MEANS OF ESCAPE IN RESIDENTIAL BUILDINGS

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1 Introduction

1.1 Background

In June 2017, the Grenfell Tower fire resulted in the death of 72 residents, many others becoming homeless with a wider impact on the local community. The incident also posed a significant challenge to the operational capabilities of London Fire Brigade. In response to the fire, Dame Judith Hackitt conducted an independent review of Building Regulations and fire safety in England where she supported the recommendation to carry out "…*further research with the construction industry to understand who uses Approved Documents, how they are used and where they are used to influence how they should be developed in the future*…". This report contributes to research that forms part of the recommended 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 goal 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)*" in relation to high-rise residential buildings.

In order to meet the BSR's goal, the work presented herein quantifies the evacuation performance using a representative set of egress scenarios that include challenging building smoke movement situations. The qualification has been achieved through the use of numerical simulations that have been informed by an understanding of the physical design measures in buildings that support evacuation, coupled with the behavioural factors that influence occupant movement and decision-making. As part of the work the study has also engaged with residents, fire and rescue service (FRS) personnel, and other professionals to gain specific insights on relevant evacuation behaviour and building design characteristics. The findings from this study have allowed for 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.

[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).

‘Building work’ is a legal definition for work covered by the Building Regulations in England. Although the guidance given by AD B is generally applied to building work associated with new construction it is important to note that “*Building work and material changes of use subject to requirement B1* [of the Building Regulations] *include both new and existing buildings*.” As such, although most of the study is assumed to related to evacuation strategies of new buildings, the work also examined elements related to existing buildings, particularly where the research focused on the interviews with residents.

1.2 Work programme

Figure 1 shows the original work plan created at the beginning of the project in which the study was broadly split into two main themes, each with a major objective. **Objective A** investigated the principal design characteristics that impact on evacuation from high-rise residential buildings and then to perform numerical simulations of relevant scenarios. **Objective B** examined occupant and FRS behaviour around evacuation from high-rise residential buildings including understanding their confidence in the associated guidance and procedures. Each objective has been subdivided into three work items, which are further subdivided into smaller elements.

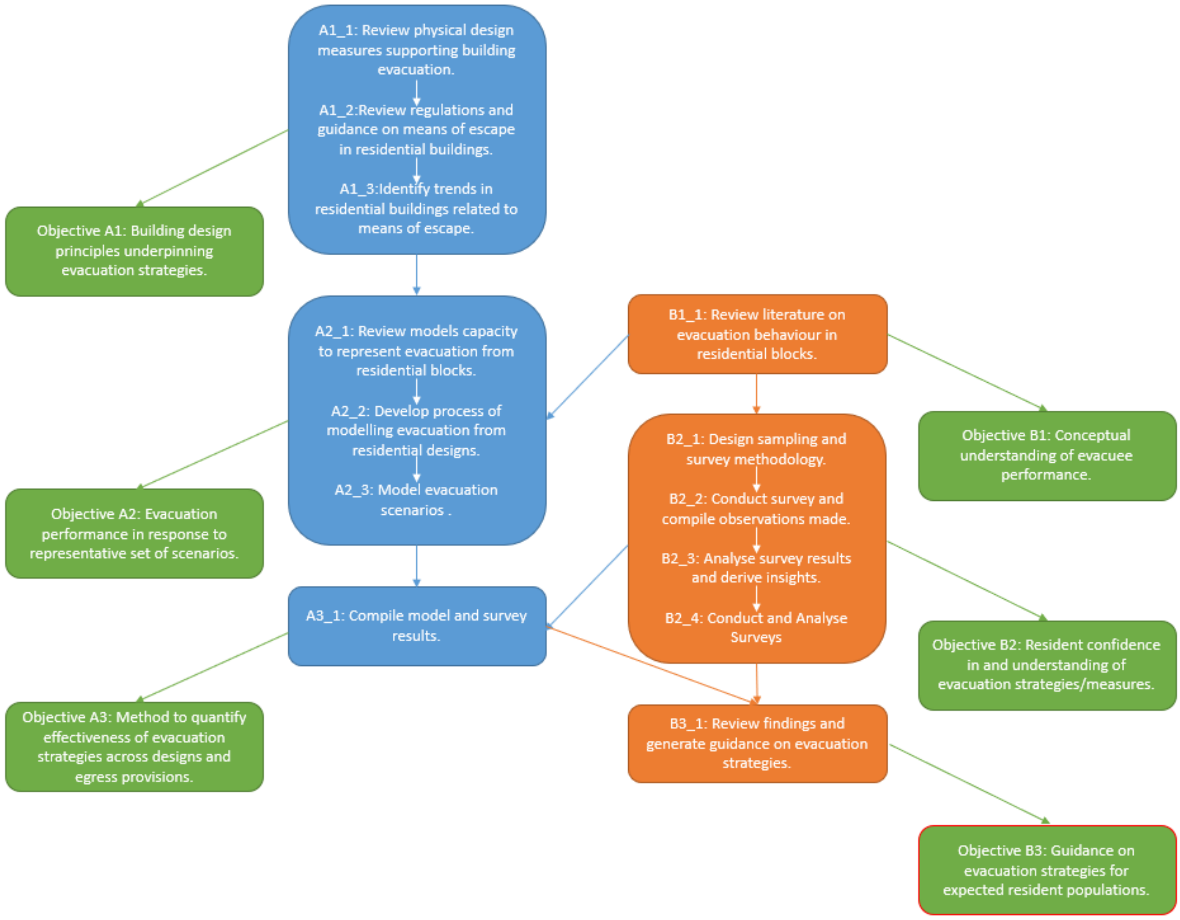

Figure 1 Structure and interaction between the study objectives

The interconnected work items conducted a series of simulations, surveys, and literature review to provide guidance on the evacuation strategies related to the effectiveness of physical design measures, fire detection and alarm systems, and human behaviour in the context of high-rise residential buildings.

Objective A1: Review of physical measures and international guidance documents and **current trends in residential buildings** is split into two reports. The first report captures **Objective A1-1** and **Objective A1-2** (Appendix A1-1 and A1-2), which examine the physical measures in buildings that support evacuation along with a review of selected international guidance documents and standards. **Objective A1-1** has been supplemented by a second report comprising **Objective A1-3** (Appendix A1-3) to understand future design and residential building use trends by engaging with a group of industry professionals and carrying out a review of selected published articles in relevant trade journals.

Objective B1: Resident decision-making (Appendix B1) is a review of the research literature and case studies on human behaviour during emergency evacuations that relates to high-rise residential buildings. This was compiled to establish a conceptual understanding of expected resident performance during evacuation. The findings of this review fed into the following objectives.

Objective A2: Proposed exemplar building and model selection (Appendix A2) defines a set of exemplar building floorplates for the simulation of a set of 'common' high-rise residential buildings. It also determines the relevant scenario parameters and gives the background to the two evacuation modelling tools selected to run the numerical simulations for **Objective A3**.

Objective B2: Methodology and findings from interviews with FRS and residents, and surveys with residents (Appendix B2) identifies the views of both residents of multi-unit buildings and FRS personnel on the understanding and confidence in fire safety and evacuation guidance. The work is split into two phases and consists of an agreed methodology followed by interviews, surveys and focus groups.

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

Objective B3: Assessment of evacuation strategies is contained within this report rather than as a separate document. Here the pros and cons of the various evacuation strategies examined by this research are compared. This comparison has brought together the findings from the previous objectives discussed above. The objective then considers the broad impact of selecting a particular change to an evacuation strategy.

1.3 Reporting

This study has been carried out by a consortium of partners that has been led by OFR. The majority of the work has been jointly undertaken by members of OFR, Movement Strategies / GHD and the University of Edinburgh, with each partner taking leadership of specific objectives. The responsibility of the members from Efectis and University College London (UCL) has been to provide internal review and critique of the work. These internal reviews have provided an important role in improving and clarifying key elements. The contributors and their organisations are identified within the reports contained within each appendix, relevant to the time of writing of the reports.

External oversight of the project has been provided by a Technical Steering Group (TSG) consisting of stakeholders from various public and private organisations. The TSG had already been previously convened by the BSR / Home Office prior to this project. Discussion led to the inclusion of three additional international members specifically nominated for this project. The new members had particular expertise in evacuation simulation and human behaviour. The three experts were unable to participate in TSG meetings but acted as corresponding members due to the time differences.

The appendices to this final report are those documents released throughout the research project with some minor editorial and formatting changes. The appendices retain the tenses as they were written at the time rather than being updated to reflect their current status. The earlier documents make reference to work that may or may not have subsequently been carried out as the result of ongoing findings, and feedback from the BSR and the TSG. The research also needed to adapt to various external factors such as newly published documents that have appeared over its duration.

Subsequent to the release of the contents of the appendices, several articles have been published in the open literature. As a result of the review process, some of these articles contain updated and or additional content that has not been included in the original documents (i.e., the attached appendices). Further articles may be forthcoming which may again differ from some elements of the work presented here in response to feedback. A list of the published articles and those currently in submission is provided below:

1. S. Gwynne, M. Spearpoint, A. Templeton, M. Arnott, H. Xie, C. Nash, M. Ramsden. ‘Assessing the impact of changes to guidance on evacuation from fire in multi-occupancy high-rise residential buildings’, Fire and Evacuation Modeling Technical Conference (FEMTC), Brno, Czechia, 12-14 September 2022.
2. A. Templeton, C. Nash, M. Spearpoint, S. Gwynne, X. Hui, M. Arnott, ‘Who and what is trusted in fire incidents? The role of trust in guidance and guidance creators in resident response to fire incidents in high-rise residential buildings’, *Safety Science*, 164, 2023. doi: 10.1016/j.ssci.2023.106172
3. A. Templeton, C. Nash, L. Lewis, S. Gwynne, M. Spearpoint, ‘Information sharing and support among residents in response to fire incidents in highrise residential buildings’, *International Journal of Disaster Risk Reduction*, 92, 2023. doi: 10.1016/j.ijdrr.2023.103713
4. A. Templeton, C. Nash, M. Spearpoint, S. Gwynne, H. Xie, ‘Trusted source, trusted information, trusted support: The role of trust in resident emergency response’, *SFPE Europe*, Issue 27, 2023.
5. M. Spearpoint, M. Arnott, X. Hui, S. Gwynne, A. Templeton, ‘Comparative analysis of two evacuation simulation tools when applied to high-rise residential buildings’, *Safety Science* (accepted for publication).
6. M. Spearpoint, S. Gwynne, X. Hui, A. Templeton, ‘A component-based approach to stochastic pre-evacuation delays’, Submitted to 4th European Symposium on Fire Safety Science, ESFSS 2024.

2 Objectives A1-1 and A1-2

Review of physical measures and international guidance documents

Objective A1-1 identified the range of physical measures that can be included in buildings that are likely to affect the means of escape as part of a fire safety strategy. The physical measures do not operate in isolation, but form part of a coupled system which supports the overall fire safety of a building. The review identified several key knowledge gaps, namely:

- There appears to be little research that investigates whether the installation of automatic smoke and heat detection systems provides an additional benefit to vulnerable occupants when compared with other population groups,
- Although not in wide use, there are several directional signage technologies available that have been specifically designed to aid emergency evacuation. Given the relative newness of these technologies and the rarity of their installation it would be beneficial to investigate their effectiveness,
- Research on the likelihood that people will use lifts in an emergency, how changing technologies and education may alter people's perception of using lifts, the management and operation of lifts need further investigation,
- Modern technology provides multiple means of communication between building occupants, between occupants and the emergency services, between building systems and between systems and people. Further work is needed on what impact these technologies can have on the evacuation strategies available to building occupants,
- The available literature on mobility impaired occupants and their operation of doors, such as when unlocking doors and escaping from a flat, is limited. However, it does point to potential difficulties in opening doors delaying progress. This could subsequently affect their escape time, as well as tenability conditions should the door from a fire affected room be opened for a prolonged period to assist in escape,
- Within the scope of human interaction, it would be beneficial to extend knowledge on the communication between alarm type and other occupant factors (activity, experience, etc.) when related to pre-evacuation time and the impact of staff type and authority on occupant reaction to instructions, and
- Finally, a clearer understanding of the impacts of the maintenance of social groups; fatigue / ill-health / obesity and the use of mobile devices on travel

speeds would help to better assess the likely escape time that might be required in the event of a fire.

Some of the knowledge gaps were addressed in the follow up objectives, while the others were beyond the scope of the study. Topics such as the use of lifts and the impact of alarms have been subsequently examined in **Objective A3**.

Objective A1-2 summarised the different approaches to fire safety design around the world for each of the different measures, with reference to relevant guidance documents and standards. The comparison between AD B (at the time of the review), and UK guidance more generally, to other documents and standards highlighted some key differences in the design approach to residential buildings:

- AD B allows for a single stair when a building is greater than 11 m in height, whereas other guidance documents typically recommend that at least two stairs be provided,
- AD B appears to be the only guidance document where the recommended fire resistance rating of the stair enclosure increases as a function of building height (i.e., when above 11 m),
- AD B recommends that dwellings with internal bedrooms or above a certain size (i.e., where travel distances are greater than 9 m) be provided with an internal protected corridor / entrance hall. In contrast, other documents allow for a much greater flexibility in the design of the internal arrangement of dwellings, with no expectation that a protected corridor be provided, and
- There is approximately a 50/50 split between the documents on whether refuge points should be included for standard residential accommodation, with AD B providing no recommendation that they need to be provided.

3 Objective A1-3

Current trends in residential buildings

This objective engaged with a group of industry professionals to understand future design and residential building use trends. It also carried out a review of selected published articles in relevant trade journals, but not an extensive appraisal of the literature. The key findings from examining the effects on evacuation of high-rise residential of these trends are given below.

As an evacuation strategy, stay put is not always well understood by residents and even by many professionals. Whilst it was generally felt to be appropriate for most residential situations, it was recognised that its success and residents' confidence in its effectiveness relies on a number of factors, including:

- Effectiveness of compartmentation,
- Use of sprinklers,
- Effective smoke management, and
- Resident awareness of required responses.

Engagement with residents on the building evacuation strategy is crucial to ensure not only that all components are understood, but that this understanding is frequently refreshed and reinforced. There is a trend of finding more effective ways in which to engage residents in their understanding of the evacuation strategy. Communicating the evacuation strategy to residents and initiating education are likely to be difficult where buildings are being used for short-term rental accommodation. This development has occurred quickly and is demonstrating the need to consider regular revisions of regulations and/or guidance.

There is increasing use of shared amenity areas, such as roof terraces, common rooms, and kitchen/dining rooms. However, there were a considerable range of opinions about how the evacuation strategy for such areas should be managed, particularly for those shared areas located higher up the building.

Modern methods of construction offer many advantages such as speed of construction and cost-savings. However, some of these systems, such as modular construction, rely for their fire integrity on extensive fire stopping around each module to preserve the compartmentation integrity throughout the building life. Experience has shown that for this to be true, there must be a greater focus on extensive, independent verification during construction than is currently the case.

Investor confidence and perceived futureproofing is an important factor in decision-making around safety and evacuation measures. This sometimes pushes designers to incorporate features, such as a second staircase and/or sprinkler systems, that would not normally be required by the then existing guidance at the time of the design or driven by the fire strategy.

Finally, the design of high-rise residential buildings needs to recognise that the needs of residents may vary during the time they live in the building – whether that be permanent or temporary impairments, the need to care for dependants, etc. Changing population demographics makes it more likely that high-rise accommodation will house elderly residents with reduced mobility, who will require the use of lifts for evacuation. The easier access to high-rise buildings should also be used as an easier means of evacuation in case of fire. It is recognised that there are problems with providing ‘triaged’ evacuation for buildings without a permanent custodian.

4 Objective B1

Resident decision-making

The scope of **Objective B1** was to establish a conceptual understanding of expected resident performance during evacuation and the associated influential factors. This objective completed a review of the research literature and case studies on human behaviour during emergency evacuations that relates to high-rise residential buildings. The review of the literature on evacuation from fire was used to develop an understanding of relevant evacuee decision-making that might be expected in resident scenarios of interest. Existing conceptual models of evacuee behaviour were used to identify key behavioural statements. Material on resident evacuation from fire emergencies (along with material on evacuation scenarios that shared common factors and social situations with residential incidents) was used to produce a structure applied to the resident decision-making process.

The findings from the above steps were used to focus the behavioural statements on resident evacuee decision-making and populate a decision-making structure. This resulted in a mapping of the modelling structures outlined by this objective to the previous matrix structure identified in **Objective A1**. The compilation of factors and actions specific to resident evacuation in multi-occupancy structures allowed the research to develop a simple resident decision-making process connecting the compiled factors and behavioural statements.

This outcome of **Objective B1** informed the survey design iterations undertaken as part of **Objective B2**. **Objective B1** also developed an interim scenario structure and provided a provisional examination of available simulation tools to establish which of them had the required functionality, both relevant to **Objective A2** and **Objective A3**.

5 Objective A2

Proposed exemplar building and model selection

Objective A2 established exemplar building floorplates for the simulation of a ‘common’ building through a probabilistic assessment of the relevant data. In some cases, the configurations meet the recommendations given by statutory guidance in Approved Document B (AD B) and in other cases the configurations were selected to extend beyond the expectations given by AD B given insights provided in **Objective A1-3**.

This objective assessed the relevant parameters for the representation of the building and the occupants using the findings from **Objective A1** and **Objective B1**. The parameters considered were:

- Event parameters – time of day, weather conditions, fire location, and fire impact,
- Building parameters – height, number of stairs, stair width, common corridor length, lifts, and presence of amenity spaces,
- Procedural measures – means of warning, use of lifts, and evacuation strategies such as ‘stay put’, phased, simultaneous,
- Occupant parameters – number of residents, number of visitors, mobility characteristics, demographics, and initial location,
- Fire and rescue service parameter – attendance time, and
- Response parameters – pre-evacuation delay, congested and uncongested travel speeds on stairs and level ground, route availability and use, and occupant tasks.

These parameters were used to build a matrix of scenarios that were further developed in **Objective A3**.

Objective A2 also provided the background to the Pathfinder and Evacuationz modelling tools used in the numerical simulations carried out in **Objective A3**. The selection process considered a range of factors including their ability to:

- Represent key evacuee behaviours including route selection, pre-evacuation delays, variation in movement/flow rates that might be achieved, and evacuee objectives,

- Reflect different population types (including those with movement impairments),
- Represent the scale and type of building,
- Assess both global (flow) and individual evacuee perspectives, and
- Generate output on the performance of the population within floors, individual stairwells, and building wide that reflects route use, arrival times, distances travelled, and congestion experienced.

6 Objective B2

Methodology and findings from interviews with FRS and residents, and surveys with residents

Following defining a methodology (also included in Appendix B2) agreed by the BSR and TSG, **Objective B2** used individual interviews with fire and rescue service (FRS) personnel, as well as surveys and focus group interviews with residents of high- and medium-rise residential buildings to identify a number of factors related to views of fire safety measures and evacuation strategies, and anticipated behaviour in the event of a fire. Specifically, the interviews with FRS focused on:

- FRS views on guidance for residents about what to do in the event of a fire,
- FRS perceptions of public behaviour in high-rise residential building evacuations, and
- FRS perceptions of reasons for public behaviour in the event of a fire.

The surveys and focus group interviews with residents explored:

- Resident understanding of evacuation strategies and fire safety measures in the buildings they reside in,
- Resident confidence in the fire safety and evacuation guidance provided to them by building managers, local councils, and the FRS,
- Residents' reported behaviour and reasons for that behaviour in prior fire incidents within their building, and
- The role of group processes in perceptions and decision-making in the event of a fire, particularly which sources of information were sought, attended to, and trusted.

Several key findings resulted from the surveys and interviews, namely that:

- The FRS personnel stressed the importance of making guidance clear, concise and accessible for residents and assessing resident understanding of the guidance,
- Both the FRS personnel and residents identified that group relations impacted residents' motivation to adhere to guidance. FRS placed importance on building links with the community to facilitate a trusting relationship that later helped promote safety in fire emergencies. Similarly, residents were motivated to adhere to implementing fire safety precautions and following guidance in fire incidents when they saw FRS as working for and with residents to keep them safe,

- In contrast to the point above, residents were less motivated to adhere to fire preparedness guidance if they did not believe a safety measure was needed and/or it conflicted with their immediate needs. For example, some residents were reluctant to implement advised changes to their building for fire safety when their immediate concern was about finances,

- Group relations impacted on whom residents looked to for information when interpreting fire incidents and deciding how to respond to them. Residents reported seeking and sharing information with others in their building (e.g., in person, through phone messaging applications, or social media) if they were unsure whether a threat was real, such as whether to respond to a fire alarm,

- Importantly, residents particularly sought and trusted information from other residents with whom they already had positive relations, were already communicating with (such as over shared building concerns), or when they believed there was a good community in the building,

- When the trusting relationships described above were in place, residents also reported that they believed others in the building would alert them if they needed to evacuate. This expectation did not exist for residents who felt isolated from the others in the building,

- Some FRS personnel suggested that residents could be a valuable source of information during fire incidents if there was a cohesive community in the building, such as by sharing the locations of vulnerable residents or helping with corralling. However, FRS were unsure how to achieve this coordination with residents under current emergency response practice,

- The interviews showed that residents' trust in the stay put guidance was very low, but the survey results showed medium levels of trust in the stay put guidance. In the interviews, the low trust in guidance to stay put was associated with the lack of trust in high-rise buildings following fires such as Grenfell Tower,

- Trust in the guidance (both stay put and evacuate) and the guidance creators were important factors in understanding willingness to follow the guidance. Residents' trust in the guidance to stay put or evacuate was also related to their belief that their building was equipped to allow for a stay put strategy or evacuation strategy to be put in place, and

- The likelihood of residents following others in a fire incident was related to the extent to which they felt part of a group with the other residents, and the expectation that other residents would provide them with help.

The results of the work carried out in **Objective B2** had implications for the evacuation simulations undertaken in **Objective A3** in the following ways:

- The data from the interviews with FRS and residents informed the selected scenarios for a fire incident in a high-rise residential building.
- The key factors identified in the interviews were mapped onto possible inputs for the simulations. This involved categorising the potential impact of the factor (e.g., seeking information from others) on delay prior to evacuation, speed during evacuation, route choice, pedestrian flow in the building, and any additional factors to consider (e.g., social influence).
- The survey data was transformed into possible sequences of events in which the distributions of agents who would take certain progressions of actions (e.g., percentage that would evacuate immediately and percentage who would stay put) has been inferred.

7 Objective A3

Develop method to quantify effectiveness of evacuation strategies

The principal aim of **Objective A3** was to quantify the evacuation performance in response to a representative set of scenarios and to then assess the effectiveness of different evacuation strategies. Two agent-based evacuation models were applied to investigate evacuation in a quantitative manner across an array of different scenarios and system designs. A method was developed to reduce the scenario envelope, enabling the capture of key results whilst operating within the constraints of the project. The simulations address the design, procedural and response variables to investigate how they individually and collectively affect the evacuation of occupants from a range of different building configurations. A structured approach to assess evacuation performance through the simulations was adopted that:

- Gave confidence in the results produced by the models in terms of their robustness, sensitivity and similarity,
- Assessed the sensitivity of evacuation performance to certain factors,
- Examined the impact of varying key factors on performance, and
- Described the detailed examination of interaction of key factors on performance.

The scenarios were configured using findings from both the literature review in **Objective A1** and the resident surveys in **Objective B2**. 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.

Building floorplates were developed in **Objective A2** to define a set of exemplar buildings ranging from 11 m to 140 m in height. The exemplar buildings were 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 customised to suit different situations and scenarios.

The science of fire development, toxic gas concentrations etc., includes highly complex phenomena that are sensitive to underlying assumptions. As such, 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. A representative hazard scenario was used in which fire and smoke spreads internally through the building via the stairs to present a significant evacuation challenge. A specific external fire and smoke spread scenario was not considered. The hazard scenario has been compared with evidence from the Grenfell Tower inquiry expert evidence.

The various evacuation strategies available to a high-rise residential building were briefly discussed, namely: stay put, evacuate to a place of safety within the building, and evacuate to the outside of the building. The focus 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 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.

Simulated results explored 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 was somewhat independent of other assumptions regarding the fire location and severity. However, reducing the total evacuation time of a building alone should not necessarily be considered a metric of increased safety. Therefore, where additional insights were required, floor clearance times and the number of agents trapped have been reported. A simple normalised measure was also developed that produced 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.

Broadly, the following conclusions were derived from the results produced:

- **Time to enter stair:** Where sufficient capacity is provided on the staircase and landings to act as an area of 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, then congestion will likely occur in the common corridors leading into the stairs. In such situations, congestion might accumulate as building height increases – requiring evacuating populations to queue at the stair entrance beyond the protection afforded by the stair. Thus, stairs (and landings) can provide an area of 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.

- **Building height:** Where the evacuation of a building is considered in the absence of congestion, then as buildings increase in height, so they produce progressively longer total evacuation times. 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. Scenarios with initial delays reflecting a detection and notification system in place and varied agent movement capabilities produce prolonged evacuation times. Overall, the total evacuation time of taller buildings is proportionally less than for shorter buildings considering movement separate from other performance elements such as alerting, pre-evacuation delays, etc. When other behavioural factors are included the total time for evacuation is more complex.

- **Stair width:** Stairs with sufficient capacity to hold the expected occupant load allows occupants to enter the stairs without producing congestion in the common corridors. Once the stair width exceeds that needed to hold the occupants then further widening has little material impact on evacuation performance. Where slower moving occupants may impede the movement of other evacuees, providing a stair width that allows for overtaking may have a benefit on evacuation times. Wider stairs may also benefit fire and rescue service personnel and reduce their negative impact on evacuating occupants.

- **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 holding capacity. Providing two stairs rather than a single stair has been shown to reduce the total evacuation time depending on the proportion of occupants that use each stair and the assumed distribution of pre-evacuation times. Should residents respond within 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 in the stair which is already a place of safety. 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 and occupant movement speeds. 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 – although the design and positioning of the stairs should maximise the delay of the second stair being similarly affected. In buildings much taller than 30 m the benefit of additional stairs becomes more complex as the ability of occupants to reach the outside is impacted by the time for individuals to traverse the required travel distance in conjunction with the demand on stair capacity.

- **Detection and notification:** The simulations suggest that a building-wide tone alarm when coupled with corridor smoke detection provides no obvious advantage over a reliance on social notification. A building-wide voice alarm reduces total evacuation time over a reliance on social notification when coupled with either corridor smoke detection or with flat heat detector. The benefit of more effective detection and notification increases with building 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 there is an increased likelihood that occupants could become trapped irrespective of the type of notification provided.

- **Lifts:** Lifts offer a means of egress for occupants who are unable or unwilling to use stairs. The benefit of providing lifts increases with building height for those using the stairs while having a consistent benefit for those using the lift system. Providing two lifts rather than a single lift has a benefit to those using the lifts but not to those using the stairs. The findings given here are only for a specific lift use behaviour[2] and may not be universal to all lift use strategies. The characteristics of the lift shall be designed accordingly.

- **Stay put:** This strategy was not the focus of this work. However, the stay put strategy does not require that occupants stay in their flats, and some may choose to evacuate even though dedicated evacuation provisions are not in place. In buildings with local detection and notification, incident awareness may not be limited to the flat of origin. Assuming incremental social communication between occupants enabling wider evacuation to take place, then only a small number of occupants are likely to become trapped for shorter buildings. However, given the variability of communication that might actually occur, social communication between occupants should not be relied upon as a primary means of response should a full building evacuation be necessary.

[2] Which complies with the recommendations in BS 9999:2017.

8 Objective B3

Assessment of evacuation strategies

8.1 Background

The purpose of **Objective B3** is to bring together the findings of the research in this project and identify the pros and cons of the evacuation strategies that have been analysed. However, before doing this it is important to put this research in the context of the fire safety regulatory environment in England that addresses the design of buildings. The primary consideration is that a fire strategy for a high-rise residential building must comply with the Building Regulations, specifically clause B1 which states:

> "*The building shall be designed and constructed so that there are appropriate provisions for the early warning of fire, and appropriate means of escape in case of fire from the building to a place of safety outside the building capable of being safely and effectively used at all material times*."

In support of the Building Regulations the Secretary of State has provided a range of measures which in their view provide the means to meet clause B1. One of these views is that:

> "*For buildings containing flats, there are appropriate provisions to support a stay put evacuation strategy*."

Either of the above could be changed subject to modifications to the Building Regulations or the view of the Secretary of State. However, given the current regulatory requirements, one question is then what provisions are deemed 'appropriate' to achieve the goals of the Building Regulations. One way to address this is to consider the statutory guidance given by Approved Document B (AD B) although these are only one means to comply with the Building Regulations. Within the current 2019, Volume 1 edition of AD B incorporating 2020 and 2022 amendments, 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."

A building evacuation strategy is backed by various forms of guidance available to the building occupants and other stakeholders. However, it is important to note that guidance comes in various forms, namely:

- Building design guidance, such as that given by Approved Document B (AD B). This guidance is in turn supported by standards, codes of practice, industry best practice, etc.

- Building fire safety guidance that may be provided to occupants by the building management, fire and rescue services etc. on what to do in the event of fire. This guidance may be specific to the building the occupant is in or may be of a more general nature. This guidance may be informed by building design guidance and/or specific building characteristics.

- Guidance given by the emergency services during an incident. This guidance may come from incident control room staff and/or emergency responders at the scene. This guidance will be related to the standard operating procedures of the responders, their knowledge of buildings in general, and of the specific building which may have its own specific incident plan.

It is reasonable to expect that occupants generally do not have a direct view of design guidance other than how that eventually manifests itself in the building in which they are in in terms of construction, arrangement, and safety systems. However, as this research has shown, occupants do have a view on the guidance provided by building managers and also the FRSs on what to do in the event of a fire. This view is affected by the trust they have in the guidance and who is providing that guidance.

8.2 Key findings

As noted above, **Objective B3** provides a review of the findings from the research conducted and identifies the strengths and limitations of evacuation strategies for given population demographics for the various high-rise residential building designs, fire protection measures and scenarios that might be faced. The goal is to provide derived guidance on the effectiveness of the physical provisions in support of escape in high-rise residential buildings based on the literature review, evacuation simulations and surveys conducted within this project.

It is important to note that to make the simulated egress scenarios challenging to the occupants it was assumed that certain fire protection measures were either absent or did not operate effectively – thus, requiring an evacuation. For example, it was assumed the buildings were not sprinklered, there was no common corridor smoke control, and doors in common areas had a limited smoke separation performance. As such this means that the requirement in the Building Regulations that "…*appropriate means of escape* […] *capable of being safely and effectively used at all material times*" and expectation within AD B that "*Sufficient protection to common means of escape is necessary*…" to support the stay put strategy were intentionally not present. The lack of such fire protection measures affected the routes available and the available safe egress time (influencing when occupants were deemed trapped); however, they did not affect the evacuee movement. These scenarios are assumed to provide reasonably conservative outcomes.

Table 3 below is a summary of the key findings from the research conducted as part of this project. The findings are presented according to the extent and consistency of their impact on outcome – primarily overall evacuation time. Rather than repeating the numerical findings given in **Objective A3,** a simple notation has been developed to categorise the impact of the interventions examined. A scale of '=' to '+++' is used to indicate the increasing strength/consistency of impact. The notation meaning is shown in Table 1.

Table 1 Category notation used in Table 3

Scale	Meaning
=	Inconsistent and/or marginal differences
+	Inconsistent and/or modest differences
++	Inconsistent and/or notable differences
+++	Consistent and notable differences

For instance, voice notification reduced evacuation time in all scenarios to a notable extent; therefore, it is assigned '+++'. Similarly, the impact of the introduction of lifts was variable – depending on the number of lifts introduced and influencing the performance of those with and without movement impairments in different ways; therefore, it was assigned '++'. A cell is designated as 'n/a' if there was no identifiable intervention relationship, or the relationship was not explicitly examined (beyond the scope of this research).

Evidence for the summary findings came from the three sources, i.e., simulation, surveys, and literature review. The font style of the entries in Table 3 have been modified to reflect the primary source. The font styles used are shown in Table 2.

Table 2 Font styles used to indicate primary evidential source used in Table 3

Font style	Meaning
Bold	Evidence derived from simulation (Objective A3)
Italics	Evidence derived from surveys (Objective B2)
Underlined	Evidence derived from literature review, subject matter expertise and feedback (Objective A1)

Table 3 shows the summary of the key findings relating to deliberate interventions to affect evacuation performance. The interventions are assessed against the evacuation factors previously identified as part of **Objective A1** (see Table A1-5 of Appendix A1). The impacts are in comparison with the expectation of *current* high-rise residential buildings such that alerting of the building occupants is via social notification, the building has a single stair of minimum width, and any lifts are not used during evacuation. In many instances, evidence was derived from multiple sources; however, only the most significant evidence is recorded. The evidence is ranked in decreasing order of priority: simulation, surveys, then review/expertise. This order was selected given that both survey and review data was used to configure the simulation work (similarly the survey was informed by the literature review), and that the simulation work examined scenarios specific to the research questions addressed by the project.

Table 3 Summary of key findings reflecting the impact of interventions to improve evacuation performance and the source of the findings presented [a]

Intervention	Pre-evacuation			Movement		Total evacuation time
	Recognition	Preparatory actions – physical	Preparatory actions – situational awareness	Wayfinding / route selection	Physical travel	
Flat heat detection [c]	++ Enables early detection allowing notification to activate quickly.	n/a	n/a	n/a	n/a	**+++** **Reduces evacuation time to a greater extent due to early notification when coupled with a building-wide voice alarm.**
Corridor smoke detection [c]	+ Enables early detection allowing notification to activate quickly.	n/a	n/a	= **Requires that sufficient smoke enters a common corridor which may reduce the evacuation availability of that route.**	n/a	**++** **Reduces evacuation time to a lesser extent when coupled with a building-wide voice alarm.**
Building wide tone alarm [d] [f]	= Limited information on nature of event.	+ Potential to reduce preparatory time for those with mobility impairments – reducing unnecessary general preparations.	++ Enables notification to be distributed widely.	n/a	n/a	**+** **No major advantage over using social notification, assuming social notification takes place. However, the reliability of social notification is likely to be highly variable and should not be relied upon.**

	Pre-evacuation			Movement		Total evacuation time
Intervention	Recognition	Preparatory actions – physical	Preparatory actions – situational awareness	Wayfinding / route selection	Physical travel	
Building wide voice alarm [d] [e] [f]	++ Considered to enhance recognition given additional provision of information.	+ Potential to reduce preparatory time for those with mobility impairments given more precise understanding of event – reducing unnecessary general preparations.	++ Enables notification to be distributed widely.	+ Opportunity to identify egress routes / systems in place and required response.	n/a	**+++** **A building-wide voice alarm reduces overall evacuation time when coupled with either corridor smoke detection (to a lesser extent) and 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 greater than 30 m in height there is an increased likelihood that occupants could become trapped irrespective of the type of notification provided.**

	Pre-evacuation			Movement		Total evacuation time
Intervention	**Recognition**	**Preparatory actions – physical**	**Preparatory actions – situational awareness**	**Wayfinding / route selection**	**Physical travel**	
Stair width	n/a	n/a	n/a	n/a	+ **Providing a stair width that allows for evacuee overtaking may have a benefit 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.**	+ **The introduction of wider stairs reduces the overall total evacuation time to a modest extent. The impact diminishes with further increase of stair width.**
Number of stairs	n/a	n/a	n/a	++ Provides alternative routes should conditions block one route (assuming adequate stair separation). *Addresses resident preference for second path.*	++ **Second stair reduces the time to enter stairs. It may also reduce congestion (hence the impact on movement) but only where a large proportion of the occupants use the stair simultaneously.**	++ **A second stair reduces overall evacuation time where occupancy levels are beyond a single stair storage capacity.** [b]

Intervention	Pre-evacuation			Movement		Total evacuation time
	Recognition	**Preparatory actions – physical**	**Preparatory actions – situational awareness**	**Wayfinding / route selection**	**Physical travel**	
Use of lifts	n/a	+ Potential to reduce preparatory time for evacuating wheelchair users given reduced need to transfer to other devices (and associated reliance on arrival of those who might assist in this process).	n/a	**+** **Provides a route for those unable to use the stairs**	**++** **Allowing movement dependent people to use lifts reduced the likelihood of them impeding other people travelling on stairs.**	**++** **Including one lift reduces evacuation times for both those using the lift system and those using the stairs in the cases examined.** **Including two lifts further reduces evacuation times only for those using the lifts.**

[a] Other factors were examined that might increase evacuation times (e.g., presence of amenity spaces), or which might place greater importance of specific egress elements (e.g. simultaneous response, or populations with no movement impairments). However, these were not explored as rigorously as the factors shown above.

[b] Impact of additional stair capacity increases with demand; such demand might increase as notification becomes more effective.

[c] Assumes single sensor detection and does not consider multi-sensor devices with associated signal processing.

[d] Assumes audible signal; however, devices may include visual and/or vibratory alerting mechanisms that might be beneficial to certain population sub-groups.

[e] Assumes that voice content is preceded by alerting tone, i.e., the message does not only include voice content, but also alert signals as might reasonably be expected.

[f] Alarm systems are assumed to be coupled with an effective detection system.

8.3 Potential challenges and negative impacts

Table 4 shows the *potential* challenges and negative impacts that might be produced through the introduction of the interventions highlighted in Table 3, noting the footnotes to that table. These challenges were not directly addressed in the survey or simulation elements of this work, and so are typically more speculative in nature and extracted from the literature review and discussion with the industry professionals as part of **Objective A3-3** or inferred from the developments identified. The significance or extent of the items have not been explored.

Table 4 Summary of the potential challenges or negative impacts of interventions to improve evacuation performance*

	Potential challenges or negative implications
Flat heat (or smoke) detection	• Cost of introduction and maintenance. Detectors within flats will need to be accessed for maintenance, • Flat smoke detection would reduce detection time compared with heat detection, and • Smoke detection may increase the likelihood of false alarms thereby reducing occupant trust in the system.
Corridor smoke detection	• Cost of introduction and maintenance. Detectors may be more likely to get damaged than when placed in flats, and • Potential for false alarms.
Building wide tone alarm	• Cost of introduction and maintenance. If alerting devices are placed within flats they will not need to be as loud as in a corridor but will need to be accessed for maintenance, • Occupants who hear an alarm are less likely to stay put should that be the primary strategy for the building, and • False alarms will impact on the whole building population.
Building wide voice alarm	• Cost of introduction and maintenance. If alerting devices are placed within flats they will not need to be as loud as in a corridor but will need to be accessed for maintenance, • Building occupants' ability to comprehend the message will need to be addressed (e.g., there may be a language barrier), • Occupants who hear an alarm are less likely to stay put should that be the primary strategy for the building, and • False alarms will impact on the whole building population.

	Potential challenges or negative implications
Stair width	• Increasing stair width will occupy additional floorspace incurring a cost, • Does not address those using wheelchairs, although might benefit those requiring assistance during stair use and those attempting to pass them during the evacuation, and • The benefits assumed for the additional width will not be realised if the stair is not effectively used in which the evacuation is determined by flow rather than speeds / delays.
Number of stairs	• Evacuation benefits are sensitive to the configuration / separation of the stairs. • Additional stairs will occupy additional floorspace incurring a cost, • Does not address the evacuation of those using wheelchairs or with severe movement impairments, and • Provision of stairs alone without signage and resident (and FRS personnel) familiarisation might not guarantee their effective (e.g., balanced use), and • Having additional stairs (or similarly any improvement in safety) could increase preparatory actions as occupants may stay put for longer or delay starting evacuation in the knowledge there are multiple escape routes available.
Use of lifts	• Cost of introduction and maintenance. Buildings with existing lifts may reduce the cost of their installation but may need them upgraded to allow them to be used for evacuation, • Need to design effective lift use protocols, • Outreach and training required to ensure use of lift in an emergency given historical guidance to avoid use, and • Need to ensure prioritisation of lift use for those with movement impairments. Likely to again involve outreach and training, and • The design of lifts to be used for evacuation is not common, and limited practices and guidance exist.

* All these findings are from literature review / subject matter expertise / feedback and so underline font style is applied throughout (refer to caption for Table 3).

8.4 Project conclusions

This research has investigated evacuation strategies related to the effectiveness of physical design measures, fire detection and alarm systems, and human behaviour in relation to high-rise residential buildings. It has used a combination of literature surveys, expert input, surveys and interviews, and an extensive set of evacuation simulations. This work has focused on the impact of various specific measures on evacuation performance, namely detection, notification, the width and number of stairs and the provision of lifts as a means of evacuation. It is important to acknowledge that measures to prevent fire spread and protect escape routes are also likely to impact on evacuation performance, but these are not investigated in this work. The work did not examine the social, economic, practical, or technological implications of adopting the specific measures of interest. This is left for potential future work or is assumed to be covered elsewhere. In addition, the research has not considered broader insights into the safety and effectiveness of the stay put strategy, which are more reliant on building design and fire protection measures along with human behaviour. However, aspects of the research touch on stay put given evacuation forms part of its strategy.

- **Stay put:** The current stay put approach assumes the potential for evacuation; it does not preclude individuals from evacuating as they see fit, or where they are instructed to do so by the fire and rescue service (FRS). As such, the effectiveness of evacuation measures is relevant whether a stay put strategy is continued or not.

  Given the prevalence of modern communication tools it is possible that residents will become aware of an incident through informal means (e.g., using their phones, accessing social media) in addition to speaking to neighbours, etc. Information will be sought informally, if not provided. If a stay put strategy is maintained, the nature of the incident and the status of the building must be clearly communicated to residents at a sufficiently early stage: allowing them to decide whether to evacuate in any case, or that the building design has not been compromised *necessitating* an evacuation. A case of particular concern where such communication is not achieved is where residents stay put for an extended period and then collectively decide to evacuate within a narrow time window. The delayed response means evacuees could be exposed to fire products and increases the chances of them having to interact with other slow-moving evacuees or arriving emergency responders. The collective decision will likely maximise demand on stair capacity.

- **Detection and notification:** Modern fire detection and alarm systems can be located in resident flats, in common areas, or in both; the system could include detectors with multiple sensors built in. Independent of the strategy adopted, the ability to provide incident information to the resident population is the key to enhance situational awareness and enhance resident decision-making. Voice notification coupled with suitable detection, reduced evacuation times and stair access across the scenarios and buildings examined. Voice notification might also enable guidance on how residents should respond in addition to the existence of the incident (i.e., go beyond simple alerting to the incident). This additional potential benefit was not addressed in this research.

  An automatic detection and alarm system provides an ‘early warning’ of a fire as required by the Building Regulations compared with a reliance on informal means. However, its introduction may lead to a change in evacuation behaviour that reduces the number of residents staying put and therefore complicates the use of a stay put strategy. Thus a resident population that is more informed is assumed to be more likely to evacuate and therefore increase demand on stair capacity.

In comparison to an evacuation alert system (EAS), an automatic fire detection and alert approach does not rely of on arrival of an FRS and require them to decide whether an alert needs to be given. The automatic system may reduce the notification delay but an EAS may allow a more effective stay put strategy to be retained.

- **Single stair:** A single stair which has sufficient accommodation for the building occupants and is able to provide a place of safety can achieve an adequate means of evacuation.
  A wider single stair provided modest reduction in evacuation times, given the demand conditions examined. It also enabled more overtaking/passing where impediments occurred (e.g., slower moving evacuees). A wider stair may also address some current concerns in which emergency responder arrival produces a bidirectional flow which may slow occupant evacuation and/or the emergency operations.[3] However, the introduction of a wider stair alone did not provide an alternative vertical escape route during evacuation.
- **Multiple stairs:** The introduction of a second stair benefited overall evacuation time and access to stairwell where demand for the stair exceeded occupancy capacity between floors. This demand might be influenced by the number of residents who live on a particular floor, those visiting the floor (e.g., community spaces, non-resident visitors, etc.) or where blockages on the stair have led to local increases in demand (e.g., by slowing moving evacuees requiring assistance, FRS personnel ascending the stairs – where the evacuation was not completed before the arrival of the FRS, where one stair has been affected by fire/smoke, etc.). Stair movement might also be affected by other factors such as the presence of smoke, material located on the stair, or loss of lighting levels.

  The benefit of additional stairs will be dependent on their continued availability during an incident, which will rely on other fire safety measures performing effectively. For lower rise buildings there is a lesser benefit (in terms of evacuation performance) in providing a second stair.

  The provision of additional stairs would help to meet the requirements of the Building Regulations to provide an "…*appropriate means of escape in case of fire from the building to a place of safety outside the building capable of being*

[3] This was not explicitly examined as part of this work given the expected analysis conducted elsewhere on behalf of the Home Office.

safely and effectively used at all material times." However, the second stair does not (in isolation) address the challenges faced by those with severe movement impairments evacuating from the building. This would also require other residents providing assistance and likely require the provision of movement devices to transport at least some of those with severe movement issues. Such assistance would become more challenging as the height of the building and hence the potential length of stair travel increased.

- **Lifts:** The provision of an emergency lift facilitated evacuation for those who would not be able to use stairs unassisted (e.g., those in wheelchairs), and where the assistance available is insufficient for stair movement. In this research it is assumed that they would do so with less need for third party assistance in comparison to stair movement (i.e., those would have more agency over their evacuation); i.e., increase individual agency.

  The evacuation of those with movement impairments who required assistance in stairs took less time via lift than via stair.[4] The introduction of a lift reduced the evacuation time of both those using the lift and those using the stairs (given the reduction of blockages on the stair). The benefit of providing lifts as a means of building evacuation increases with building height for those using the stairs.[5] Therefore, similar to the provision of additional stairs, the combination of a stair and lift would help meet the requirements of the Building Regulations to provide an appropriate means of escape to a place of safety outside the building but with an increase in effectiveness for specific population groups.

In reality, the impact of these approaches is highly coupled. For instance, egress routes might be formed from one of several options (single stair, single wider stair, single stair/lift, wider stair/lift, etc.). Also, more effective notification will likely reduce the distribution of pre-evacuation times, placing more demand on the egress routes over a short period of time – having a knock-on effect on evacuation performance. Social and technological factors beyond the influence of fire safety practitioners will also influence evacuation performance. Resident access to social media combined with fluctuating trust in authorities and building managers means that people will more easily (and more willingly) gain access to information independent of any notification system in place. Therefore, the question is not just whether residents can be selectively informed of an incident (to manage the timing of their response), but whether credible information can be provided to enhance occupant situational awareness and subsequent decision-making given information from sources of

[4] Simple lift operation following the recommendations in BS 9999:2017 was simulated as part of this work.
[5] While having a consistent benefit for those using the lift system, albeit these findings only relate to buildings up to 30 m, as taller buildings were not examined in the simulations.

variable reliability. In addition, given demographic changes, the proportion of residents with movement impairments will likely increase – increasing the number of slower moving individuals on staircases should that be the only means of egress and those who are not able to use staircases at all. The analysis conducted here assumed a proportion of residents with movement impairments that is currently representative. As this proportion increases, the benefit of alternative means of egress might increase, but would require management in some form to provide prioritised access, etc.

As noted, current fire safety strategies allow for the potential of evacuation. The possibility for large-scale evacuation cannot be ruled out – given matters of trust, technology, and social change. It is therefore important to provide means of egress sufficient to evacuate those who wish to do so and ensure that they can decide at the earliest opportunity for current and emerging evacuation scenarios. Correspondingly, it is important to provide the means to allow occupants to stay within their flats should they wish to do so by providing adequate fire protection measures and provide sufficient information for these occupants to decide to stay. It is not to say that these expectations are not already addressed by AD B, which have likely been enhanced by changes that have been made to AD B (e.g. sprinklers in residential buildings above 11 m tall and the introduction of evacuation alert systems, EAS) while this research has been ongoing.

8.5 Further work

Objective A3 provides a list of suggested further work specific to evacuation simulations. In addition, this research has identified several broader research areas that could be further investigated, namely:

- Examine whether voice notification systems might also enable guidance on how residents should respond in addition to the existence of the incident.
- Investigate whether there is an optimum stair width that allows bidirectional flow / overtaking of slower moving occupants. Stairs that are too narrow may preclude these actions whereas stairs that become too wide will need a central handrail to aid users to descend.
- Coupled with the previous point, the research assumes that slower occupants may constantly block the movement of other faster moving people behind them. This may not necessarily be the case and instead faster moving people may be able to negotiate around slower movers. Further work on this assumption would further indicate benefits of a wider stair.
- Lifts technology has improved, in particular for tall buildings, but there is a lack of understanding associated with their use in emergencies. Further work could investigate whether lifts are being more commonly used by FRS personnel. It

could also investigate how lift use might in practice ensure that those need to use the lifts can get priority over others who are able to use the stairs. This may require residents be educated about their building fire safety strategy to give them an understanding of the role that lifts might play. There may also be specific management technologies that could be incorporated into the building. Findings could contribute to new guidance on the use of lifts during an emergency.

- A more detailed investigation of the interaction between different measures and their combined impact on evacuation performance. For instance, stair configuration, the introduction of emergency lifts and the lift strategies to be employed.