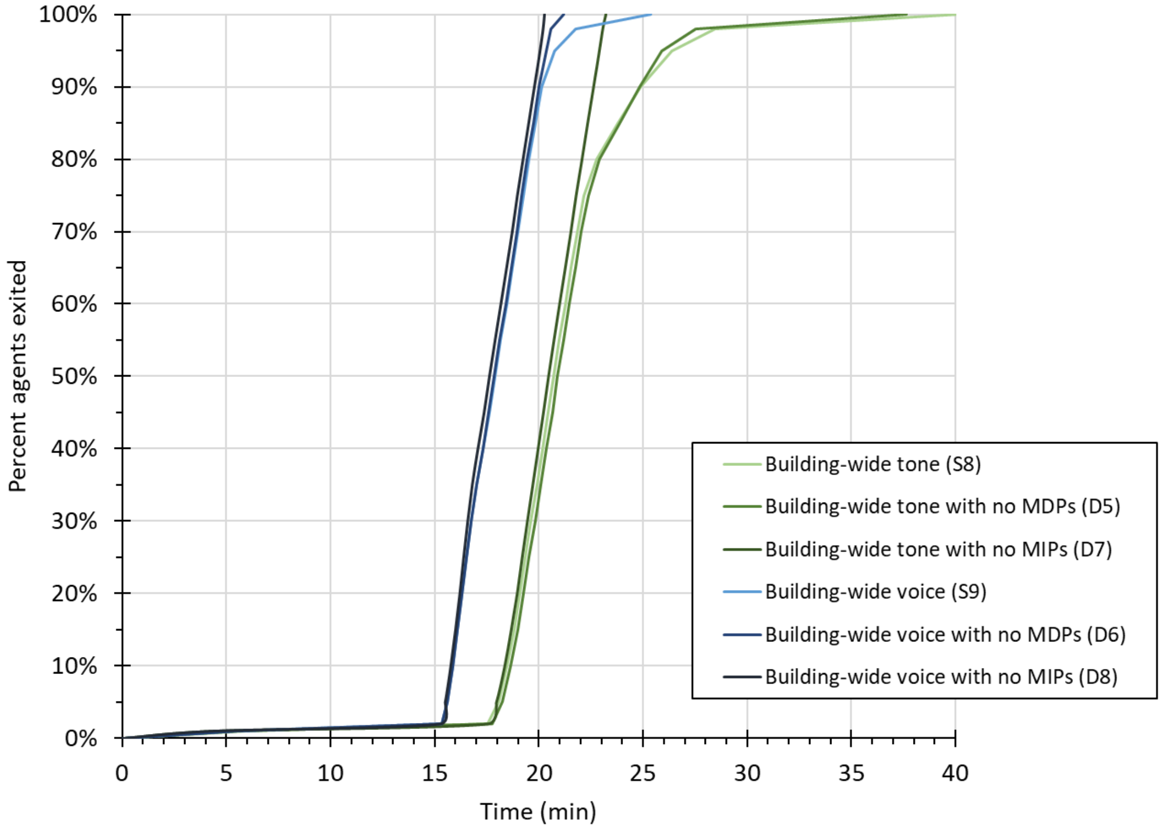


Figure A3-36 Comparison of automatic alert system evacuations with and without including Movement Dependent Persons (MDP) or Movement Impaired Persons (MIP) assuming all agents respond to cue. Building-wide alarm activation on smoke detection in the adjacent corridor with results for agents that exit the building

It would be possible to extend the above analysis to other combinations of detection type, detection location, building height and where no MDPs are present, although the limitations of the other detection type / location combinations have been discussed previously in Section A3-8.5.

A3-10.3 Full simultaneous evacuation – Scenarios D9 to D11

Scenarios D9–D10 further examine the effect of assigning agents a pre-evacuation delay distribution, as discussed in Section A3-4. Scenario D9 includes no pre-evacuation delay time (i.e., agents start evacuation at t = 0 s), however agents include the percentage of MIPs given in Table 3. These individuals are randomly located around their respective flats. Scenarios D10 and D11 compare the use of the implied pre-evacuation delay (Scenario D10) and the equivalent component delay (Scenario D11), employing the method discussed in Section A3-4.6. These two scenarios assume a building-wide tone alert in which all agents then follow their pre-evacuation delay given in Table 4. The results from Scenarios D9 to D11 are compared to a baseline case in which all agents start at the door of their flat (i.e., a 0 m starting distance), all have an unimpeded movement speed of 1.20 m/s, have a body size of 0.35 m, and have no pre-evacuation delay. This Baseline scenario replicates Scenario B2 in Section A3-7. The Baseline scenario has no agent response or pre-evacuation delays, i.e., representing an immediate full (simultaneous) evacuation. This is not intended to represent a real-life event, but to indicate the maximum congestion that might be generated given a simultaneous response – suggesting the limits of reducing the response distribution.

Figure A3-37 shows the comparison between four full evacuation simulations using various pre-evacuation delay distributions, with average total evacuation times shown in Table A3-47. There is little difference between the Baseline case and Scenario D9 where the pre-evacuation delay is 0 s as these two scenarios are similar, other than the exclusion of the starting position and unimpeded movement speed distributions in the Baseline case. The case with no pre-evacuation delay does exhibit a tail off that illustrates the impact of having the MIP agents in the simulation – who prolong the evacuation time by their restricted movement.

Table A3-47 Average total evacuation times for Diagnostic scenarios D9–D11

Scenario	Evacuation time (min)
D9	8.1
D10	19.0
D11	18.3

As expected, other than the agents in the flat of fire origin, the percentage of agents that have exited the building versus time is affected by the distribution of pre-evacuation times. The simulations further illustrate that using the implied (derived from the data available) and component methods (where the pre-evacuation times are broken down to enable the constituent elements to be recombined to reflect a wider range of scenario conditions, see Section A3-4.6) give equivalent results, supporting the utility of these approaches.

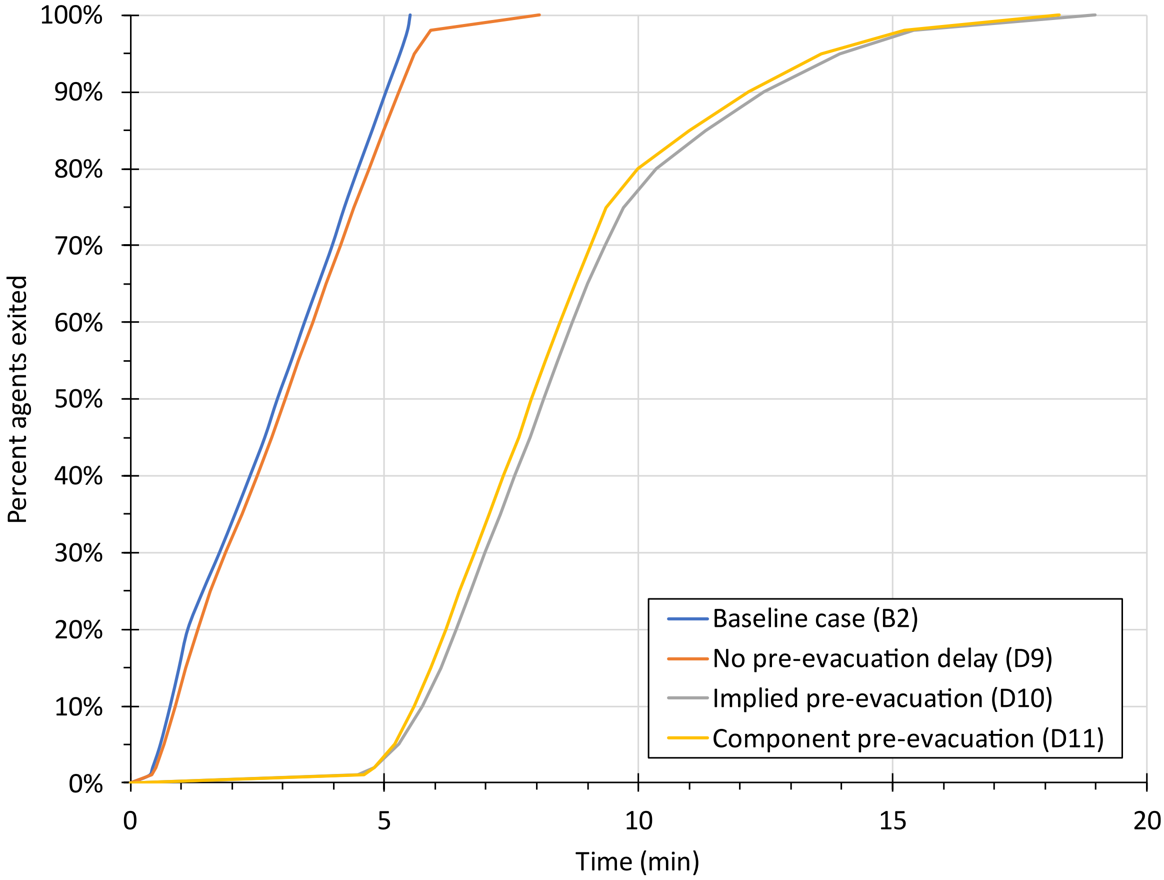


Figure A3-37 Comparison between full evacuation scenarios: Scenarios B2, Baseline, D9 (no pre-evacuation with MIPs), D10 (implied pre-evacuation delay) and D11 (component pre-evacuation delay)

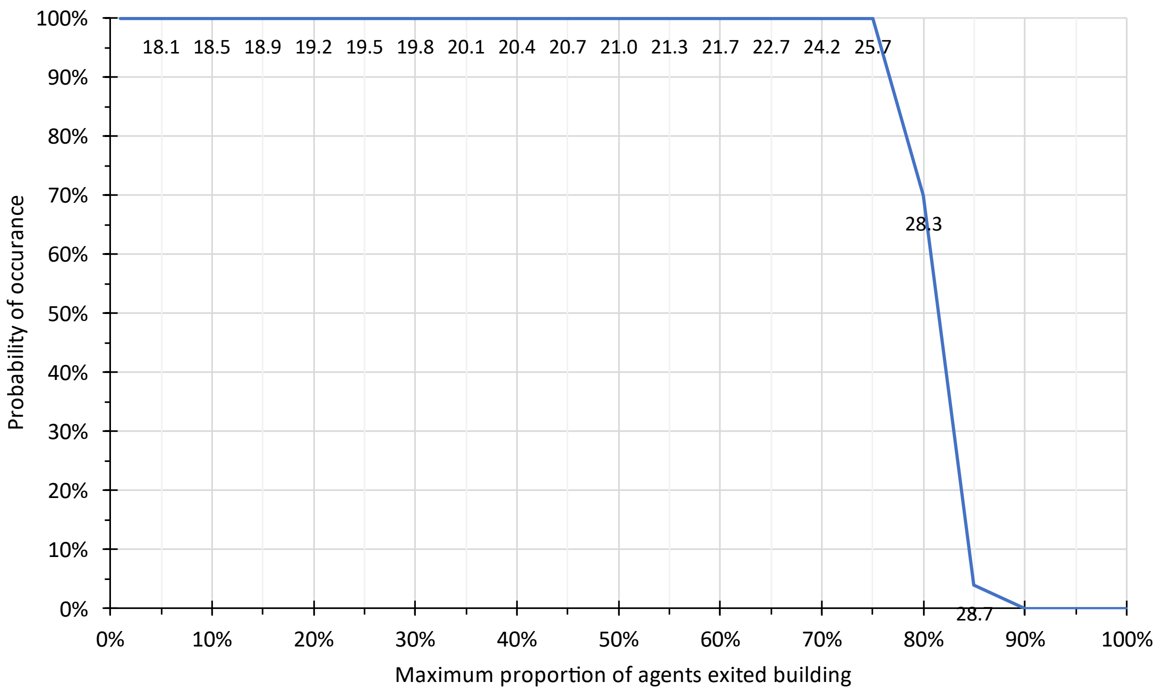
The key findings here are that the presence of MIPs amplifies the congestion produced during the simultaneous response conditions, the inclusion of pre-evacuation times has a significant impact on the overall evacuation time, and that the mechanism derived to break down the pre-evacuation distribution into its constituent parts produces comparable results to the empirically derived approach.

A3-10.4 Extent and nature of response to notification – Scenarios D12 to D14

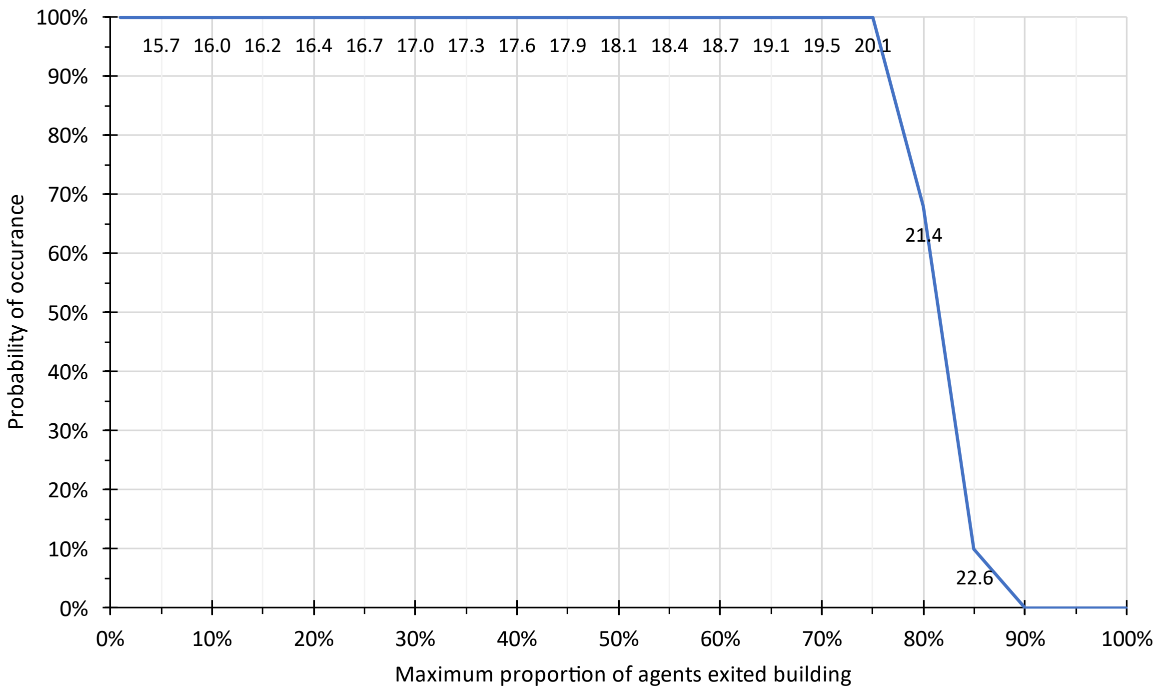
A3-10.4.1 Alarm with no social communication – Scenarios D12 and D13

Previously scenarios have considered the situation in which some form of an automatic smoke detection system was present in the common corridor adjoining the flat of fire origin that raises an audible alarm signal in every flat simultaneously (see Scenarios P1A to P36F). This system is similar to elements of the Technical Guidance Document [52] in Ireland, as discussed in Section A3-5.2. It has also been previously assumed that agents in the flats are able to hear the alarm signal and they always respond by initiating evacuation at some point. However, as discussed in Section A3-4.8, research from this project (see Appendix B2) suggests that the likelihood of an occupant to initiate evacuation is 80% on average, as per Table A3-9. In this section Scenarios D12 to D14 are simulated to investigate the impact of not assuming all agents respond to an alert, but instead have a probability of responding to the alarm (i.e., 80%). For the purposes of this investigation smoke is assumed to enter the corridor and trigger the automatic detection and alarm system after 13 min.

Figure A3-38 shows the influence of the building-wide automatic smoke detection and alarm system for 50 simulations of a building-wide tone alarm (Figure A3-38(a) reflects Scenario D12) and 50 simulations using a building-wide voice alarm (Figure A3-38(b) reflects Scenario D13) – with no social communication assumed between evacuating agents. The two agents in the flat of fire origin begin their evacuation prior to the activation of the alarm as it is assumed they became aware of the fire either from smoke cues and by a local detection and alarm system (i.e., within the flat) – the rest of the population rely on the notification process. Once the smoke is detected in the adjacent corridor then the building-wide alarm system is assumed to activate, and the remaining agents are notified. Given there is a 20% likelihood that agents may choose to not respond to the alert by initiating their evacuation then this is reflected by the results.



(a) Scenario D12



(b) Scenario D13

Figure A3-38 Comparison of automatic alert system evacuations assuming not all agents respond to cue: (a) Scenario D12 – tone alarm; (b) Scenario D13 – voice alarm. Numbers adjacent to curve indicate average time of evacuation in minutes

Figure A3-38(a) **shows for a tone alarm that there are no simulations in which the building is totally cleared**, i.e., people will not be able to evacuate prior to conditions on the egress route becoming untenable. There is a 4% likelihood that 85% or less of the agents have exited after 28.7 min and there is a 100% likelihood that 75% or less of agents have exited in 25.7 min. As expected, the actuation of the voice alarm system reduces the evacuation time for that majority when compared with the tone alarm. Figure A3-38(b) shows there is a 10% likelihood that 85% or less of the agents have exited after 23.9 min and there is a 100% likelihood that 75% or less of agents have exited in 20.1 min. **The key finding from this analysis is that it is reasonable to expect that some residents of a building may choose to ignore a tone or voice notification system and therefore a building will not likely achieve a full evacuation should such systems be present, given the assumptions made.**

Were a different building-wide alarm initiation assumed in the simulations, such as a different corridor smoke entry time or an alternative detection event, then the results would be shifted accordingly. This is further discussed below. The introduction of the voice alarm does not affect the overall number of people that eventually evacuate but does reduce the evacuation time of those that evacuate. This is directly affected by the (likely conservative) assumption that voice alarms only affect the time to initiate movement, but not the probability of initiating movement.

It might be argued that this means of automatic communication is similar to when people in the flat of fire origin have the desire and means to alert all of the other building occupants through a tool such as a social media post. This would rely on several factors including the people in the flat of fire origin deciding to make a post in a timely fashion, a mechanism available to facilitate this (for example, a building-wide social media group), the ability for other building users to actively access the group, and the decisions made thereafter by the receivers of the notification. The use of social media as a means of social communication has been briefly discussed in Section A3-4.8.3.

A3-10.4.2 Alarm and inter-agent communication response – Scenario D14

As discussed in Section A3-10.4.1, if it is assumed that there is an 80% likelihood on average that agents respond to an alarm then around 20% of the agents in the building do not initiate their evacuation. However, it is possible that in a real situation people that do decide to respond to the alarm may make contact with their neighbours. In such a case, the building will have technological notification (via the alarm system) and social notification (via inter-agent communication). The effect of this inter-agent social communication is discussed in Section A3-8.6. Scenario D14 combines the response to an alarm with floor-by-floor inter-agent communication to include the impact of possible social communication.

Figure A3-39 shows a comparison between the findings discussed in Section A3-10.4.1 and Scenario D14 that combines the technological and social notification. The results from Scenario D12 for the building-wide tone alarm only shows the simulations in which 75% or less of the occupants exited the building. In the inter-agent communication simulations of Scenario D14 it is found that in 17 of 50 simulations (34%) all agents evacuated the building, whereas in the remaining 66% of simulations from 1 to 6 agents, with a mean of 2.1 agents, remain trapped. Figure A3-39 only shows the results where a full building evacuation occurred. However, what is clear is that combining the alarm with inter-agent communication results in a greater proportion of agents exiting the building with the evacuation time produced being of the order of 33 min.

The key finding from this investigation is that the combined technological and social notification strategies increase the proportion of occupants that will initiate an evacuation although this will result in an extended evacuation period and still does not guarantee all occupants will leave the building. However, encouraging the social notification process is beyond regulatory guidance – although might be enhanced through local outreach and education.

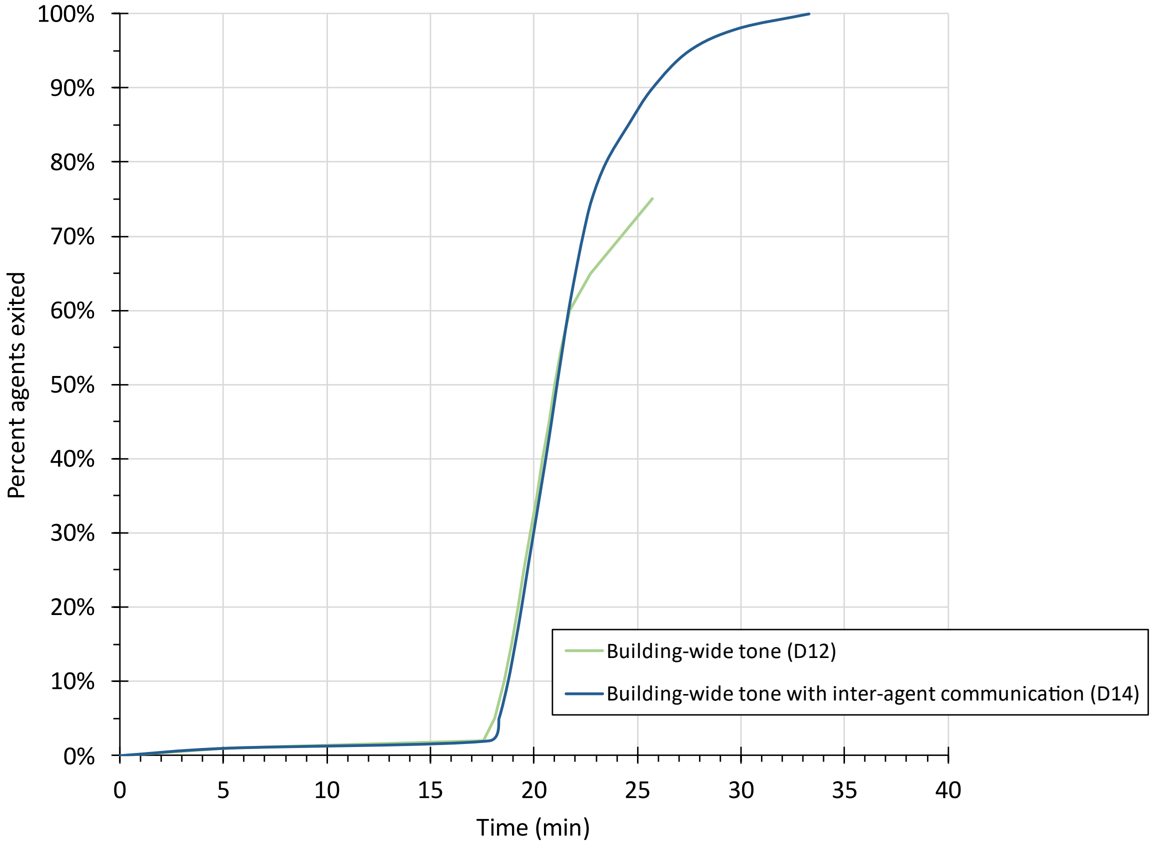


Figure A3-39 Comparison of automatic building-wide tone alert system evacuations assuming not all agents respond to cue (Scenario D12) but where inter-agent communication may occur (Scenario D14)

A3-10.5 Inter-agent communication – Scenarios D15 to D18

A3-10.5.1 Likelihood of alert and response

The simulations described in Section A3-8.6 assume that an agent will always alert other agents encountered, and when an agent receives an alert from another agent then the recipient always responds, i.e., inter-agent alert and response is always 100% effective. Where the likelihood of agents contacting agents on other floors is taken from Table A3-9 then on average around 50% of simulations result in a full building evacuation. This is driven by the fact that if none of the agents in the flat of fire origin (i.e., two agents in these simulations) contact agents on their neighbouring floors then those remote agents are unable to make a response. Scenarios D15 to D17 investigate how the number of agents in the building and the likelihood of agent interaction affect the evacuation response when technological notification is absent. This analysis is necessary to explore the reliance upon agent communication as a means of notification, and the robustness of this approach – along with the sensitivity of this performance to small changes in population and response.

A3-10.5.2 Occupant numbers

To demonstrate how the number of occupants in the building affects the evacuation Scenario D15 consists of simulations with around half the number of occupants (i.e., 99 agents, as two agents are retained in the flat of fire origin) which results in the full clearance of the building in a time of 30.1 min similar to that for the fully occupied building with the fire on the ground floor and where agents in the flat of fire origin always contact neighbouring agents. However, when the total number of agents is reduced in Scenario D16 to a quarter (i.e., 51 agents, with two agents in the flat of fire origin) then only around 85% of the simulations result in the building clearing in around 30 min. **When reliant on inter-agent social communication, the proportion who evacuate is dependent on the occupancy loading.**

In simulations that did not clear the building, in some instances only around 30% of the agents exited the building. The decreased number of agents present in the building means that agent-to-agent contact is reduced – limiting the chance of social communication and response. There appears a critical number of agents that enable a full evacuation to occur for the given building geometry and occupant characteristics used in the simulations. Counter-intuitively, increasing the population size where technological notification is minimal reduces the population response time and increases the response rate. The benefits of increasing the population are constrained in the movement where subsequent congestion might eventually negatively impact overall evacuation performance.

Scenario D17 uses a more evidence-based estimate of the number of agents in the building taken from the findings from Hopkin et al. [2] using data provided by the

English Housing Survey. As above it has been assumed there are two agents in the fire flat that always contact neighbouring agents. The number of agents in the building varied from 79 to 103 with a mean of 92.6. In this case 2 in 75 simulations (2.7%) did not result in a full building evacuation, in which the number of agents were 83 and 94, suggesting the critical value is around 90 agents. **As such, in expected occupancy loading the absence of a building-wide notification technology would have led to some people not being told about the fire – even where optimistic assumptions are made regarding social communication.**

A3-10.5.3 Likelihood of inter-agent communication

The previous analysis illustrated by Figure A3-35 (Scenarios S11–S13) assumes that agents in contact with other agents on their neighbouring floors provided an alert to every flat and every individual agent. This assumption is likely very optimistic; it might be more realistic to assume some form of probability distribution to represent the number of flats and agents that are actually alerted. One method to investigate the likelihood of an agent contacting other flats is to modify the alerting probability given in Table A3-9. The probability is reduced by the proportion of flats on the neighbouring floors. Thus, for the ground floor of the Floorplate 1 exemplar building there are six other flats on the ground floor and seven flats on the floor above, i.e., 13 flats. Therefore, the uniform probability distribution for an agent contacting other agents after receiving personal communication is reduced to a minimum of 22 / 13 = 1.7% and a maximum of 50 / 13 = 3.8%.

Scenario D18 has used this reduced uniform distribution in the seven-storey building populated with 196 agents which results in only around 3% of cases in which the building is fully evacuated. Examining the proportion of agents that evacuate where the fire is on the ground floor of the building (for example) is shown Figure A3-40. Up to 25% of the agents always exited the building in 12.2 min on average. However, the likelihood of 30% or less of the agents exiting drops to just below 60% of the simulations and only around 5% of simulations resulted in 100% of the agents exiting the building at an average time of 40.5 min.

These results show the sensitivity of the results produced to the population size within the building and the likelihood of inter-agent social communication (as reflected by the modelling assumptions). As such, real-world reliance on such behaviour, should there be a need to initiate a full building evacuation, would need to have significant justification.

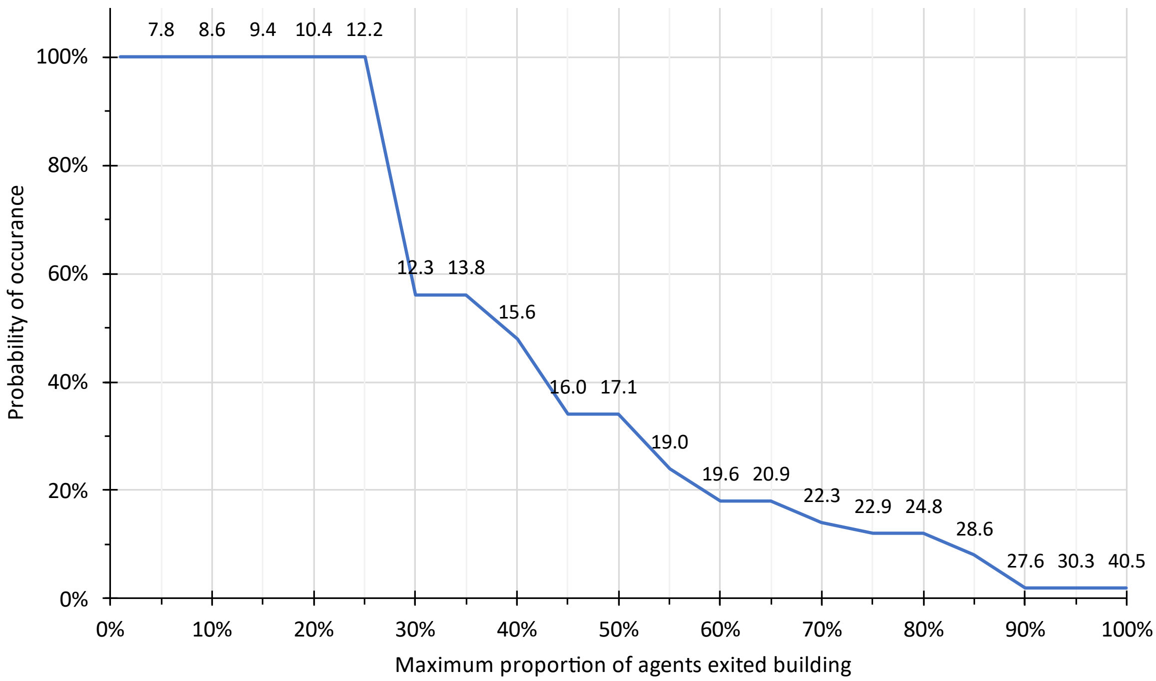


Figure A3-40 Likelihood of a given proportion of agents to exit the building with reduced inter-agent interaction. Numbers adjacent to curve indicates average time of evacuation in minutes

A3-10.5.4 Inter-agent social communication combined with automatic system

The analysis in Section A3-10.5.3 has been extended in Scenario D19 to investigate what happens if there is an 80% likelihood of agents responding to a building-wide tone alarm on smoke detection in corridor at 13 min. The objective is to extend the case in which technological and social notification strategies are combined to reflect what might represent some form of reality with its inherent complexity. Thus, the procedure is as follows:

- Agents in the ground floor flat of fire origin are alerted to a fire by local detection and alarm, or other means,
- Agents from the flat of fire origin contact neighbouring flats (i.e., ground and first floor) with a 100% likelihood,
- As previously, agents in remote flats have an 80% likelihood of responding to an alert from another agent with a 1.7–3.8% likelihood of contacting neighbouring flats,
- Agents that have not responded to inter-agent communication have an 80% likelihood of responding to the building-wide automatic fire detection and alarm system when it activates, and

- Agents that respond to the alarm also have a 1.7–3.8% likelihood of then contacting neighbouring flats.

Figure A3-41 shows that 16% of simulations result in a full building evacuation in around 32 min. For the 84% of simulations that do not result in a full building evacuation, then between 1 to 4 agents, with an average of 1.9 agents, remain trapped. Clearly the results would change if it was assumed that agents in the flat of fire origin did not always attempt to contact their neighbouring flats. Simulations to investigate the effect of agents in the flat of fire origin either contacting others or not have not been carried out herein.

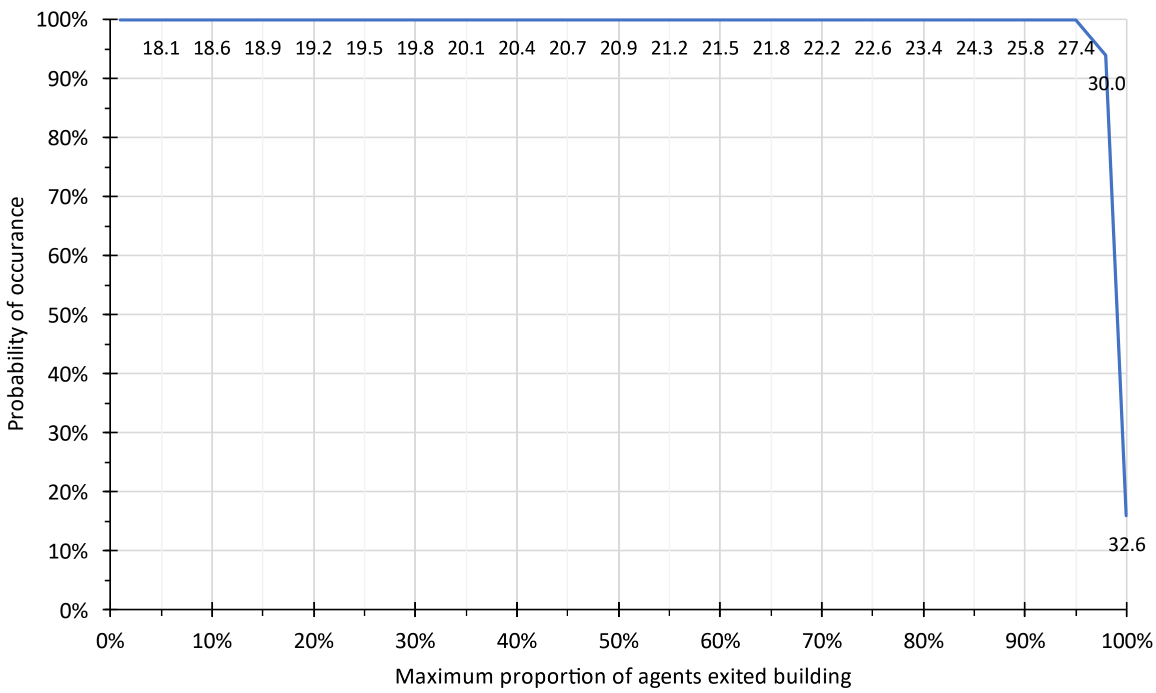


Figure A3-41 Likelihood of a given proportion of agents to exit the building where agent interaction is combined with the response to an automatic smoke detection and alarm system. Numbers adjacent to curve indicates average time of evacuation in minutes

A3-10.5.5 Summary

The above analysis shows that although relying on resident interaction as a means of evacuation may result in the clearance of the building, its effectiveness is also sensitive to a range of assumptions which can lead to situations in which only a proportion of the residents become aware of an incident before deciding a course of action. The simulations also assume there is a single mode of agent interaction where communication is via a remote means such as a text message etc. It is likely that in a real incident there will be a mixed mode interaction. For example, a more complex simulation would be to assume the contact on the same floor is face-to-face but contact on other floors is via digital message.

Inter-agent social communication can be combined with the activation of a building-wide automatic detection and alarm system which enhances the likelihood that all occupants will decide to evacuate the building. Although simulating a combined means of notification is viable within the Evacuationz tool, it can only represent relatively simple situations that rely on numerous assumptions.

A3-10.6 Alerting by Fire and Rescue Service – Scenarios D20 to D21

A3-10.6.1 Arrival delay

The arrival of fire and rescue service (FRS) personnel provides opportunities to alert the occupants of the building either by knocking on doors or, where available, activating a dedicated alerting system. Both mechanisms can be simulated in Evacuationz, but in both cases there will be a delay before the FRS arrives, begin their operational activities, and make the decision to alert the building occupants. This delay must be reflected in the modelling.

In previous work by Hopkin et al. [58] FRS arrival has been represented by a lognormal distribution with a mean of 23.7 min and standard deviation of 29.2 min. As discussed by Hopkin et al. this arrival time is a combination of the 'ignition to discovery', 'discovery to call' and 'response time' values reported in the Dwelling Fires Database. The ignition to discovery time is an approximation of the time elapsed from the ignition of the fire to its discovery. As such, the arrival time might be considered 'conservative' for the simulations as the ignition to discovery time is already incorporated into the detection, arousal, assimilation and contact times. However, the arrival time does not include the time needed for FRS personnel to set up operations and any time elapsed before deciding to alert the occupants. Therefore, in the absence of further information the same 'delay' time lognormal distribution given by Hopkin et al. has been adopted herein.

A3-10.6.2 Dedicated FRS alert system

BS 8629:2019 [59] is a code of practice for evacuation alert systems (EAS) for use by fire and rescue services in buildings containing flats. The standard describes a system as one "…*that enables occupants of flats to be alerted by the incident commander* [which] *can support the operations of the fire and rescue service*…" The system is designed so that the building is divided into individual evacuation alert zones that should not extend beyond a single building storey. Responding FRS personnel can select which evacuation zones they wish to alert and when it is deemed appropriate to do so.

Given there are various strategies that the FRS could use to facilitate a building evacuation using an EAS, Scenario D20 assumes the FRS activate a building-wide tone alert after the arrival time has elapsed. This scenario is similar to Section A3-8.5

where it is assumed that on average 80% of agents respond to the notification by starting their evacuation procedure.

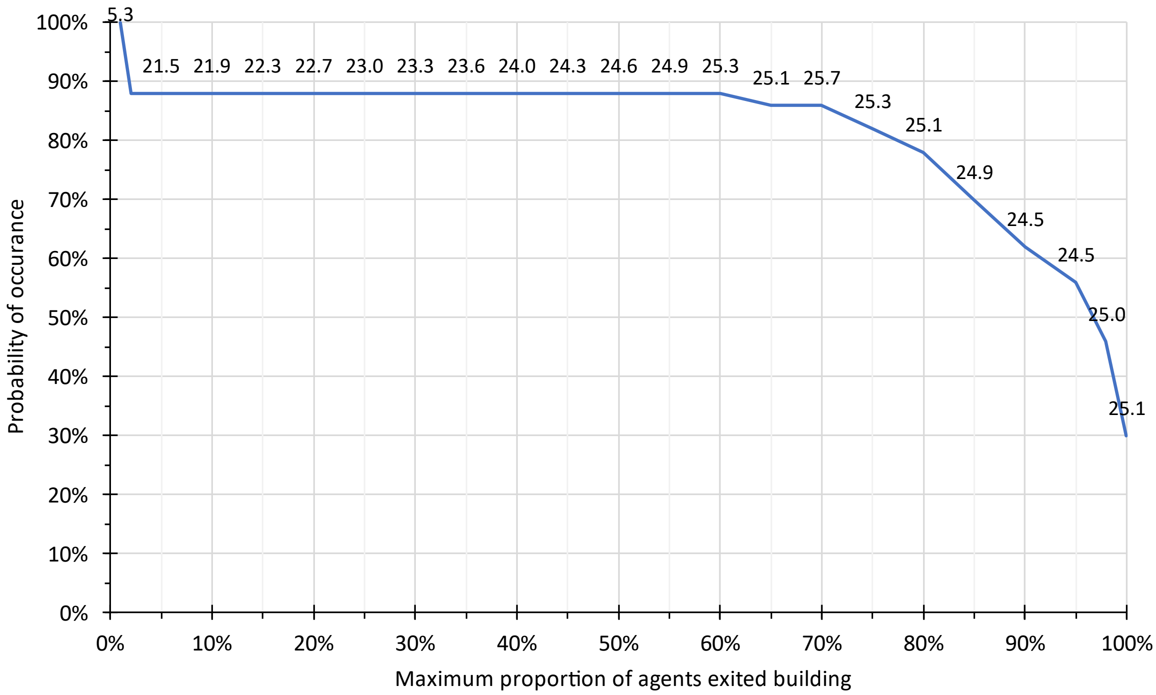


Figure A3-42 Likelihood of a given proportion of agents to exit the building when FRS activates a tone alarm on arrival. Number indicates average time of evacuation in minutes

Figure A3-42 shows the results of 50 simulations conducted for Scenario D20. There is a 100% likelihood that 1% or less of the agents will exit with an average of 5.3 min as these are the agents in the flat of fire origin. Between more than 2% and less than 60% of agents the likelihood remains at just below 90% with average times going from 21.5 min to 25.3 min. Thereafter as the proportion of agents increases to 100% that exit the building, the likelihood falls away towards 30% with average times varying around the 25-minute mark.

A3-10.6.3 FRS alerting occupants face-to-face

In the introduction to BS 8629:2019 [59] it notes that "*If, on rare occasions, the fire and rescue service consider that occupants of other flats do need to evacuate, they will alert these occupants simply by knocking on the doors of their flats. This is only likely to apply to a small number of flats…*" As such, a scenario in which FRS personnel alert the building occupants face-to-face is similar to the scenario discussed in Section A3-4.6.3 where in this case FRS personnel move from floor to floor, alerting occupants by knocking on flat doors. Clearly there are various strategies that could be applied by the FRS on which floors to visit in which order. For example, might it be optimal to start from the top of the building and travel downwards, or start at the most fire and smoke affected floors, etc. In addition, with appropriate resources the FRS may be able to dispatch multiple teams to go to different floors simultaneously. It is beyond the scope of this study to assess all these options and further engagement with FRS personnel to understand their procedures in these situations would be necessary.

However, as an indication of how this might be simulated in Evacuationz, a relatively simple scenario is presented here in which it is assumed a single team starts at the bottom floor and systematically works up the building. As an approximation Scenario D21 assumes FRS personnel travel 30 m per floor to allow them to reach each flat along the 15 m corridor and return to the stairs before ascending the next flight of stairs which has 16 steps. Claridge and Spearpoint [60] measured fire-fighter ascent speed from a minimum of 0.3 m/s (or 0.4 steps/s) and a maximum of 1.1 m/s (or 1.7 steps/s) for travel up 5 to 10 levels in a building. Therefore, the travel time travel would take around between 37 and 140 s (0.6 min and 2.3 min).

Similar to the discussion in Section A3-4.6.3, there would be waiting for the time for each flat to respond (which may mean waking occupants up) plus the communication time which has been previously taken to be 60 + 10 = 70 s (1.2 min). With seven flats on a floor then the total interaction time would be 490 s (8.2 min). Thus, the total response delay per floor could be taken as a uniform distribution between 527 s and 630 s (8.8 min and 10.5 min). However, FRS personnel may knock on all the flat doors effectively simultaneously and then wait for a response from any flat before communicating with those occupants. The interaction time might then be the travel time plus 60 s (1.0 min) waking delay to alert the flat occupants, followed by 10 s communication time per flat. This would make the floor delay between $37 + 60 + (7 \times 10) = 167$ s (2.8 min) and $140 + 60 + (7 \times 10) = 270$ s (4.5 min).

The simulations carried out for this analysis have a single agent (representing a responder fire-fighter) on the ground floor that responds to an ‘alarm’ set to the FRS arrival time distribution discussed in Section A3-10.6.2. This agent then alerts the other agents on the ground floor who in turn alert the next floor up after a delay of between 167 s and 270 s (2.8 min and 4.5 min). This is then repeated on the floors above. It is assumed that when an agent representing a resident is contacted, they always respond by evacuating, with an awake, FRS implied delay time from Table A3-6 (since the waking time is already incorporated into the floor-to-floor delay).

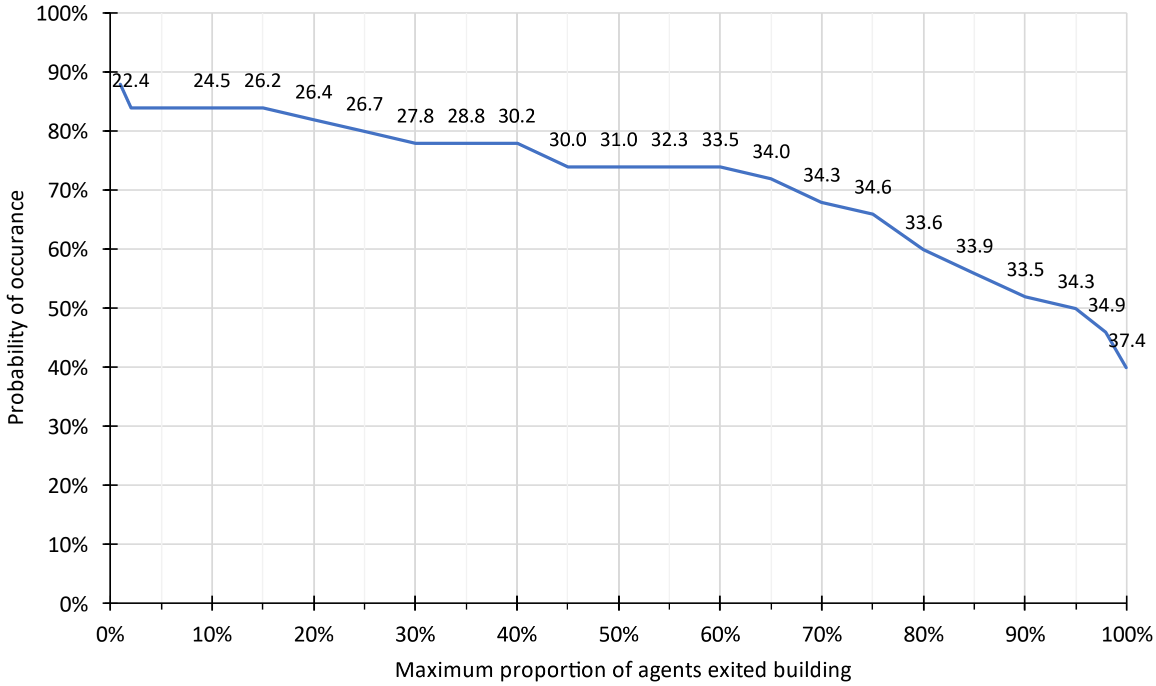


Figure A3-43 Likelihood of a given proportion of agents to exit the building when FRS alerts occupants face-to-face travelling up the building floor by floor. Number indicates average time of evacuation in minutes

Figure A3-43 shows the results of the simulations in which around 40% of cases where all agents exit the building in an average time of 37.4 min. The average time for a given proportion of the building occupants steadily decreases with proportion rather than there being a sharp transition as in the case of the remote alerting mechanisms.

A3-10.6.4 Interaction with FRS activities

The work presented above represents a small number of the scenarios reflecting potential interaction between the FRS, the building, and the occupants. The simulation results are sensitive to the expected arrival time of the FRS and subsequent times to carry out operational activities along with the time it might be expected for parts of the building to be affected by smoke. Section A3-10.6.1 applied a lognormal distribution with a mean of 23.7 min and standard deviation of 29.2 min for the FRS arrival delay which when compared with the times in Table A3-16 means it is likely that parts of the exemplar building would have smoke already present. Further work would be needed to assess whether the lognormal delay distribution is representative of high-rise residential buildings which are likely to be in urban areas rather than FRS arrival times across all dwellings. In addition, the assumed delay does not consider how the height of the building and the location of the fire in a building might affect the delay time. Again, further work would be needed to investigate these factors.

It is also important to note that simulating the FRS personnel alerting occupants face-to-face does not include the effect of those personnel potentially restricting the descent of building occupants – it instead focuses on the impact of the personnel on resident response. The simulations do not consider whether charged hose lines have any impact on the movement of occupants. In addition, the effect of these impediments on those less able-bodied may be greater than more able-bodied occupants, and anecdotal experience of the authors would suggest charged hose lines may be sufficient to create a significant barrier to the use of some evacuation devices. One approach to assess the movement between the FRS and their equipment with agents evacuating could be to consider that a narrower stair provides a measure of this impact. This would likely provide a conservative outcome given the interactions would only manifest themselves once the FRS arrives rather than being present throughout the earlier stages of the evacuation.

The analysis in Section A3-10.6.2 was limited to assuming that the FRS alerted all agents in the building using the EAS rather than only limiting the alert to individual zones and the decision to alert was cognisant on the smoke conditions within the building. Simulations using Evacuationz could be carried out to investigate these elements in more detail in future work. Examples of phased evacuation simulations are given in Section A3-10.7.

Further simulations in which both the dedicated FRS alert system and a floor-by-floor sweep by FRS personnel could be investigated. In this case the number of occupants that would need face-to-face communication would be reduced given the expectation is that the majority would have likely responded to the alert. This could mean that FRS personnel do not need to spend as much time on each floor when compared to the scenario presented in Section A3-10.6.3. Simulating the variable number of occupant agents that directly interact with FRS personnel is beyond the current capabilities of Evacuationz.

Figure A3-43 shows the evacuation times for given proportions of occupants, e.g., there is a 40% likelihood of 100% of the agents evacuating with an average time of 37.4 min. This might be compared against the results shown in Figure A3-40 where there is a 3% likelihood of 100% agents evacuating in average time of 40.5 min; i.e., face-to-face FRS alerting is more effective at getting a full building evacuation compared with the resident communication. **The findings from the analysis of FRS involvement with a building evacuation procedure suggest that a floor-by-floor sweep of a building resulting in a face-to-face interaction with residents may be more effective than using a manually activated alarm system. However, the results shown herein require a wide range of assumptions in support of its findings and the scenarios simulated are very limited in their scope.**

A3-10.7 Phased alarm notification – Scenarios D22 to D23

An alternative to having a simultaneous building-wide alert is to use a phased alert (and associated phased evacuation response). Typically, phased evacuation is used in buildings in which the exit capacity of stairs is limited by the potential number of occupants that might want to simultaneously use them. BS 9999 [61], for example, provides commentary on the use of phased evacuation. However, there is no universal approach to the order in which alarms zones are activated, nor the delay times between zones. In terms of delay times, applying a short delay would be similar to having a simultaneous building-wide alarm and applying a long delay would eventually mean that occupant evacuation times would become significantly extended. BS 9999 notes that fire marshals/wardens should be appointed who will provide information that govern the time periods between evacuation phases. However, it is not expected that such dedicated resources would be required in residential buildings covered by ADB.

To illustrate how a simple phased alert could be implemented the simulations assume that each floor is a unique alarm zone. The tone alarm signal is used with smoke detection on the corridors, the same as Scenario S8. All agents respond to the alarm, and the delay between floors is the sum of the arousal time and the assimilation time given in Table A3-6 for sleeping occupants, i.e., 95 + 60 = 155 s (2.6 min). Agents are assigned the pre-evacuation delays as per Table A3-6. Figure A3-44 compares the results from Scenario S8 with Scenario D22. The delay in alerting agents in Scenario D22 means that the average final evacuation time moves from around 40 min to around 56 min. This result is not very surprising given a delay of 155 s for each of the six upper floors is 15.5 min.

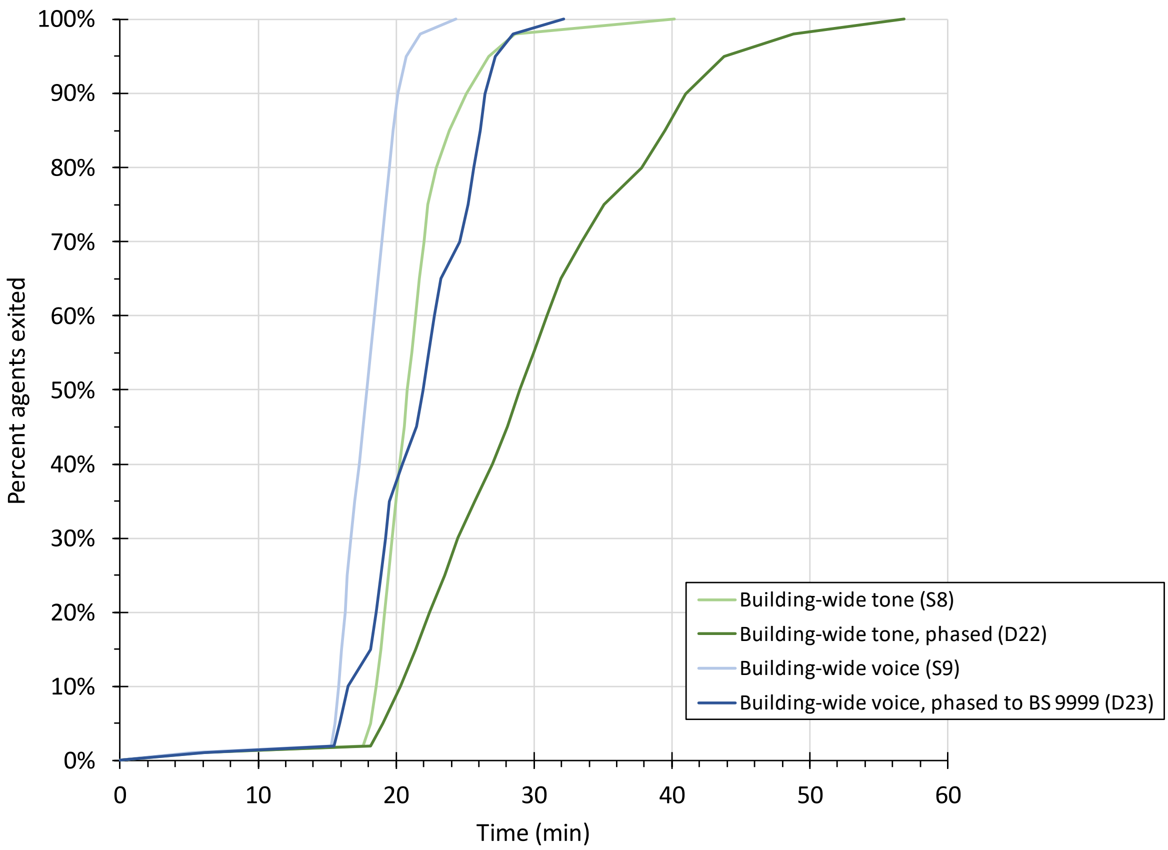


Figure A3-44 Comparison of automatic building-wide tone alert system evacuations using simultaneous (Scenarios S8-S9) and phased alerting (Scenarios D22-D23)

Clearly there are a multitude of other options available for the delay time and/or the number and order that floors are alerted that could be simulated. For example, BS 9999 recommends that where phased evacuation is used then a voice alert should be provided. The standard also suggests that the normal sequence of evacuation should be:

- The floor of origin of the fire,
- The next two floors above,
- The remaining floors in groups of two working up the building, and
- Floors in groups of two below the floor of origin working downwards.

noting that the sequence may need to be altered depending on the situation. Scenario D23 simulates the BS 9999 recommendation, with the result shown in Figure A3-44 compared to Scenario S9 with a building-wide simultaneous alert. The combination of the voice alarm and floor alerting results in the total evacuation extending from around 24 min to around 32 min. As previously identified, the difference is simply because of the applied alert delay time, in this case $3 \times 155 = 465$ s or close to 8 min.

Where a building includes amenity spaces there may be benefits phasing evacuation from those areas when compared to the parts of the building that has the residential accommodation. Such benefits will likely depend on the time of day, the number of people using the amenity space, how people evacuating from the amenity space utilise the escape routes, etc. Such factors have not been investigated in this study.

Selected simulations using phased evacuation suggest that this approach may have limited application in high-rise residential buildings as they essentially extend the total evacuation time by the delay in alerting floors. The simulations have not considered how fire marshals/wardens might be used to control the evacuation procedure. Phased evacuation may be of benefit when amenity spaces are present within a building as the inclusion of such spaces may disrupt the routine occupant distribution and cluster people in specific locations affecting the demand on vertical egress components.

A3-10.8 Occupant state in amenity scenarios – Scenarios D24 to D25

The scenarios with amenity spaces in the Parametric analysis assume that all the building occupants are awake as this is considered to be a more reasonable / realistic occurrence given the use of the space (i.e., people will not be sleeping in the amenity space) and the amenity space will likely be in use when people are in the building and awake (e.g., in the evening). Scenarios D24 to D25 investigate this assumption by varying the agent state (i.e., awake or asleep). Due to the nature of the use of the space, the agents in the amenity space are always assumed to be awake.

To assess the impact of the state of the flat occupants on evacuation, the same building configuration described in Section A3-10.1 is examined – with the amenity space located at the topmost storey (the impact of amenity location has been examined previously in Section A3-7.2.4). Occupants are assigned the corresponding ‘tone’ pre-evacuation delay distribution subject to whether they are awake or asleep. Scenario P25C is the corresponding Parametric scenario whereby all occupants are assumed to be awake. Scenario D24 considers a situation where occupants in the flats are asleep with the amenity occupants awake.

To assess the impact that the amenity space has in both flat occupant state scenarios, the corresponding scenario with no amenity spaces has been modelled. Scenario D25 considers where there is no amenity space, but occupants of the flats are awake, with Scenario P7C the equivalent scenario where the flats are asleep (from the Parametric analysis). Table A3-48 presents the results of the four scenarios.

Table A3-48 Impact of amenity spaces and agent state on evacuation time

Scenario	Alarm	Amenity	Building population	Amenity population	Evacuation time (min)
P25C	Tone	Yes	Awake	Awake	26.5
D24	Tone	Yes	Asleep	Awake	31.1
D25	Tone	No	Awake	-	28.1
P7C	Tone	No	Asleep	-	31.5

Figure A3-45 compares the results of the four scenarios. Investigating the impact of the state of the flat occupants, when flat occupants are asleep, there is little difference between the total evacuation time results produced in these scenarios with amenity spaces (31.1 min in Scenario D24) and without amenity spaces (31.5 min in Scenario P7C) by the end of the evacuation. This implies that the overall building evacuation time is driven by the flat occupants and that the amenity space has little bearing on the end result, while it might have a modest impact on the evacuation dynamics.

Conversely, when the flat occupants are also awake, the presence of an amenity space impacts both the total evacuation time and the evacuation performance throughout, as can be seen in the difference between Scenarios P25C and D25 in Figure A3-45. This reaffirms the adoption of all building occupants being awake in the Parametric analysis due to the more prevalent impact of this combination of occupant state.

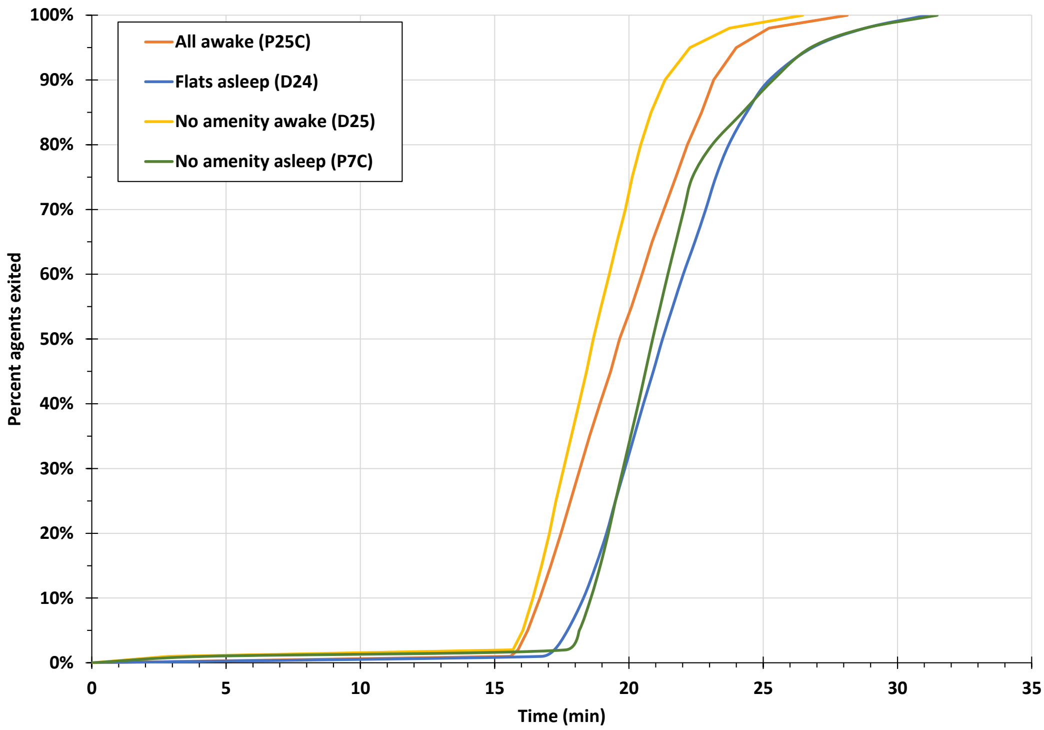


Figure A3-45 Comparison of different occupant states with amenity spaces (Scenarios P25C and D24) and without amenity spaces (Scenarios D25 and P7C)

As noted in Section A3-10.7, and depending on specific circumstances, the adoption of a phased evacuation strategy may be appropriate when amenity spaces are included in a building. For example, depending on the relative location of the fire and amenity space/s may mean alerting the occupants of the amenity space ahead of the flat occupants could have a beneficial impact on evacuation times. These conditions have not been examined in this study though might be best considered on a building case-by-case basis rather than attempting to provide specific guidance.

The findings currently suggest that including amenity spaces are likely to affect evacuation times, but the maximum expected time is unlikely to be much different to the case for a similar building in which the flat occupants are asleep.

A3-10.9 Modelling evacuation involving movement impaired people and use of lifts – Scenarios D26 to D31

A3-10.9.1 Modelling lifts

Traditionally, lifts (elevators) have been excluded as a means of escape for safety concerns in operating the lifts in emergency evacuation, especially when there is a fire in the building. However, the potential benefit of using lifts in evacuation might be safeguarded if lifts are protected by certain safety features (e.g., emergency power, protection of the power and control wiring, etc) and provided with suitable controls and control logic. Benefits might take several forms. Firstly, lifts are generally faster in comparison with using stairs to move occupants vertically in high-rise buildings if the number of people to be evacuated by lifts is managed so that their accumulated waiting time is less than their stair traversal time (should they elect to use stairs). Secondly, movement impaired occupants can benefit from using lifts as they may either walk slowly on stairs or be unable to use stairs at all without the help of other people.

There is an increasing interest in calling for a change in the policy of not using lifts as a means of emergency evacuation. At present, there is no published guidance on occupant self-evacuation and associated prioritisation with the use of evacuation lifts in residential flats buildings in England. However, BS 9999 [61], which covers safety in the design management and use of buildings, provides recommendations for the evacuation of disabled people using lift under certain conditions. In addition, a draft British / European standard on the evacuation of disabled persons using lifts (prEN 81-76 [21]), which was issued for public consultation in 2019 and is understood to be in the ‘comment resolution’ stage of the publication[13], may introduce new changes. As such, there remain gaps in guidance as to the practical application of evacuation lifts in buildings, particularly when considering the operation of these; e.g., by residents, by building management (where applicable), etc. In light of a lack of applicable guidance on the wider application of evacuation lifts in residential buildings, the authors have followed the recommendations in BS 9999 to simulate the evacuation of movement impaired people using lifts with the recommended lift operation, as detailed below.

The recommendations in BS 9999 address various aspects of using lifts to evacuation disabled people. Of these, three are directly related to the simulation work:

(1) The types of lift that can be used and the requirements.

> **BS 9999 Clause 45.9** - “*A lift to be used for the evacuation of disabled people should usually be either an evacuation lift or a firefighters lift, and should be operated under the control of the fire safety manager or a delegated representative, or otherwise by someone trained and authorized in the use of the lift.*”

[13] As of 14/08/2023, per the BSI Standards Development website: standardsdevelopment.bsigroup.com/projects/2018-03148#/section

“A lift that is not explicitly designed for evacuation may be used for evacuation, provided that it provides the same functionality as an evacuation lift.”

(2) Who should use the lifts in evacuation.

BS 9999 Annex G.2.1 - *“Where evacuation lifts are provided, their use to evacuate people requiring assistance should be a matter of priority. Once under staff control, the lift should normally only used to evacuate those persons in need of assistance. ... Other building occupants should be directed to escape via the alternative vertical circulation routes provided for that purpose.”*

(3) The operation of lift.

BS 9999 Annex G.2.3 - *“The lift car should be taken only to those levels where a person is in need of assistance.*
An operator ... take control of the lift and proceed to move people requiring assistance to the final exit level.
Unless a different order has been agreed with the fire authority, evacuation should normally be in the following order:
1) the fire floor;
2) the floor immediately above the fire floor;
3) other floors above the fire floor starting at the top storey;
4) all remaining floors.”

The simulation of lift use in evacuation carried out in this work is based on the above recommendations, which assumes:

(1) The lift(s) (either evacuation or general passenger lift), which meet the requirements for use in evacuation, is available for evacuation of movement dependant people from the high-rise buildings modelled, and that the lift(s) is controlled by an authorised person. It was deemed unnecessary to explicitly include an agent in the model to represent the lift operator, but instead represent their actions in the form of lift operation.

(2) The lift(s) is only used by MDP agents, i.e., movement dependant people. In scenarios with evacuation lifts, MDP agents do not use other means of evacuation.

(3) Given that the fire location is not represented in the scenarios, steps 1) and 2) of the lift operation order defined in Annex G.2.3 are not simulated, but only steps 3) and 4) (i.e., evacuate people in a top-down order), so the approach is a simplification given the unknown variable of fire location.

(4) Given the MDP agent is represented by a wheelchair in Pathfinder and the size of lift defined, a lift car can only take one MDP agent at a time.

(5) The modelled lift(s) only goes to the storeys with calls of MDP agents and takes them one by one in a top-down order to the ground floor (i.e., final exit floor) without stopping at any intermediate floor.

The modelling of the lift operation in this work mirrors the recommendations of BS 9999. However, there are several factors that were not or were unable to be considered.

(1) The delay for a lift operator to be in place and take control.

(2) The impact of fire location on lift operation, especially the pick-up order.

(3) Other pick-up orders not defined in BS 9999.

(4) The capacity of lift (given the lift car can take one MDP at a time, the simulations produce a conservative estimate).

(5) The variation in lift specification, such as lift speed, door opening time, etc.

However, the approach adopted is consistent across the scenarios allowing relative performance to be established.

To examine the impact of using lifts in evacuation that involve movement impaired occupants from high-rise residential buildings, Scenarios D26 to D31 are implemented, using two building designs selected from those used previously and the same population. The only difference among these scenarios is that a sub-population (i.e. the MDP agents) do not have access to a lift, have access to one lift or two lifts respectively during the evacuation process. The variation of lift availability along with two selected buildings, the lift operation, the assumptions, and the simulation results are now described. Note that this work employs Pathfinder only, as explained in Section A3-6.1.

The two buildings selected for the three scenarios is a 7-storey, 18 m and an 11-storey, 30 m tall building based on Floorplate 1 (see Section A3-2.1) which comprises a mixture of seven 1-, 2- and 3-bedroom flats and a single staircase (1 m wide for the former and 1.1 m wide for the latter). Each building is populated with two persons per bedroom across all floors. These two buildings have been selected for this analysis based on the assumption that taller structures would unduly amplify the benefits of lift introduction. Therefore, benefits seen for these two buildings might allow the work to capture a range of impacts while conservatively estimating the benefits of the other buildings examined here (e.g., 140 m, etc.).

The total number of occupants is 196 for the 7-storey building and 308 for the 11-storey building, given the assumed occupancy levels of each flat. Of these, 20% are assumed to have a movement impairment (i.e., MIPs) – such that 15% of the overall population can descend stairs unaided (i.e., MRPs), and 5% would only be able to descend stairs with assistance, (i.e., MDPs). Their unimpeded movement speeds are defined in Section A3-3.1. Each agent has a single derived pre-evacuation time, which is based on the state (asleep), means of notification (tone/bell) and their level of impairment (See Table A3-5 in Section A3-4.5). To simplify the scenario, the MDPs are modelled as wheelchair users that can operate their devices without assistance (see Section A3-3.2). It is assumed that only those that must use the lifts to reach a place of safety outside of the building (MDPs) during an emergency will do so. As such, the lifts are assumed not to provide additional capacity for those without a movement impairment which also means those without impairments do not take away lift capacity for those with impairments – that lift use is for MDP alone. The selection of these parameters and assumptions intends to make a conservative estimation of the evacuation performance.

Two lift shafts are modelled by the stair core in the building with lift doors opening towards the central corridor on each floor. Each lift has a maximum load of nine standing agents. However, it is assumed that only MDP agents can use the lifts where the lifts are simulated as being available in the corresponding evacuation scenario. Given the size of the wheelchair and the space required to manoeuvre it (see Section A3-3.2), the lift is assumed to carry one wheelchair and its user at a time (again to be conservative). The lifts are operated following the egress-mode operation defined in Pathfinder, which can be summarised as:

- At the beginning of the simulation, the lifts start at the discharge floor, which is the ground floor,
- The lifts serve called pickup floors (i.e., any floor above the ground) with the default priority system from top to bottom, and
- Once a lift has picked up agents, it travels to the ground floor and lets the agents off before responding to next call in the priority system.[14]

[14] BS 9999:2017 states that an evacuation lift should be controlled by a designated operator evacuating the fire floor, the two floors above the fire floor, and then top down. The fire location affects this process. Given that results from this study are more location-agnostic, the simulations simplified this to evacuating the building from the top-down. So, although simplified, it largely complies with BS 9999:2017.

Three scenarios are examined for both buildings:

- 18 m / 7-storey building:
  - Scenario D26 – no lifts in use,
  - Scenario D27 – one available lift, and
  - Scenario D28 – two available lifts.
- 30 m / 11-storey building:
  - Scenario D29 – no lifts in use,
  - Scenario D30 – one available lift, and
  - Scenario D31 – two available lifts.

In all cases a single stairwell is available that all non-MDP agents are assumed to use. In addition, all lifts are assumed to be operable by the evacuating population and do not require staff to arrive.

These scenarios are used to examine the difference in evacuation performance given the three different levels of evacuation lift availability (0, 1 and 2). For each scenario, 50 simulation runs have been performed and each time the location of the population are randomised across the whole building within the flats, so that the sensitivity to a particular population distribution can be minimised.

A3-10.9.2 Simulation results and discussion

Table A3-49, Table A3-50 and Figure A3-46 present the overall evacuation performance of the three scenarios for each building in terms of total evacuation time, average congestion experienced and average travel distance. It is apparent that **the total evacuation time of all three scenarios is primarily determined by the time required by the 5% MDP population to escape**, as not only do they have a longer pre-evacuation times, but also reduced travel speeds. Although the 5% MDP population start their evacuation later, on average, they still interact with the other agents during the evacuation process (e.g., both in corridors and on stairs in the control Scenarios D26/D29 which have no lift available in the evacuation), given their starting location within the building and the existence of congestion that might delay the movement of people leaving various floors. These interactions might disrupt the movement of those without movement impairments (see Figure A3-47 for a snapshot of a simulation run).

Table A3-49 Comparison of the evacuation performance with no lift, one lift and two lifts in evacuation across the two building designs with evacuation times in seconds.

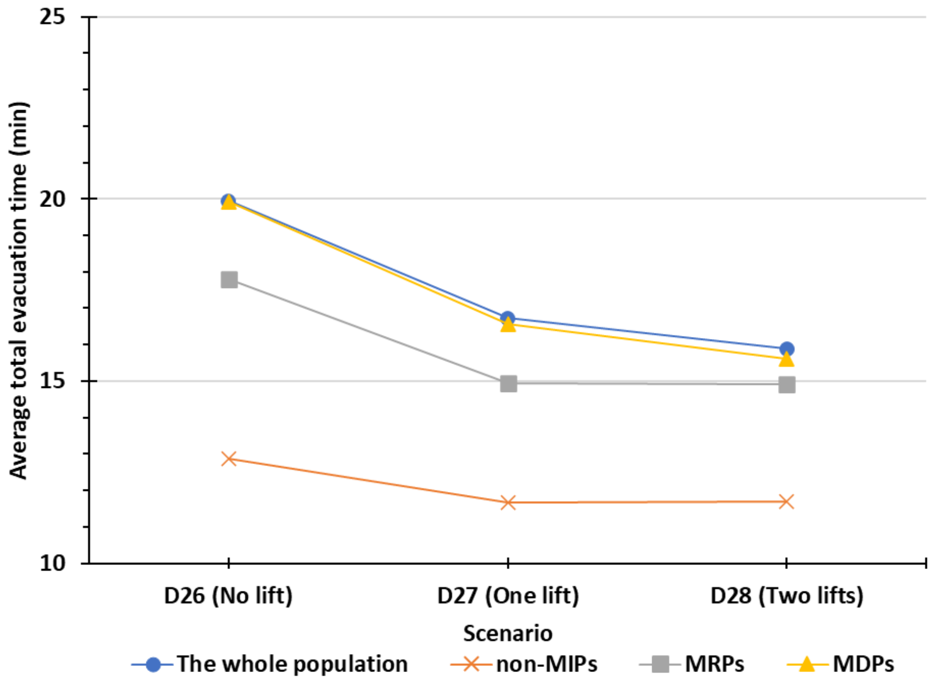
Building	Scenario	Lift / stairs	Total evacuation time (s)				Mean con-gestion (s)	Mean travel dist. (m)
			All	Non-MIPs	MRPs	MDPs	All	All
18 m / 7-storey	D26	0 / 1	1197 ± 161	772 ± 125	1067 ± 109	1196 ± 162	23 ± 9	51 ± 0
	D27	1 / 1	1004 ± 79*	701± 67	897 ± 49	994 ± 94	10 ± 4	49 ± 1
	D28	2 / 1	953 ± 48*	701 ± 67	895 ± 44	937 ± 68	9 ± 3	49 ± 1
30 m / 11-storey	D29	0 / 1	1429 ± 199	989 ± 142	1313 ± 165	1429 ± 200	54 ± 13	71 ± 0
	D30	1 / 1	1213 ± 151	794 ± 48	979 ± 72	1213 ± 151	28 ± 7	68 ± 1
	D31	2 / 1	1066 ± 77*	795 ± 49	972 ± 53	1058 ± 85	24 ± 5	68 ± 1

* It should be noted that in most instances the last agent out during Scenarios D27–D28, D31 were MDPs. However, in some cases a few agents (mostly MRP agents) were caught in congestion on the stairs or had a longer pre-evacuation time – prolonging the evacuation time beyond the lift movement.

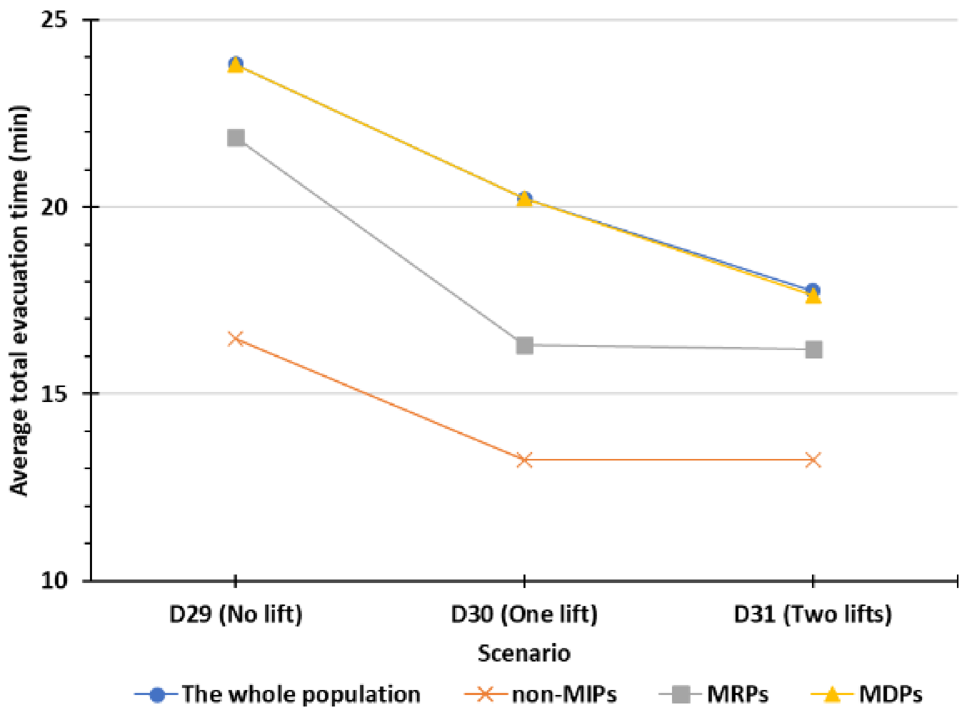
Table A3-50 Comparison of the evacuation performance with no lift, one lift and two lifts in evacuation across the two building designs with evacuation times in minutes

Building	Scenario	Lift / stairs	Total evacuation time (min)			
			All	Non-MIPs	MRPs	MDPs
18 m / 7-storey	D26	0 / 1	19.9 ± 2.7	12.9 ± 2.1	17.8 ± 1.8	19.9 ± 2.7
	D27	1 / 1	16.7 ± 1.3	11.7 ± 1.1	15.0 ± 0.8	16.6 ± 1.6
	D28	2 / 1	15.9 ± 0.8	11.7 ± 1.1	14.9 ± 0.7	15.6 ± 1.1
30 m / 11-storey	D29	0 / 1	23.8± 3.3	16.5 ± 2.4	21.9 ± 2.7	23.8 ± 3.3
	D30	1 / 1	20.2 ± 2.5	13.2 ± 0.8	16.3 ± 1.2	20.2 ± 2.5
	D31	2 / 1	17.8 ± 1.3	13.2 ± 0.8	16.2 ± 0.9	17.6 ± 1.4

When one lift is added to the evacuation in Scenario D27 (that is then exclusively used by the MDP population) for the 7-storey building, the total evacuation times of all three population groups (non-MIP, MRP and MDP) decreases by 9.3%, 16.0% and 16.9% respectively in comparison to Scenario D26 where no lift is present. Similarly, when one lift is added in Scenario D30 for the 11-storey building the total evacuation times of the non-MIP, MRP and MDP groups decrease by 19.7%, 25.4% and 15.1% respectively in comparison to D29 where no lift is present.



Scenarios D26–D28 (7-storey building)



Scenarios D29–D31 (11-storey building)

Figure A3-46 The set of evacuation times of three scenarios with no lift, one lift and two lifts in evacuation across the two building designs

When a second lift is added in Scenario D28 for the 7-storey building, only the total evacuation time of the MDP population further reduces by 21.7%, while the total evacuation times of the MRP and non-MIP populations remain largely unchanged. Similarly, when a second lift is added in Scenario D31 for the 11-storey building, only the total evacuation time of the MDP population further reduces by 25.9%, while there is no further reduction in total evacuation time for the MRP and non-MIP populations. The addition of a second lift therefore provides benefits for the MDP population, with little impact on the other evacuees.

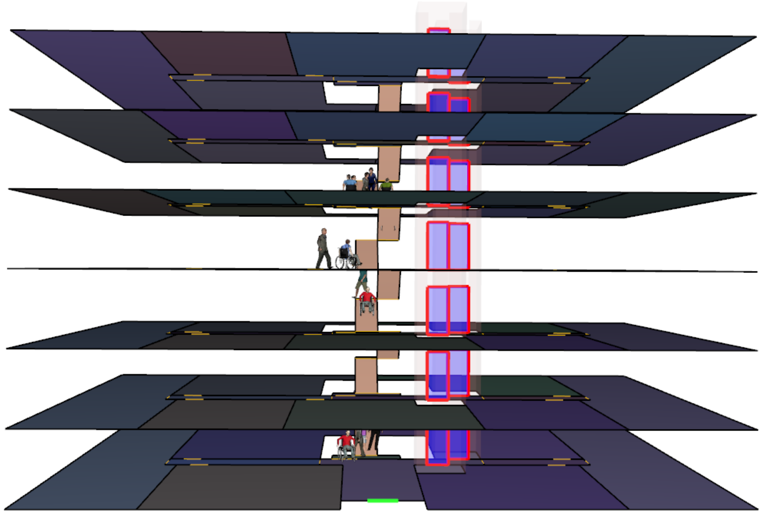
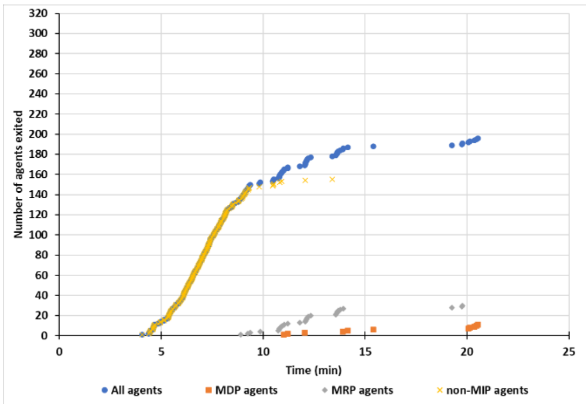
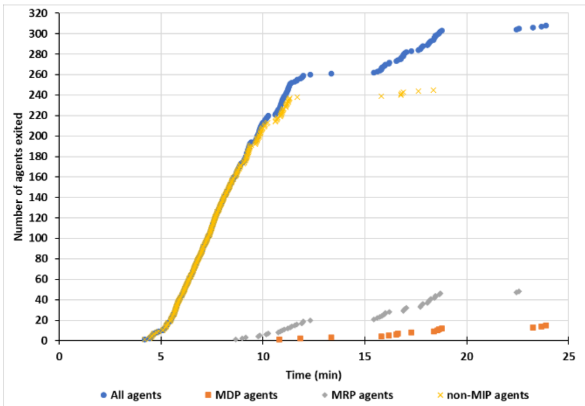


Figure A3-47 A few MDP agents disrupt the movement of the others on stair in Scenario D26 with no lift in use

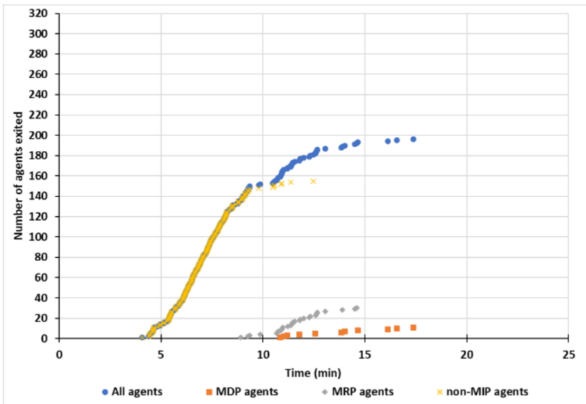
As the lifts are only used by the 5% MDP population in Scenarios D27, D28, D30 and D31, the improvement in mean travel distance is negligible compared with the control Scenarios D26 and D29. However, the population experienced half of the congestion time on average when a lift is available (or more than one lift) compared with the control scenarios in which no lift is available for both buildings. For the 7-storey building, evacuees queue in congestion for an average of 23 s of their evacuation in Scenario D26, while they queue for an average of 10 s and 9 s in Scenarios D27 and D28 respectively (where one or two lifts were present). The population travel an average of 50.9 m, 49.1 m and 49.2 m (largely on stairs) before reaching safety in these three scenarios respectively. The difference is due to variability in agent starting location. For the 11-storey building, evacuees queue for 54 s on average in Scenario D29 (where no lift is present) while they queue for 28 s and 24 s on average in Scenarios D30 and D31 respectively (where one or two lifts are present). The population travel 71.4 m, 68.2 m and 68.3 m on average (largely on stairs) before reaching safety in these three scenarios respectively.



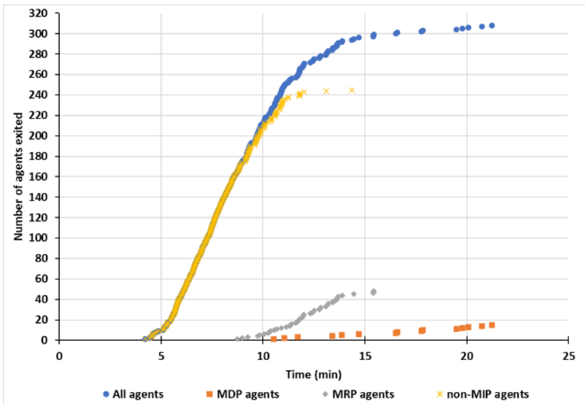
Scenario D26 (7-storey, no lift)
(a)



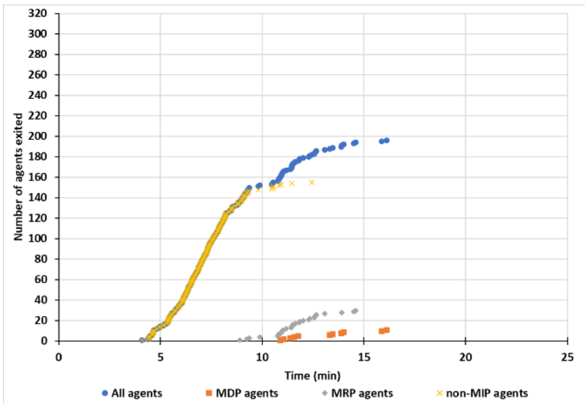
Scenario D29 (11-storey, no lift)
(b)



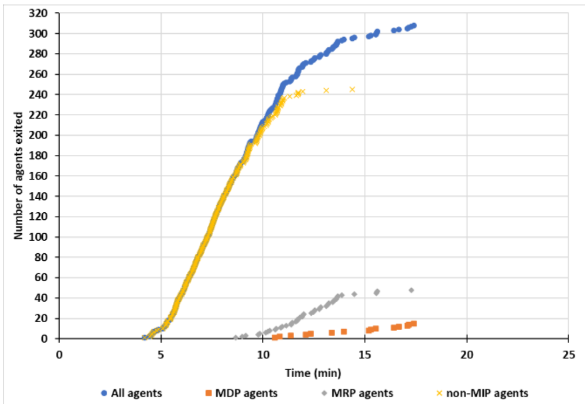
Scenario D27 (7-storey, 1 lift)
(c)



Scenario D30 (11-storey, 1 lift)
(d)



Scenario D28 (7-storey, 2 lifts)
(e)



Scenario D31 (11-storey, 2 lifts)
(f)

Figure A3-48 The exit curves of Scenarios D26–D31

Figure A3-48 shows the exit curves of the three groups of agents from a typical simulation run of each scenario.[15] The exit curves in Figure A3-48 (a) and (b) (i.e., the control Scenarios D26 and D29) are the longest among the three scenarios for the corresponding building examined; they show more frequent and prolonged gaps in arrivals, signifying the disruption caused by the slower agents evacuating on the stairs. It is apparent that the MIP population significantly prolonged the evacuation (by over 400 s or 7 min) for both buildings. The added lift(s) in Scenarios D27/D28 and D30/D31 (reflecting the introduction of one or two lifts respectively) segregate the MDP agents from the other evacuees, producing curves (see Figure A3-48 (c)–(f)) that reflect shorter evacuation times with fewer gaps in the arrival curve due to less disruption. The maximum reduction of the overall evacuation time through the introduction of one or two lifts for the 7-storey building is about 4 min (20.4%), and for the 11-storey building the maximum reduction is about 6 min (25.4%). In addition, the exit curves of the MDP population in these four scenarios reflect the patten of lift movement, i.e., the cycle of one or two lifts picking up the MDP agents.

These results show that lifts can improve occupant evacuation performance from high-rise residential buildings in two ways. Firstly, **lifts can be used to segregate the movement of impaired people from those without impairments, allowing the former to evacuate without the discomfort and physical challenges imposed by stair movement and the latter to move at their intended speeds and hence improve their evacuation performance.** As shown previously, the interaction between unimpaired evacuees and those with impairments can slow movement for both parties. It should also be noted that none of the modelling conducted here captures the physical and mental discomfort likely to occur when people with profound impairments are physically assisted during vertical movement. In addition, the modelling assumes that all people may receive sufficient assistance to traverse stairs. This is very optimistic.

Secondly, **the introduction of a lift system reduces the arrival time of those with significant movement impairments (MDPs), and hence the overall evacuation time**. The introduction of a single lift reduces MDP arrival times by 203 s (or 16.9%) for the 7-storey building examined in Scenario D27 and by 216 s (or 15.1%) for the 11-storey building examined in Scenario D30. The introduction of a second lift for the 7-storey building in Scenario D28 has only a marginal additional impact on performance, i.e., further reducing overall arrival times by 51 s (or 4.3 percentage points) over a single lift. However, it should be noted that this benefit might evolve for taller buildings where the numbers of significantly impaired occupants would increase. For instance, the introduction of a second lift for the 11-storey building in

[15] Where typical in this context measures producing an evacuation time close to the mean.

Scenario D31 further reduce overall arrival times by 148 s (or 10.3 percentage points) over a single lift.

For the buildings examined, the introduction of one lift benefits those using the lift and those using the stairs. The introduction of the second lift primarily benefits the lift users (making it more efficient), without reducing the evacuation times for those using the stairs.

It is apparent that if the total evacuation time is largely determined by the time required by the slowest population group to escape (as was the case in Scenarios D26 and D29), then the provision of a lift alleviates this dependence and that more lifts to facilitate movement impaired people might further improve the overall evacuation performance – up to a point where there are diminishing returns. This point is between one and two lifts for the 18 m tall building and between two and three lifts for the 30 m tall building; however, this point might change for taller buildings – indicating that the simulation of additional scenarios including taller buildings might be of value for more precise recommendations.

The normalised results from these scenarios are shown in Table A3-51, Table A3-52 and Table A3-53. It is apparent that the introduction of lifts (1) reduces evacuation time by approximately 20% for the entire population, (2) although still typically generating the overall evacuation time, the presence of lifts enabled the MDP to reach safety in times comparable to non-MDP populations when no lifts were present, and (3) the second lift had more of a benefit to the MDP evacuation performance, while having limited impact on the non-MDP evacuation time (when averaging across all building – see Table A3-52 – and for each building examined – see Table A3-53).

Table A3-51 Evacuation performance according to number of lifts across comparable scenarios (D26–D31)

Number of lifts	0	1	2
Evacuation time (min)	21.9	18.6	16.8
Normalised value	1.0	0.85	0.77

Table A3-52 Relative performance according to number of lifts across comparable scenarios (D26–D31)

	Non-MDP			MDP		
Number of lifts	**0**	**1**	**2**	**0**	**1**	**2**
Evacuation time (min)	17.3	14.0	14.0	21.9	18.4	16.6
Normalised value	1.0	0.81	0.81	1.0	0.84	0.76

Table A3-53 Relative performance according to number of lifts and building height across comparable scenarios (D26–D31)

<table>
<tr><th colspan="2"></th><th colspan="3">Non-MDP</th><th colspan="3">MDP</th></tr>
<tr><th colspan="2">Number of lifts</th><th>0</th><th>1</th><th>2</th><th>0</th><th>1</th><th>2</th></tr>
<tr><td rowspan="2">Storeys</td><td>7</td><td>1.00</td><td>0.87</td><td>0.87</td><td>1.00</td><td>0.83</td><td>0.78</td></tr>
<tr><td>11</td><td>1.00</td><td>0.77</td><td>0.77</td><td>1.00</td><td>0.85</td><td>0.74</td></tr>
</table>

A3-10.10 Floor clearance time – Scenarios D32 to D40

The Parametric analysis (Section A3-9) focused on the time to clear the building as an indicator of performance. This indicates the overall performance of the structure assuming that a full evacuation is required. Assuming that behavioural and system performance allows, the staircase might also be considered a place of safety (as discussed in Section A3-2.4.1). In such circumstances, arrival at the stair might be considered relief from unsafe conditions. **However, it should be acknowledged that although evacuees might effectively be safe, this is not in line with the survey responses from residents many of whom indicated that they would not wish to remain in the building.** This issue is left for discussion elsewhere. This section examines the time for evacuating occupants to reach the stair in different circumstances.

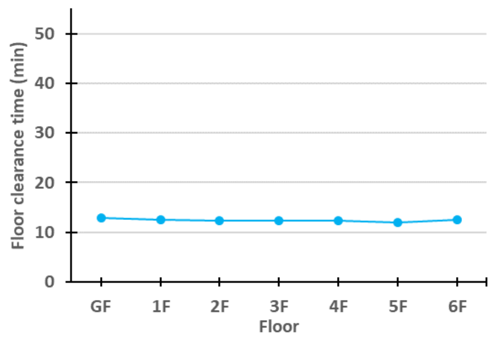
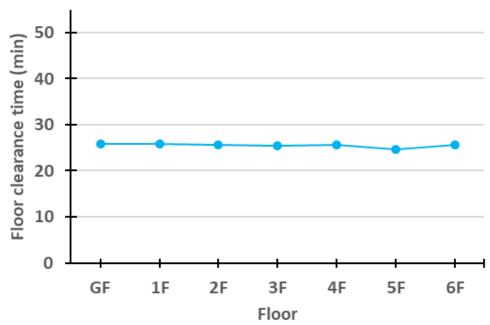
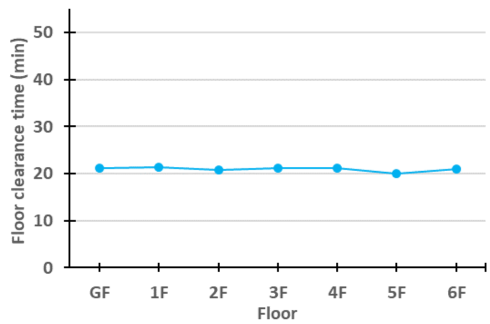
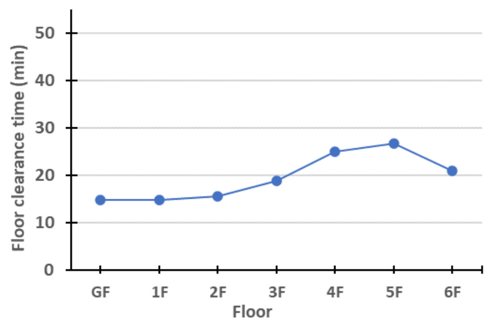
The time to clear floors has already been discussed in Section A3-7.2.2 (where stair width is the dominant factor). However, those simulations did not include the impact of a pre-evacuation delay, variable movement capabilities, nor whether one or two stairs were available. In Table A3-26, the potential for staircases to act as ‘refuges’ for storing evacuees is explored, i.e., the physical capacity of the staircases (including landings) to allow occupants to stand and shelter during an incident. It is apparent that there are several instances where the occupant densities produced exceeded levels typically assumed to allow movement (e.g., greater than 3.8 pers/m^2 which would prevent movement according the SFPE hydraulic calculation) or that would have hampered standing – especially on stairs (e.g., greater than 8 pers/m^2 [62]).

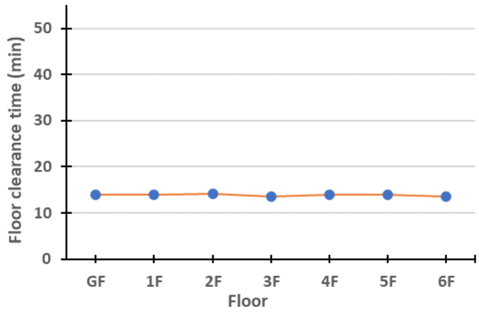
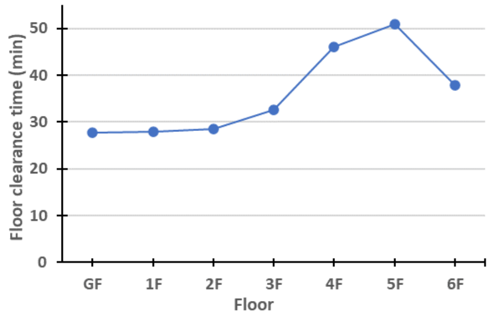
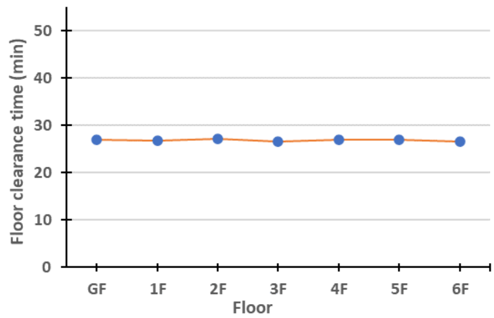
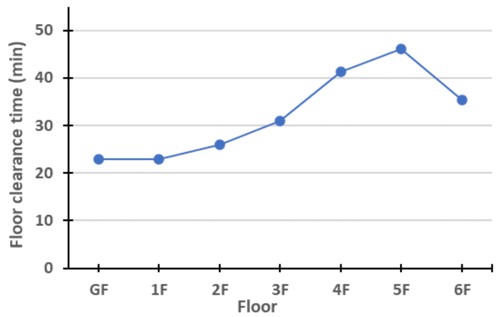
The analysis presented here examines the impact of those scenarios that place the highest demand on the available staircases (assuming credible scenario conditions) to determine whether congestion develops at the entrance of the stair – undermining the use of the stair as a refuge. Extensive queuing might suggest further remedial actions are required. In addition, this analysis is also designed to provide an indication of floor clearance times in scenarios when such local congestion is either present or absent.

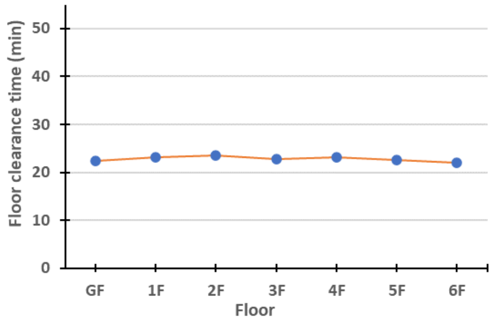
Table A3-54 shows the floor clearance times produced in Pathfinder across scenarios with the 15 m long corridor/single stair design and the longer 30 m corridor plate design (i.e., those buildings with larger populations that place a greater demand on the stair capacity) with either one or two stairs, and assuming the use of different detection systems (no detection or smoke detection in the corridor). All other factors are fixed (including building height, which is set to 18 m). This allows the impact of the varied factors to be explored and also simplify the estimates of floor clearance times (discussed later in this section).

It is apparent that floor clearance time is consistent within each scenario and independent of the floor location in Scenarios D32, D33, D34, D36, D38 and D40 (equivalent to Parametric Scenarios P7A, P7C, P7D, P12A, P12C, and P12D). Although Scenarios D32, D33 and D34 have 15 m long corridor and one stair, and Scenarios D36, D38 and D40 have 30 m long corridor and two stairs, all of them had relatively low estimated standing occupant densities (3.2 pers/m^2 and 4.7 pers/m^2 respectively) given a combination of the floor loading or the available floor space in the stair. This is important as in these simulations the low occupant density on the stair allows continuous vertical movement – preventing congestion to accumulate on the stairs and affect access to stairs on the floors above. This was confirmed by visually examining the simulated conditions produced.

Table A3-54 Floor clearance times produced for high-demand scenarios

Scenario (and parametric equivalent*)	Building attributes	Occupant density ** (pers/m²)	Detection / notification	Floor clearance time (min)
D32 (P7A)	18 m height, 15 m long corridor, 1 stair (1 m wide)	3.2	No detector/ global tone	
D33 (P7C)	18 m height, 15 m long corridor, 1 stair (1 m wide)	3.2	Corridor smoke detector/ global tone	
D34 (P7D)	18 m height, 15 m long corridor, 1 stair (1 m wide)	3.2	Corridor smoke detector/ global voice	
D35 (P10A)	18 m height, 30 m long corridor, 1 stair (1 m wide)	9.5	No detector/ global tone	

Scenario (and parametric equivalent*)	Building attributes	Occupant density ** (pers/m^2)	Detection / notification	Floor clearance time (min)
D36 (P12A)	18 m height, 30 m long corridor, 2 stairs (1 m wide)	4.7	No detector/ global tone	
D37 (P10C)	18 m height, 30 m long corridor, 1 stair (1 m wide)	9.5	Corridor smoke detector/ global tone	
D38 (P12C)	18 m height, 30 m long corridor, 2 stairs (1 m wide)	4.7	Corridor smoke detector / global tone	
D39 (P10D)	18 m height, 30 m long corridor, 1 stair (1 m wide)	9.5	Corridor smoke detector/ global voice	

Scenario (and parametric equivalent*)	Building attributes	Occupant density ** (pers/m²)	Detection / notification	Floor clearance time (min)
D40 (P12D)	18 m height, 30 m long corridor, 2 stairs (1 m wide)	4.7	Corridor smoke detector/ global voice	

* Reference should be made to Table A3-19 and Table A3-20 for the associated attributes of the original parametric scenarios.

** Reference should be made to Table A3-26 for the original calculation of the occupant density in the stairs for these buildings.

In Scenarios D35, D37 and D39 (equivalent to Parametric Scenarios P10A, P10C, and P10D) with one stair and much higher estimated standing occupant densities of 9.5 pers/m^2, several things can be noted: (1) floor clearance times are elevated in comparison to the equivalent scenarios with two stairs (i.e., Scenarios D36, D38 and D40), (2) floor clearance times varied between floors – typically rising up the building until the top floor is reached, and (3) congestion has been produced at the entrance to the stair (noted from numerical analysis and inspection of animations of each of the scenario simulations). The conditions produced in these scenarios are then qualitatively different from those examined above – for those cases where stair occupancy allows for those originally located on each floor to seek refuge. It should be remembered that these simulations (and all those performed here) assume two persons per bedroom, which is likely higher than an actual building population (see Section A3-10.5.2). The simulations here also exclude the use of amenity spaces, which would produce elevated local occupant populations.

These results suggest that the *simulated* clearance times from each floor are formed from the following elements:

> ***Floor clearance time = Detection time + pre-evacuation time + horizontal traversal time + floor congestion time***[16]

[16] The floor congestion is the congestion experienced by those leaving the floor and so will account for all the congestion experienced in the corridor, accessing stairs, etc.

Given that the above scenarios have been designed to control for these various factors, the floor congestion time can be estimated for the two types of outcomes produced: where floor clearance times were apparent or absent. The values can be derived by examining the original scenario conditions or by comparing the difference in the maximum floor clearance times produced where two stairs are present and the time produced where only one stair is present for otherwise equivalent scenarios (i.e., where congestion developed, or it did not). This produces an upper bound estimate of the floor clearance time in such situations. This is also tested by comparing the results of the equation with the simulated outcomes.

It should be noted that floor congestion time might include delays incurred while moving along the corridor or at the stair door. However, from inspecting the simulated output, the vast proportion of congestion experienced was at the stair door – either due to localised demand exceeding door capacity or stair congestion delaying access.

The additional time produced through congestion at the stairs can be derived by comparing scenarios that are equivalent in all ways other than the number of stairs (i.e., where insufficient room is available to 'store' evacuees in the stairwells) and where congestion at the stair has been recorded to exist. Detection time is set depending on the system employed. The pre-evacuation delays are assumed to be those experienced by those with impairments given the notification system employed.

Table A3-55 Floor congestion times for an 18 m tall building

Scenario	Detect. time (s)	Average pre-evac. time (s)	Traversal time (s)	Calculated floor clearance time (s / min)	Average max. simulated floor clearance time (min)	Upper bound floor congestion time derived from simulation (min)
D32(P7A)	0	600	75	675 (11.3)	12.8	1.6
D33(P7C)	780	600	75	1455 (24.3)	25.9	1.7
D34(P7D)	780	300	75	1155 (19.3)	21.4	2.2
D35(P10A)	0	600	150	750 (12.5)	26.8	14.3
D36(P12A)	0	600	150	750 (12.5)	14.1	1.6
D37(P10C)	780	600	150	1530 (25.5)	51.0	25.5
D38(P12C)	780	600	150	1530 (25.5)	27.1	1.6
D39(P10D)	780	300	150	1230 (20.5)	46.1	25.6
D40(P12D)	780	300	150	1230 (20.5)	23.6	3.1

Traversal time is a function of the corridor length, and a speed 0.1 m/s as a lower bound of an evacuee with impairment who has to negotiate movement within their flat, may also be moving in smoke. This is a simplification. Floor congestion levels are derived in Table A3-55, in which the average pre-evacuation times for impaired agents from Table A3-5 are used to get a first order calculated floor clearance time and the average maximum floor clearance times are taken from Table A3-54. These results relate to an 18 m tall building.

Again, the simulations have not included the impact of including occupants from amenity spaces which are left for future work. Clearly, if the stairs are to be used as a place of safety, then the stair capacity needs to be appropriate. However, consideration would also be required on the expected time of the amenity space occupants to flow into the stairs and whether localised congestion may occur even if the stair capacity is ultimately sufficient given the proximity of the relatively large / high-density population. From these results some simple queuing upper bounds might be suggested for an 18 m tall building: 5.0 min for where the stair loading densities allow some movement (e.g., less than or equal to 4.7 pers/m^2) and 30 min for where the stair occupant densities would severely hamper movement (more than 4.7 pers/m^2). These two values represent an upper bound of the congestion seen in both scenario conditions. These are provided alongside the basic stair loading limits provided earlier (see Table A3-56). These are certainly a crude estimate – however, such an approach might form the basis for the time evacuees might be expected to be between their flat and the stair given the design of the egress components.

Table A3-56 Estimated upper bound floor congestion delaying entering to the stair for 18 m tall building

Building height (m)	No. of stairs	Stair width (m)	Corridor length (m)	No. of residents	Occupants per storey	Occupant density (pers/m^2)	Upper bound floor congestion time (min)
18	1	1	15	196	28	3.2	5.0
18	1	1.5	15	196	28	1.7	5.0
18	1	2	15	196	28	1.1	5.0
18	1	1	30	588	84	9.5	30.0
18	2	1	15	196	28	1.6	5.0
18	2	1	30	588	84	4.7	5.0

It is apparent that there is a relationship between the holding capacity of the stair and the extent of the congestion produced at the stair door, given sufficient stair demand. Congestion within the staircase itself was also observed to influence evacuee access to the exit. It is reasonable to assume that this effect is sensitive to building height – with the stair congestion accumulating along the height of the building prolonging delays further up the building. The potential for developing such floor clearance guidance for taller buildings is now briefly explored using selected baseline scenarios with maximum building height and varying stair holding capacity, so that the accumulating congestion (if present) can be easily identified while the impact of the other confounding factors can be avoided.

The floor clearance times from three sets of Baseline scenarios are compared:

- Scenarios B11–B14: include four buildings ranging from 11–140 m in height, all with the extended 30 m floor plate and a single stair (the holding capacity of the stair measured as occupant density of 8.2 pers/m^2).

- Scenarios B15–B18: these are equivalent scenarios to Scenarios B11–B14 with the same building heights and the extended 30 m floor plate, but with two stairs (the holding capacity of the stairs measured as occupant density of 4.1 pers/m^2).

- Scenarios B4 and B10: include two buildings of 140 m in height, both with the 15 m floor plate, and one and two stairs, producing holding capacity of the stair measured as occupant density of 2.7 pers/m^2 and 1.4 pers/m^2 respectively.

As these are baseline cases, the population responds immediately – removing detection and pre-evacuation delay distributions from the analysis – encouraging stair demand levels. It is apparent from Figure A3-49 that the first two sets of scenarios produce floor clearance times that typically increase with the height of the floor. The extent of this increase (i.e., the gradient of the curves generated) are dependent on whether one or two stairs are present, hence two different levels of holding capacity of the stair respectively – generating two closely clustered sets of curves. The floor clearance times for Scenarios B4 and B10 are also shown in Figure A3-49 to test the contrary position, i.e., where occupant levels are low and do not overload the refuge stair capacity. It is apparent that even at this most extreme building height the floor clearance times do not accumulate in line with expectation.

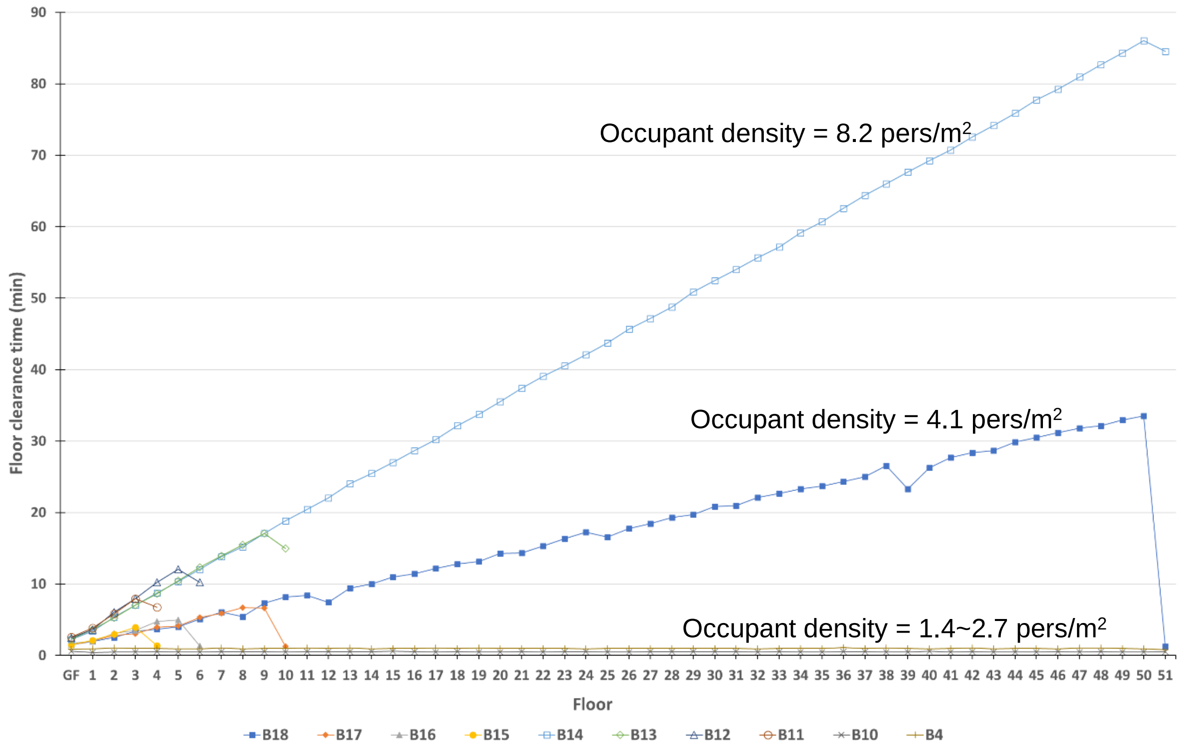


Figure A3-49 Floor clearance times across different building heights and stair availability and holding capacity

It is apparent that this reduces the complexity of the evacuation process, while increasing the simultaneous demand on the stair. It is possible to make a direct comparison between these results and those produced in the 18 m tall building. Previously, the floors in the overloaded situation (extended plate with single stair) were assumed to be clear by 30 min, while floors in the two-stair extended plate / reduced plate scenario were clear in less than 5 min (see Table A3-56). These results can be compared against Figure A3-49. After correcting for the travel time to reach the exit (in this instance, an unimpaired movement speed of 1.0 m/s is assumed), the upper bound floor congestion times of Scenario B12 and B16 here are approximately 12 min (rounded up from 11.8 min) and 5 min (rounded up from 4.7 min) respectively. A simple modifier might be derived from these two cases and applied to the other building height results derived from Figure A3-49, given that the congestion is shown to accumulate further up the building. Modifiers of *3 times* and *2 times* (for single stair and two stair buildings respectively with extended plate) have been derived by comparing the results for the 18 m tall building case (as it appears in both analyses). This might then be applied to the two cases to provide guidance across building heights on floor clearance times for more representative scenarios. The values are expected to be conservative estimates.

Table A3-57 Estimated floor clearance times for building heights 11–140 m with 30 m floorplate for one and two stairs. These Baseline cases have both detection time and pre-evacuation time set to 0 s, simplifying the analysis

Scenario (building height)	Modifier	Max. simulated floor clearance (min)*	Upper bound floor congestion (modifier applied and rounded to nearest minute) (min)	AD B Corridor/ stair fire resistance (min)
B11 (11 m)	3	7.9 = 7.7+0.25**	23	60/60
B12 (18 m)	3	12.1 = 11.8+0.25	35	60/60
B13 (30 m)	3	17.1 = 16.9+0.25	51	60/90
B14 (140 m)	3	86.0 = 85.8+0.25	257	60/120
B15 (11 m)	2	3.9 = 3.65+0.25	7	60/60
B16 (18 m)	2	5.0 = 4.7+0.25	9	60/60
B17 (30 m)	2	6.7 = 6.5+0.25	13	60/90
B18 (140 m)	2	33.5 = 33.3+0.25	67	60/120

* Total value extracted directly from equivalent building /scenario in Figure A3-48.

** Traversal times assume 15 m distance (i.e., half of floorplate given location of stair) and 1.0 m/s travel speed.

These results suggest a few general points:

- The generation of floor congestion (and then floor clearance times) is sensitive to the stair holding capacity and the demand placed on the stair.
- Low demand cases (e.g., 15 m floorplate with no amenity population) produces no floor clearance congestion of note.
- High demand cases (e.g., 30 m floorplate with no amenity population) produce floor clearance congestion that accumulates with building height. The gradient of this accumulation is steeper for the single stair design leading to higher floor clearance times throughout.
- The presence of an amenity population will change the dynamics considerably – affecting the floor clearance time for the amenity floor location and all floors above it, according to the level of demand (i.e., the occupancy level of the amenity space).
- The floor clearance times of 140 m tall buildings (single or two stairs) with an extended 30 m floorplate have maximum floor clearance times beyond the current stair and corridor fire resistance requirements, noting the previous comments on making such comparison in Section A3-5.1.4.

- The floor clearance times of 30 m tall buildings (single stair) with 30 m extended floorplate have maximum floor clearance times approaching the current corridor fire resistance requirements. This may warrant further sensitivity analysis, should stair refuge be considered a viable means of life safety.

Finally, to assess whether Evacuationz gives similar outcomes to Pathfinder, the maximum floor clearance times in the case of 30 m tall, long corridor buildings with one and two 1.1 m wide stairs where there is smoke detection in the corridor and a voice notification system (i.e., Scenarios P16F vs. Scenario P18F) have been examined. For the two stair building (Scenario P18F) the average maximum floor clearance is 21.8 min, and when compared to the calculated time of 21.3 min for the equivalent Scenario P12D in Table A3-55 this gives a floor congestion time of 0.5 min. For the single stair building (Scenario P16F) the average maximum floor clear time is 29.5 min, giving a floor congestion time of 7.7 min. Although the increase in the average maximum floor clearance time with one stair over two stairs is not the same as given by Pathfinder, the trend is the same – almost no congestion with two stairs but an indication of congestion with the single stair. Given the more refined method used by Pathfinder to simulate agent interaction and congestion resolution, it is expected that its estimates are more sensitive to local conditions and more conservative in this instance.

A3-10.11 Equivalence of stair capacity and number of stairs

The Baseline analysis given in Table A3-33 shows how a single 2 m wide stair can give similar total evacuation times to two stairs of half the width. Similarly, it would suggest that having a single 2.2 m wide stair should be equivalent to have two 1.1 m wide stairs, noting that the total boundary layer impact would differ between the two widths.

Table A3-58 Differences between average total evacuation times (min)

Scenario	Evacuation time (min)		Difference in total evacuation time (%)
	Number of stairs (Stair width)		
	1 (1 x 2.2m)	2 (2 x 1.1m)	
D41A	22.3	20.6	1.7
D41B	42.6	42.8	-0.2
D41C	37.6	37.6	0
D41D	29.3	28.0	1.3
D41E	28.4	26.4	2.0
D41F	22.4	21.1	1.3

Table A3-58 shows an examination of the 30 m tall building with the 15 m long corridor with one stair (Scenarios P15A–P15F) against two stairs (Scenarios P17A–P17F) in which the difference in average total evacuation times is no greater than 2 min, with an average difference of 1 min. The results therefore support the hypothesis that the two building configurations are broadly equivalent assuming comparable resident use of the stair capacity and that all of the capacity is available throughout the incident (i.e., that one stair is not blocked).

A3-11 Key findings

Several core outcomes have been distilled to address a number of basic questions – derived from the original remit, reviewing underlying factors that might affect evacuation performance and that also might affect the provisions included within AD B.

Lessons are derived from the four stages of analysis conducted. Key insights are stated alongside the supporting evidence – with the scenarios from which they are drawn. Data are categorised according to the factor being examined – effectively, the factor being kept constant while allowing its impact to be assessed across the other conditions examined. Only directly comparable scenarios are included in each factor examined. Depending on the scenario involved, normalisation of the results is conducted on the total time for agents to fully evacuate from the building or the number of agents that become trapped by smoke. Having agents trapped may be taken to be an unacceptable outcome as this could lead to fatalities; however, it should be acknowledged that conservatism was incorporated into the simulations which may have inflated the numbers trapped, and how acceptance criteria might then be defined.

A3-11.1 Time to enter stair

Time to enter stair has been examined in Baseline and Diagnostic analyses: Scenarios B2, B5 and B6, and Scenarios D32–D40.

In the case of extreme stair demand (i.e., where all occupants evacuate simultaneously) and where there is sufficient capacity to 'store' the occupants (i.e., where the expected occupant density in the stairs is at or below 4.7 pers/m^2 or less) then the results suggest it might take up to 5 min for occupants to get into the stairs. It is expected this is the case regardless of the building height (based on equivalent behavioural assumptions), although the specific analysis has been carried out on the 18 m tall building.

Where sufficient capacity is provided in the stairs to 'store' the residents then the time needed for the population to enter the stairs is a function of the detection, response and floor movement times but is independent of the storey and of building height. Conversely, if the stair floor area is insufficient to 'store' the population (e.g., significantly beyond the 4.7 pers/m^2 level) then congestion can occur in the common corridors leading into the stairs. This may extend up to 30 min for the 18 m tall building, under extreme resident demand. This has been used to estimate equivalent delays for all building heights under more representative conditions. For 30 m tall /single stair / extended floorplate designs, congestion at the stair door reaches 55 min – approaching the 60 min corridor fire resistance rating required in AD B. For 18 m high/one and two stair / extended floorplates designs the congestion at the stair door reaches significantly surpasses the 60 min corridor fire resistance rating required in AD B.

Where there might be a concern that keeping the stair clear may not be achieved, then consideration needs to be made about the active and passive fire safety measures in place. Solutions include the use of common corridor smoke control systems, and/or the provision of additional barriers (e.g., more fire and smoke doors in the corridor, or the provision of lobbies to the stairs) and/or increasing the performance of barriers. It is interesting to consider that although AD B expects the fire resistance of doors to stairs to increase with building height, the performance of smoke seals does not change in the same manner. One approach might be to examine the practicality of having higher performing smoke seals on doors with a greater fire resistance rating.

- For an 18 m tall building with resident response producing extreme stair demand, where stairs have sufficient space for the occupants to stand (e.g., stair occupancy is between 3.2-4.7 pers/m^2), limited congestion develops at the stair entrance of approximately 5 min. Access to the stair is independent of storey height above ground.
- For an 18 m tall building with resident response producing extreme stair demand, where stairs have insufficient space for the occupants to stand (e.g., stair occupancy is at 9.5 pers/m^2), congestion develops at the stair entrance of up to 30 min and accumulates across floors.
- Where representative evacuation scenarios are assumed (e.g., distributed resident response and variable movement rates), upper bound estimates of floor congestion may challenge AD B protection levels for 30 m tall buildings when expressed by the fire resistance rating (single stair with extended floorplate) and for 140 m tall building. However, care must be exercised directly comparing fire resistance times with evacuation times.

A3-11.2 Building height

Building height has been examined in the Baseline and Parametric analyses (see* Table A3-29, Table A3-30, Table A3-40)*: Scenarios B1–B4; Scenarios P1–P6 vs P7–P12 vs P13–P18 vs P19–P24.

As expected, where the total evacuation of a building is considered then **as buildings increase in height, so they produce progressively longer evacuation times** – although the increase is less than the increase in height (e.g., the 140 m tall building is 12.7 times the height of the 11 m tall building but produces a total evacuation 9.6 times longer).

The impact of building height has been further examined during the Parametric analysis (see Table A3-40) – where a more representative population has been represented (including those with impairments producing a distributed response and range of movement capabilities). The additional complexity produced by the simulated differences in evacuee response means that the results from these more complex scenarios are more representative of actual incidents. The total evacuation times for a given building height increase when the representative population is assumed as compared to when it is not included (e.g., where movement abilities exclude impairments). However, it is apparent that these conditions reduce simultaneous demand on stair capacity thereby reducing the relative impact of building height on evacuation performance (e.g., reducing the increase of total evacuation performance in 30 m vs 11 m tall buildings from 2.0 to 1.4).

A building fully populated with unimpaired agents extended the total evacuation time in comparison to the evacuation of a single evacuee (see Table A3-29 and Table A3-30). This increase (by over 300%) indicates that evacuee interaction and the aggregate conditions generated on the egress components (e.g., congestion) affect arrival time **and performance cannot be derived directly from travel distance alone**.

- Given extreme stair demand (with no initial delays and unimpaired movement simulated), total evacuation time increased as building height increased with a 30 m tall building producing evacuation times 2.0 times longer than an 11 m tall building.

- Given representative stair demand (with initial delays reflecting a detection and notification system in place and varied movement capabilities simulated), total evacuation time increased as building height increased, with a 30 m tall building producing a total evacuation time 1.4 times longer than an 11 m tall building. This reduced impact is likely partly due to the increased complexity of resident response – placing less simultaneous demand on stair capacity, noting that the detection time is fixed to the same value for a given scenario across building heights.

- Under representative conditions, the total evacuation time does not increase linearly with building height. The findings in this study do not include movement fatigue which may become a factor in taller buildings and/or for people with specific health conditions, further complicating the total evacuation times produced.

- Introducing impaired agents into the simulations results in longer total evacuation times as not only do such agents have assumed longer pre-evacuation delays and slower unimpeded movement speeds when compared to unimpaired agents, but impaired agents may also slow the movement of unimpaired agents by increasing congestion and slowing movement speed further.

A3-11.3 Stair width

The impact of stair width on total evacuation time has been first examined in the Baseline analysis (see Table A3-32): Scenarios B2, B5 and B6.

The analysis includes unimpaired evacuees who respond immediately during the evacuation of an 18 m tall building – increasing the simultaneous demand on the stairs. Given the impact of stair widths are localised and that such demand levels may appear periodically under any conditions, such insights are deemed sufficient. **The introduction of the 1.5 m wide stair reduces the overall total evacuation time by 30% from that produced when the 1.0 m wide stair is used. The introduction of the 2.0 m wide stair reduces the overall total evacuation 40% from that produced when the 1.0 m wide stair is used, but with a reduction of only 14% compared with the use of the 1.5 m wide stair.**

Stair width has also been included as part of the Parametric analysis in which the relative total evacuation time performance of having a wider stair has no material impact in terms of building height and detection / notification combination. In these simulations the demand on the stairs is less than the Baseline scenarios since agents enter the stairs at different times due to their pre-evacuation delays.

Furthermore, the impact of slower moving agents that have the potential to block the movement of others has been investigated as part of the Diagnostic analysis (Section A3-10.2.1). The simulations suggest that providing a stair that is wide enough to allow for evacuee overtaking may be of benefit. However, should lifts be available then the impact of increasing stair width is likely to be diminished as such occupants who might otherwise use the stairs have an alternative means of egress.

- Given the analysis discussed in Section A3-11.1 has shown that if sufficient capacity is provided in the stairs to ‘store’ occupants has no impact on floor clearance times then it can be inferred that having wider stairs for the same number of occupants will also have no material impact. Wider stairs may provide a benefit to floor clearance times where amenity spaces are present although the impact has not been investigated in the simulations that have been carried out.

- Given extreme stair demand (with no initial delays and unimpaired movement simulated), increasing stair width from 1.0 m to 1.5 m initially reduces total evacuation times by 30% for an 18 m tall building. The total evacuation time was further reduced when stair width is increased from 1.0 m to 2.0 m (by 40% in comparison with 1.0 m width), representing a diminishing impact.

- Providing a stair width that allows for evacuee overtaking may have a benefit on evacuation times depending on what other provisions are available in the building and the specific incident in terms of demographics, building height, pre-evacuation delays, occupant location, etc.

A3-11.4 Number of stairs

This was first examined in the Baseline analysis (see Table A3-33) and the Parametric analysis (see Table A3-43): Scenarios (B1–B4, B7–B18) and Scenarios (P1, P4–P6, P7, P10–P12, P13, P16–P18).

The impact of the number of stairs was examined during the Baseline analysis (see results from Scenarios B1–B4, B7–B18 in Table A3-33). This assumes immediate resident response and unimpaired movement across the population. **In this situation, having a second stair reduces total evacuation time to 64% of the performance when there is a single stair.** The reason for the reduction is simply because approximately half of the residents utilise each stair when two are available which lowers the occupant density and hence lessens the impact on movement speed. Should stairs become less evenly distributed, then the outcome will eventually approach the evacuation performance when only one stair is available.

The impact of the number of stairs has also been examined during the Parametric analysis (see Table A3-43). These scenarios include a range of pre-evacuation responses and a range of representative movement capabilities. **Here, the availability of the second stair reduces the total evacuation time to 92% of the single stair performance.** Compared to the Baseline scenarios, the total evacuation time reduction between two and one stairs is 28 percentage points less (i.e., 64% vs 92%) as the total evacuation time is primarily influenced by the pre-evacuation delay in many of the scenarios and the individual movement speeds of impaired agents rather than the occupant density in the stairs. The evacuation dynamics are frequently more complex. The Parametric analysis also shows that **a building with a single wide stair is equivalent (in terms of evacuation performance) to a similar building other than it has two stairs with the same aggregate width as the wide stair**. For instance, the difference in total evacuation time for the 30 m tall building with the detection and notification combinations is no more than 2 min.

The impact of the number of stairs derived from the Parametric analysis can also be broken down by the building height (see Table A3-44). **Increasing the number of stairs from one to two has a modest impact on 11–18 m tall buildings (less**

than 10% reduction in total evacuation time). This impact increases in 30 m tall buildings to just over a 10% reduction in total evacuation time.

Performance can also be assessed by comparing the number of residents trapped; i.e., not able to avoid deteriorating environmental conditions during their evacuation. **The number of trapped individuals in buildings of height 11–30 m range between 0.7–1.0 individuals for a single stair and between 0.30–0.33 individuals for two stairs** (see Table A3-45). However, the analysis suggests that as buildings get taller the numbers of trapped agents increase markedly. Having two stairs produces one third the number of trapped residents (461) in comparison to the number produced when one stair is available (1576) when the building was 140 m in height.

Thus, there may be a potential benefit of having a second stair up to some limit which will depend on if, and thereafter when stairs might be affected by smoke where there are extended evacuation times as the result of the means of notification, pre-evacuation delays, and/or travel times. Such limits have not been specifically identified through the current simulations.

Where stairs are assumed to be a place of safety, similar to providing wider stairs, two stairs would provide a benefit if a single stair did not have sufficient capacity to 'store' the occupants. The presence of fully occupied amenity spaces might affect the demand profile of evacuees reaching the stair.

- Given extreme stair demand (with no initial delays and unimpaired movement simulated), the introduction of a second stair reduced the total evacuation time by **45%** across building heights 11–140 m. This is likely an upper bound for the potential impact of the second stair on evacuation time.
- Given a more representative array of stair demand conditions (with initial delays ranging from being in a narrow time window to reflecting detection/notification system in place, accompanied by a range of movement capabilities simulated), the introduction of a second stair reduced the total evacuation time by **8%** across building heights 11–30 m, reflecting the more complex dynamics reducing the benefits of increased capacity. However, the benefit of the second stair gradually increases with building height – going from a 3% reduction of evacuation time for an 11 m building to a 13% reduction for a 30 m tall building. This is likely a more credible estimate of the impact of the second stair on evacuation time. The reduction in total evacuation time for the 140 m tall building cannot be evaluated since most, if not all, simulations resulted in trapped agents leading to the evacuation time only reflecting a reduced population size.

- Given the assumptions made, a building with a single wide stair will give similar total evacuation times to a similar building other than it has two stairs with the same aggregate width as the wide stair.

- For very tall buildings the benefit of a second stair may be limited where it is assumed that stairs eventually become compromised by smoke (given the number of simulated agents shown to be trapped). **There needs to be reliable fire safety precautions in buildings to limit the movement of smoke into escape routes irrespective of the number of stairs. This requires further investigation.**

A3-11.5 Detection and notification

The impact of detection and notification has been examined in the Parametric analysis (see Table A3-39 to Table A3-42): Scenarios P1–P24.

The impacts of the detection and notification systems in place are initially assessed as part of the Parametric analysis (see the results from Scenarios P1–P24 in Table A3-39 to Table A3-42). This assumes a representative set of evacuee responses and a range of movement capabilities across the population. It also assumes that any detection and alarm system is fully operational in the event of a fire.

The introduction of a building-wide tone alarm when coupled with corridor smoke detection provides no obvious advantage over a reliance on social notification (i.e., resident communication). In cases in which all agents are able to exit the building, the introduction of a building-wide voice alarm coupled with corridor smoke detection reduces the total evacuation time by an average of 15% over a reliance on social notification. The introduction of a building-wide tone alarm when coupled with flat heat detection reduces total evacuation time by an average of 20% over a reliance on social notification. **The introduction of a building-wide voice alarm when coupled with flat heat detection reduces total evacuation time (across the all the relevant scenarios examined) by an average of 38% over a reliance on social notification.**

The impact of notification/detection systems on evacuation performance given the building height has also been examined in the Parametric analysis (see Table A3-41). **It is apparent that the benefits of introducing more effective notification and detection increase as the building increases in height.** For instance, the combination of voice notification and flat heat detection provides a 31% reduction in total evacuation time for an 11 m tall building, a 38% reduction in an 18 m tall building and a 40% benefit for the 30 m tall building.

There may be a point at which the reduction in pre-evacuation times produced by the notification system across the building increases congestion on the stairwell (or lift system) that then undermines the benefits of reducing delay. However, this point was not reached in this analysis.

The impact of notification and detection on the ability of residents to evacuate without interacting with deteriorating environmental conditions is shown in Table A3-42. **Social communication and voice notification effectively traps no occupants for buildings between 11 m and 30 m in height – when used in combination with corridor smoke or flat heat detection**, while tone notification traps no occupants when flat heat detection is used. Tone notification trapped an average of just over two agents when coupled with corridor smoke detection. All combinations of notification and detection generate traps occupants when the 140 m tall building is simulated, ranging from an average of 517 (voice notification / flat heat detection) to nearly 1200 (social notification) occupants. This suggests that provisions for buildings that might be deemed currently beyond the scope of AD B (e.g., 140 m tall buildings) will require more constraints on the egress provisions and notification systems in place to ensure appropriate levels of safety as implied for lower buildings.

In terms of a stay put strategy, the introduction of a detection and building-wide alarm system would likely mean (1) more occupants will decide to evacuate from a building when compared to a case in which social notification is relied upon, and (2) the population will then likely evacuate in a smaller time window (e.g., given the impact of flat heat detection and voice notification). Whether that results in the building being 'safer' will depend on many factors such as whether a hazard develops outside of the flat of fire origin and to what extent, when occupants decide to leave compared to the eventual onset of any hazard, whether the actions of leaving increases other risks such as trips and falls, and whether the movement of occupants impacts on FRS activities or vice versa.

- Given the assumed initial delays representative of the detection/notification systems in place (with varied movement capabilities simulated), the introduction of
    - A tone alarm with corridor smoke detection had **limited impact,**
    - A tone alarm with flat heat detection reduced total evacuation time by an average of **20%,**
    - A voice alarm with corridor smoke detection reduced total evacuation time by an average of **15%,**

- a voice alarm with flat heat detection reduced total evacuation time by an average of **38%,**

in comparison with social notification (communication between residents) for single and two stair buildings with heights ranging from 11–140 m.

- In all cases, **the beneficial impact of a tone and voice system increased with building height.** For instance, voice alarm and flat heat detection reduced total evacuation time by 31% for an 11 m tall building and 40% for a 30 m tall building.
- The introduction of voice alarms and flat heat detection avoided trapped residents in 11–30 m tall buildings.

A3-11.6 Introduction of lifts

This was first examined in the Diagnostic Analysis (see Table A3-51–Table A3-53): Scenarios D26–D31.

The purpose of this work is to examine the impact of using lifts in evacuation that involve movement impaired occupants from high-rise residential buildings. In light of a lack of applicable guidance on wider application of evacuation lifts in residential buildings, the authors have followed the recommendations in BS 9999 [61] to simulate the evacuation of movement impaired people using lifts, with the recommended lift operation. The impact of one or two lifts for use by those incapable of unassisted evacuation has been examined during the Diagnostic analysis (see results from Scenarios D26–D31 in Table A3-51–Table A3-53). This analysis assumes a representative set of evacuee initial responses (e.g., assuming global tone notification) and a range of movement capabilities across the population.

The lifts functioned following the egress-mode operation in which they started at the ground floor, called pickup floors (i.e., any floor above the ground) with the default priority system from top to bottom, and once a lift had picked up agents, it travels to the ground floor to let the agents off before responding to next call in the priority system. This may not be necessarily how lifts work in real buildings, but the simulations followed the lift operation order recommended in Annex G of BS 9999.

The introduction of a single lift reduces the total evacuation time by 15% in comparison with the scenario where no lift is present; the introduction of the second lift reduces the total evacuation time by 23% (see Table A3-51). **The introduction of a single lift reduces total evacuation time by 19% for those using the stairs** (e.g., those without impairments or those with impairments who do not require assisted movement) **and by 16% for those requiring use of the lifts** (see Table A3-52). **The introduction of a second lift reduces total evacuation**

time by 19% for those using the stairs and by 24% for those requiring use of the lifts (see Table A3-53).

As expected, **the introduction of lifts broadly has an increasing impact on evacuation performance as the building height increases** (see Table A3-53). For instance, the introduction of two lifts reduces total evacuation time for those who can evacuate without assistance (non-MDP) by 13% in the 18 m tall building and 23% in the 30 m tall building. Similarly, the introduction of two lifts reduces total evacuation time for those who cannot evacuate without assistance (MDP) by 22% in the 18 m tall building and 26% in the 30 m tall building.

- Given representative demand on vertical egress components whilst assuming the need for vertical assistance (i.e., with varied movement capabilities simulated affecting stair movement or lift use depending on lift availability), **the availability of one lift /one stair reduces total evacuation time by 15% for 18–30 m tall buildings, while a two lift/one stair design reduces total evacuation time by 23% in comparison to when one stair/no lift is present.**
    - The introduction of the first lift benefits those using the stair with a 19% reduction in total evacuation time (those able to self-evacuate) and benefits those using the lifts (those unable to self-evacuate) with a 16% reduction in comparison to the single stair performance.
    - The introduction of a second lift only benefits those using the lifts (those unable to self-evacuate) reducing total evacuation time by 24% in comparison to the single stair performance.
- **Based on the assumptions made in the simulations for lift evacuation the benefit of the lifts typically increases with building height for those using the stairs (i.e., those that might self-evacuate), while having a consistent benefit for those using the lift system across the heights examined (for those unable to self-evacuate).**

A3-11.7 Stay put

Instead of focusing on assessing all the elements required to make stay put strategies safe, the work described herein focuses on the impact of those building design and fire safety provisions on evacuation performance. This was the proposed objective of this work as outlined in the original request for work from the client. This is important given the implications of the survey results presented in Appendix B2 – that residents are reluctant to remain in place during an evolving incident – and becomes more so should the trust of the public not return regarding stay put strategies in which remaining in their flats is a reasonable option. This trust will likely be further diminished should other comparable incidents occur (especially in the UK).

Where occupants remain in their flat as part of a stay put strategy their safety primarily relies on the state of the building and the associated fire safety provisions to mitigate smoke and fire spread to the unit, i.e., to ensure that the fire is contained as intended. However, the stay put strategy does not **require** that occupants stay in their flats and instead they may decide or be advised to leave. As has been shown in Appendix B2, 80% of occupants indicated that they would attempt to evacuate once they were aware of an incident. Where occupants leave their flats then the state of the building and its ability to support evacuation becomes relevant, just as it does in the case of having a full evacuation, or having occupants use the stairs as a place of safety.

The simulations carried out in this study that most likely represent the current implementation of a stay put strategy are those in which there is local detection and notification in the flat of fire origin and other building occupants become aware of the incident via social notification. In such scenarios the results have indicated that **almost no occupants were trapped for buildings between 11 m and 30 m in height – however the assumed interaction between occupants might be considered optimistic.**

Where the occupants under a stay put strategy decide to evacuate a building in which the expectations are not as optimistic (e.g. where communication is not as effective, not as widespread, and not as impactful) then the outcome will depend on several factors such as the likelihood of residents initiating and/or responding to social notification, the number of residents in the building and whether they are awake or asleep, whether notification is via remote means or face-to-face, etc. The results suggest that **social communication between residents is not relied upon as a primary means of response should a full building evacuation be necessary**.

Where stay put strategy is applied to a building it is important that occupants are informed of expectations. For example, Proulx et al. [14] note that

> "*When providing information on fire safety in highrise buildings, a number of points need to come across very clearly […] Many [occupants] do not fully understand the dangers of smoke and the importance of sealing their units and closing windows and doors. This should be emphasized in fire safety information […] Finally, in a fire situation, rescue can take a long time. If occupants are not in immediate danger, they should be prepared to wait for as long as a few hours before rescue personnel can assist them to evacuate; this fact should be made clear to occupants*."

The introduction of an evacuation alert system (EAS), as briefly discussed in Section A3-10.6.2, will likely have an impact on resident decisions to stay put. Notwithstanding the presence of an EAS, the stay put strategy depends on if and how residents become aware of a fire and, in turn, what proportion of residents decide to stay put by the time the FRS attend the incident. Where an FRS activates an EAS then residents that remain in the building may receive an alert signal depending on how the FRS decide to use the EAS in terms which zones are alerted and when that occurs. The residents may or may not be able to initiate their evacuation, should they wish to, as a result of conditions along any escape paths coupled with their physical capability to do so. The presence and activation of an EAS may still need FRS personnel to move through a building to investigate whether residents remain in place because of their unawareness, unwillingness or inability to make their own escape.

A3-12 Future work

Given the available resources, this work does not provide results for every conceivable scenario of interest. Therefore, opportunities for further work are listed (in no particular order) below. It is important to note that any reasonable level of resourcing that could be expected for this kind of project would never be able to address every possible scenario.

- For completeness, it would be appropriate to simulate the cases of building-wide alerts that are the result of smoke detection in the flats or heat detection in the corridors. However as already discussed in Section A3-8.5, it is not expected that either of these combinations will provide practical options.

- More detailed analysis of the impact of MIPs on evacuation where lifts are either present or absent and where narrower or wider stairs are present. Simulations could investigate the likelihood of MDPs using the lifts or using the stairs and the subsequent impact on evacuation time. Simulations could also examine various lift operation options (e.g., in response to different fire location, prioritisation, etc.) to assist in the development of emerging guidance on the wider challenge in the practical application of evacuation lifts in residential buildings.[17]

- For the two stair building scenarios it has been assumed that agents use the stair nearest to their flat which will lead to an optimal evacuation time, all other things being equal. Further simulations could be carried out in which the choice of stair is not assumed to be equal to demonstrate that the evacuation time would be dominated by the higher utilised stair. Where a higher utilised stair is the first to be affected by smoke then this will likely have a greater impact on the overall evacuation time. The extreme position of this imbalanced use of available stair capacity is the use of one stair, which has already been examined in this report.

- Other than having a distinction between doors to stairs vs. other doors, the current hazard scenario assumes that the time for escape paths to be hindered and compromised by smoke are unconnected to the fire resistance

[17] This would require simulations to be carried out using Monte Carlo sampling which is more difficult in Pathfinder compared with Evacuationz. Evacuationz does have the potential capability to include lift egress in its simulations although this capability requires some further development and testing.

of a door. This means that it has been assumed that the time for stairs to be affected by smoke is independent of building height even though AD B requires that the fire resistance increases as a building gets taller. Further work could be carried out to consider how the number of trapped agents may change were it possible to vary the smoke separation characteristics in line with fire resistance. This investigation would indicate how stairs might be better protected to allow them to give more time to occupants should they need to spend longer in the stairs.

- Scenarios in which interaction between occupants and FRS personnel have not included any impact of movement restrictions on either party when using egress components. Similar to the comments made above regarding stair usage in buildings with two stairs, this occupant-FRS interaction may have more impact on stairs that have a proportionally higher utilisation.[18]

- The simulations in which either a tone or voice notification system is present either assume that agents always initiate their evacuation or there is a fixed 80% likelihood of initiation. Whether residents of a building are more or less likely to respond to the two types of notification system has not been investigated in further detail for this study. An initial search of the literature did not reveal any data to confirm there is a difference although it may be useful to conduct a more in-depth review at some point.

- Where there has been a need to include FRS operations as part of the modelling it has been necessary to assume that their arrival time is an adequate measure of the delay involved. Statistical data for arrival time has been taken from the Dwelling Fires Database, however this may not represent those delays that only involve high-rise residential buildings nor likely account for any decision-making activities that may be undertaken before alerting residents. Further research into these aspects could be conducted should this be an area of interest.

- It has only been possible to simulate a relatively simple scenario in which interaction between FRS personnel and residents occurs. There are a multitude of alerting strategies that could be applied to a building by the FRS which might be affected by the building height, the fire location and any subsequent smoke spread, the number of responding crews, the extent to which resident evacuation has already begun, etc. Although it may be

[18] It should be noted that this factor is being examined currently in another project. It would be viable with some further development to incorporate some elements of this in Evacuationz using the blocking agent capability and inserting agents into the building at the point of FRS arrival. Using Pathfinder for this aspect may also reveal some useful insights.

possible to examine these through further simulations, such a task extends beyond the current research goals.

- Simulations that include a phased evacuation have shown that this strategy has limited application for residential buildings. However, this conclusion is only based on simulations in which a building does not have amenity spaces present. Further simulations could be considered in which there are occupants in both flats and an amenity space that attempt to evacuate from a building simultaneously. In this scenario a phased evacuation strategy may be a viable approach to reduce potential congestion on the means of escape, for example where the stairs are to be used as a place of safety.

- Following on from the previous point, it could be useful to examine how a phased evacuation using designated and available floor wardens might work in residential buildings. Wardens may be from the resident population and/or the building management company. Simulations could either be where there is fixed delay between each floor being alerted or floors waiting until the neighbouring one has been cleared. However, such scenarios might be impractical for a residential building unless there was a continually present concierge and/or the reliability of resident engagement as wardens could be reasonably assessed and might be difficult to require within guidance.

- In the simulations in which lifts are present several assumptions have been necessary including:

    - Only those movement dependant agents that must use the lifts to reach a place of safety outside of the building will do so,

    - A lift is assumed to carry one wheelchair at a time,

    - Lifts are assumed not to provide additional capacity for those without a movement impairment which also means those without impairments do not take away lift capacity for those with impairments,

    - Lifts are assumed to be operable by the evacuating population and do not require staff intervention, and

    - Once a lift has picked up agents, it travels to the ground floor and lets the agents off before responding to next call in the priority system.

These assumptions have partly been necessary due to the functionality provided by Pathfinder and may also provide a level of conservativeness. It is reasonable to debate whether these assumptions are reasonable in practice. For example, how would sole access to the lifts for those with movement impairments be managed and what would be the impact were those without impairments be able to use the lifts, or would the evacuation be affected by lifts stopping at floors before reaching the ground floor? Further work using a Monte Carlo analysis could be considered to investigate the above factors although this would likely exceed the capabilities of Pathfinder. However, as noted elsewhere, Evacuationz does have the potential to include lifts within its simulations.[19]

- In addition to the preceding comments regarding lifts, simulations have only been carried out on 18 m and 30 m tall buildings. Simulations of additional scenarios for taller buildings might be of value for more precise recommendations regarding the provision of additional lifts in which there is a point of diminishing return (e.g., greater than 30 m tall buildings).

- The simulations caried out in this work does not link the fire and smoke conditions with agent movement such as when doors are being used it would allow smoke to move from one space to another (i.e., that evacuee movement can affect environmental conditions). Simulations of this nature have the potential to become complex given the large number of parameter permutations present.[20]

- Additional diagnostic analysis to assess use of models for a wider range of different scenarios (e.g., assess the different movement modes in Pathfinder, assumptions regarding overtaking evacuees in wheelchairs, comparison between Parametric scenarios when using Pathfinder as well as Evacuationz, the impact of selecting certain input parameters such as assuming uniform distributions for walking speed rather than a non-uniform distribution such as normal or triangular, the proportion of agents set to be movement impaired persons (MIPs) (and consequently also movement dependent persons (MDPs) and movement reduced persons (MRPs)), etc.).

- It is speculated that the presence of a second stair (along with, and potentially independent to, other fire safety features including the presence of lifts) may have an impact on resident perception of safety within the building regardless of their actual impact on performance. Assessing by how much residents might be willing to pay for a second stair through increases in rent or purchase price could be a useful insight into the cost-benefit of their inclusion. However, there are also anecdotal indications that residents may not want to

[19] The lift evacuation capability of Evacuationz requires further assessment before it is ready to be used more widely.

[20] Linking Evacuationz to the B-RISK fire and smoke spread model has been undertaken previously as a proof of concept but no recent work has been carried out to develop this further.

live in flats that are directly next to stairwells as people are concerned about being disturbed by noise.

- This work has not investigated the likelihood of smoke spreading to and from flats, corridors, and stairs. As a result, no judgement has been made on the likelihood of the proposed challenging scenario used in this study. Additional work could be used to assign such probabilities which in turn could be used as input to some form of risk assessment.

- The analysis has used a representative fire scenario in which it has been assumed smoke and heat travels internally via the common corridors and stairs. As discussed in Section A3-5.1, there are other means of spread such as via other internal pathways (e.g., lift shafts, or HVAC systems) or via external routes (e.g., via windows, or balconies) that could be considered. It has been argued that the representative scenario presents a challenging case that is on par with that experienced in Grenfell Tower. However, it is appropriate to note that in the case of an external fire then the order that areas of the building become affected by smoke and/or heat may differ from that used in this analysis. Therefore, it might be appropriate to consider such an alternative fire scenario to investigate what (if any) impact it had on the findings.

- The sensitivity analysis determined the number of repeated simulations of a scenario that was sufficient to get a convergence although this assessment was not carried out across every scenario. More sophisticated statistical methods were identified in the literature. It would be beneficial to examine whether these methods could be integrated into the simulation tools to allow convergence to be assessed for every scenario as part of the simulation procedure.

A3-13 References

[1] D. Hopkin, ‘A Review of Fire Resistance Expectations for High-Rise UK Apartment Buildings’, *Fire Technol*, vol. 53, no. 1, pp. 87–106, Jan. 2017, doi: 10.1007/s10694-016-0571-9.

[2] C. Hopkin, M. Spearpoint, D. Hopkin, and Y. Wang, ‘Residential occupant density distributions derived from English Housing Survey data’, *Fire Safety Journal*, vol. 104, pp. 147–158, Mar. 2019, doi: 10.1016/j.firesaf.2019.01.010.

[3] R. Booth, ‘Planners set to approve 51-storey London tower with only one staircase’, *The Guardian*, Jan. 12, 2022. Accessed: Jan. 27, 2022. [Online]. Available: https://www.theguardian.com/society/2022/jan/12/planners-set-to-approve-52-storey-london-tower-with-only-one-staircase

[4] BSI, ‘PD 7974-6:2019 Application of fire safety engineering principles to the design of buildings. Human factors. Life safety strategies. Occupant evacuation, behaviour and condition (Sub-system 6)’, BSI, London, 2019.

[5] Thunderhead Engineering, ‘Pathfinder Technical Reference’, 2019.

[6] S. Gwynne and E. Rosenbaum, ‘Employing the hydraulic model in assessing emergency movement’, in *SFPE Handbook of Fire Protection Engineering*, 5th Edition., Springer, 2016, pp. 2115–2151.

[7] I. Hagiwara and T. Tanaka, ‘International comparison of fire safety provisions for means of escape’, in *Fire Safety Science*, 1994, pp. 633–644.

[8] R. W. Bukowski and J. Tubbs, ‘Egress concepts and design approaches’, in *SFPE Handbook of Fire Protection Engineering*, 5th edition., Springer, 2016, pp. 2012–2046.

[9] H. L. Malhotra, ‘Fire safety in buildings’, Fire Research Station, Borehamwood, Herts, 1987.

[10] R. W. Bukowski, ‘Emergency egress from buildings’, NIST, Gaithersburg, MD, USA, NIST Technical Note 1623, 2009.

[11] C. Wade, ‘Means of escape in multi-storey buildings’, BRANZ - Building Research Association of New Zealand, Wellington, New Zealand, BRANZ Study Report no. 38, 1991.

[12] P. Stollard, ‘Report of the review panel on building standards (fire safety) in Scotland’, Building Standards Division, Livingston, Scotland, Jun. 2018.

[13] ‘Final business and regulatory impact assessment: Amendment to the building regulations and building standards technical handbook guidance - Section 2: Fire’, Building Standards Division, Livingston, Scotland, Jun. 2019.

[14] G. Proulx, J. Pineau, J. C. Latour, and L. Stewart, ‘Study of the occupants’ behaviour during the 2 Forest Laneway fire in North York, Ontario January 6, 1995’, National Research Council of Canada, Ottawa, Canada, Internal Report No. 705, Sep. 1995.

[15] HM Government, ‘The Building Regulations 2010, Approved Document K (Protecting from falling, collision and impact) (2013 edition)’, 2013.

[16] M. J. Spearpoint, *Fire Engineering Design Guide*, 3rd ed. New Zealand Centre for Advanced Engineering, 2008.

[17] D. Nilsson and R. Fahy, ‘Selecting scenarios for deterministic fire safety engineering analysis: Life safety for occupants’, in *SFPE Handbook of Fire Protection Engineering*, 5th edition., Springer, 2016, pp. 2047–2069.

[18] Ministry of Business, Innovation & Employment, ‘C/VM2, verification method: framework for fire safety design, for New Zealand Building Code clauses C1-C6 protection from fire’, New Zealand Government, Wellington, New Zealand, Amendment 6, 2020.

[19] Arup, ‘Part M Research - Objective 1 Interim Report’, PMR1-ARP-00-XX-RP-Y-0002, Sep. 2021.

[20] J. Fraser-Mitchell, G. Forbes-Pepitone, and C. Williams, ‘Fire safety: Means of escape for disabled people - Review of current approach’, BRE Global, P117941-1004 (M5D5V3), Sep. 2021.

[21] BSI, ‘prEN 81-76. Safety rules for the construction and installation of lifts. Particular applications for passengers and goods passenger lifts. Part 76. Evacuation of persons with disabilities using lifts (draft for public consultation)’, BSI, London, Nov. 2019.

[22] Greater London Authority, *The London Plan: The spatial development strategy for greater London*. Greater London Authority, 2021.

[23] A. Hunt, E. R. Galea, and P. J. Lawrence, ‘An analysis and numerical simulation of the performance of trained hospital staff using movement assist devices to evacuate people with reduced mobility’, *Fire and Materials*, vol. 39, no. 4, pp. 407–429, 2015, doi: 10.1002/fam.2215.

[24] M. Spearpoint and H. A. MacLennan, ‘The effect of an ageing and less fit population on the ability of people to egress buildings’, *Safety Science*, vol. 50, no. 8, pp. 1675–1684, Oct. 2012, doi: 10.1016/j.ssci.2011.12.019.

[25] K. E. Boyce, T. J. Shields, and G. W. H. Silcock, ‘Toward the characterization of building occupancies for fire safety engineering: Capabilities of disabled people moving horizontally and on an Incline’, *Fire Technology*, vol. 35, no. 1, pp. 51–67, Feb. 1999, doi: 10.1023/A:1015339216366.

[26] J. Lord, B. Meacham, A. Moore, R. Fahy, and G. Proulx, ‘Guide for evaluating the predictive capabilities of computer egress models’, National Institute of Standards and Technology, Gaithersburg, MD, USA, NIST GCR 06-886, 2005.

[27] T. J. Shields, K. E. Boyce, and N. McConnell, ‘The behaviour and evacuation experiences of WTC 9/11 evacuees with self-designated mobility impairments’, *Fire Safety Journal*, vol. 44, no. 6, pp. 881–893, Aug. 2009, doi: 10.1016/j.firesaf.2009.04.004.

[28] T. Jin, ‘Studies on human behavior and tenability in fire smoke’, in *Fire Safety Science - Proceedings of the Fifth International Symposium*, 1997, pp. 3–21.

[29] R. Chagger and D. Smith, ‘The causes of false fire alarms in buildings’, BRE Global, Graston, England, BC2982, 2014.

[30] K. F. Wong, ‘Study on reliability of manual call points in residential buildings’, *International Journal on Engineering Performance-Based Fire Codes*, vol. 6, no. 4, pp. 344–352, 2004.

[31] S. Tan, D. Weinert, P. Joseph, and M. Khalid, ‘A dynamic probabilistic fire risk model incorporating technical human and organisational risks for high rise residential buildings’, presented at the Interflam, Royal Holloway College, UK, 2019.

[32] S. Gwynne and K. Boyce, ‘Engineering data’, in *SFPE Handbook of Fire Protection Engineering*, 5th Edition., Springer, 2016, pp. 2429–2551.

[33] R. Lovreglio, E. Kuligowski, S. Gwynne, and K. Boyce, ‘A pre-evacuation database for use in egress simulations’, *Fire Safety Journal*, vol. 105, pp. 107–128, Apr. 2019, doi: 10.1016/j.firesaf.2018.12.009.

[34] P. Geoerg, F. Berchtold, S. Gwynne, K. Boyce, S. Holl, and A. Hofmann, ‘Engineering egress data considering pedestrians with reduced mobility’, *Fire and Materials*, vol. 43, no. 7, pp. 759–781, 2019, doi: 10.1002/fam.2736.

[35] R. Pearson and M. Joost, ‘Egress behavior response time of handicapped and elderly subjects to simulated residential fire situations’, National Institute of Standards and Technology, Gaithersburg, MD, USA, 1983.

[36] M. Spearpoint, ‘The effect of pre-evacuation on evacuation times in the Simulex model’, *Journal of Fire Protection Engineering*, vol. 14, no. 1, pp. 33–53, Feb. 2004, doi: 10.1177/1042391504034742.

[37] J. Vistnes, S. J. Grubits, and Y. He, ‘A stochastic approach to occupant pre-movement in fires’, *Fire Safety Science*, vol. 8, pp. 531–542, 2005.

[38] M. Spearpoint, R. Lovreglio, and S. Gwynne, ‘The response of sleeping adults to smoke alarm signals in the Evacuation Decision Model’, *Fire Safety Journal*, vol. 123, p. 103379, Jul. 2021, doi: 10.1016/j.firesaf.2021.103379.

[39] D. Bruck and M. Ball, ‘Optimizing emergency awakening to audible smoke alarms: An update’, *Hum Factors*, vol. 49, no. 4, pp. 585–601, Aug. 2007, doi: 10.1518/001872007X215674.

[40] M. Nagarajan, D. Shaw, and P. Albores, ‘Disseminating a warning message to evacuate: A simulation study of the behaviour of neighbours’, *European Journal of Operational Research*, vol. 220, no. 3, pp. 810–819, Aug. 2012, doi: 10.1016/j.ejor.2012.02.026.

[41] M. Kobes, I. Helsloot, B. de Vries, and J. Post, ‘Exit choice, (pre-)movement time and (pre-)evacuation behaviour in hotel fire evacuation — Behavioural analysis and validation of the use of serious gaming in experimental research’, *Procedia Engineering*, vol. 3, pp. 37–51, Jan. 2010, doi: 10.1016/j.proeng.2010.07.006.

[42] E. Nober, H. Peirce, A. Well, C. C. Johnson, and C. Clifton, ‘Waking effectiveness of household smoke and fire detection device’, National Bureau of Standards, Gaithersburg, MD, NBS-GCR-80-284, 1980.

[43] E. D. Kuligowski, ‘Human behavior in fire’, in *SFPE Handbook of Fire Protection Engineering*, 5th Edition., Springer, 2016, pp. 2070–2114.

[44] D. Canter, 'Overview of human behaviour', in *Fires and human behaviour*, 2nd Edition., D. Canter, Ed., Northwester University: Fulton, 1990, pp. 205–234.

[45] J. Poushter, C. Bishop, and H. Chwe, 'Social media use continues to rise in developing countries but plateaus across developed ones', Pew Research Center, Jun. 2018.

[46] D. Purser and J. McAllister, 'Assessment of hazards to occupants from smoke, toxic gases, and heat', in *SFPE Handbook of Fire Protection Engineering*, 5th Edition., Springer, 2016, pp. 2308–2428.

[47] G. Proulx, M. J. Ouellette, P. Leroux, and K. R. Bailey, 'Study of the occupant's behavior during the Ambleside fire in Ottawa on January 31, 1997', National Research Council of Canada, Internal Report 771, Oct. 1998.

[48] B. Lane, 'Grenfell Tower — fire safety investigation: The fire protection measures in place on the night of the fire', Expert witness report to the Grenfell Tower Inquiry, Apr. 2018.

[49] ABCB, 'International Fire Engineering Guidelines', Australian Building Codes Board, Canberra, ACT, Edition 2005, 2005.

[50] M. J. Spearpoint, J. V. Murrell, P. Rock, and J. N. Smithies, 'An experimental study of a detector-operated water discharge system to enhance life safety', *Fire Safety Journal*, vol. 26, no. 2, pp. 151–179, Mar. 1996, doi: 10.1016/0379-7112(95)00034-8.

[51] Y. Yashiro, M. Ebihara, and H. Notake, 'Fire safety design and fire risk analysis incorporating staff response in consideration of fire progress stage', presented at the 15th meeting of the UJNR panel on fire research and safety, Mar. 2000.

[52] Department of Housing, Planning and Local Government, 'Building Regulations 2006: Fire Safety - Technical Guidance Document (2020 edition with amendments & corrections)'. Government of Ireland, 2020.

[53] E. Ronchi and D. Nilsson, 'Modelling total evacuation strategies for high-rise buildings', *Build. Simul.*, vol. 7, no. 1, pp. 73–87, Feb. 2014, doi: 10.1007/s12273-013-0132-9.

[54] H. Alnabulsi and J. Drury, 'Social identification moderates the effect of crowd density on safety at the Hajj', *Proceedings of the National Academy of Sciences*, vol. 111, no. 25, pp. 9091–9096, Jun. 2014, doi: 10.1073/pnas.1404953111.

[55] E. Ronchi, P. A. Reneke, and R. D. Peacock, 'A method for the analysis of behavioural uncertainty in evacuation modelling', *Fire Technol*, vol. 50, no. 6, pp. 1545–1571, Nov. 2014, doi: 10.1007/s10694-013-0352-7.

[56] A. Grandison, 'Determining confidence intervals, and convergence, for parameters in stochastic evacuation models', *Fire Technol*, vol. 56, no. 5, pp. 2137–2177, Sep. 2020, doi: 10.1007/s10694-020-00968-0.

[57] A. Tinaburri, 'Principles for Monte Carlo agent-based evacuation simulations including occupants who need assistance. From RSET to RiSET', *Fire Safety Journal*, vol. 127, p. 103510, Jan. 2022, doi: 10.1016/j.firesaf.2021.103510.

[58] C. Hopkin, M. Spearpoint, Y. Wang, and D. Hopkin, 'Design fire characteristics for probabilistic assessments of dwellings in England', *Fire Technology*, 2019, doi: 10.1007/s10694-019-00925-6.

[59] BSI, 'BS 8629:2019 Code of practice for the design, installation, commissioning and maintenance of evacuation alert systems for use by fire and rescue services in buildings containing flats', BSI, London, 2019.

[60] E. Claridge and M. Spearpoint, 'Fire fighter stair climbing speeds in high rise buildings', in *8th Asia-Oceania Symposium on Fire Science and Technology (AOSFST)*, Melbourne, Australia, Dec. 2010.

[61] BSI, 'BS 9999:2017 Fire safety in the design, management and use of buildings. Code of practice', BSI, London, 2017.

[62] V. V. Kholshevnikov, T. J. Shields, K. E. Boyce, and D. A. Samoshin, 'Recent developments in pedestrian flow theory and research in Russia', *Fire Safety Journal*, vol. 43, no. 2, pp. 108–118, Feb. 2008, doi: 10.1016/j.firesaf.2007.05.005.