Assessing the Impact of Changes to Guidance on Evacuation from Fire in Multi-Occupancy High-rise Residential Buildings

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ABSTRACT

The Building Regulations in England are supported by Approved Documents which provide statutory guidance to meet the functional requirements expressed by these regulations. Fire safety is specifically addressed in the two volumes of Approved Document B (AD B), part of which deals with means of egress. In response to the Grenfell Tower fire and following a call for evidence, the government has commissioned a programme of research to examine future technical guidance contained within AD B.

As a result of the research programme, the authors of this paper are conducting research into the means of escape in high-rise residential buildings. This research has involved a review of expected occupant behaviours in response to an emergency and the factors that might affect such behaviours in high-rise residential properties; and the performance of interviews and surveys of residents of multi-occupancy buildings to assess perception of building safety with respect to a 'stay-put' strategy post-Grenfell Tower, and the subsequent modelling of an array of evacuation scenarios involving building designs to identify which behaviours, procedures and design features affect evacuation outcomes. This work employs performance-based tools to test the 'prescriptive' statutory guidance – supported by information on changing public perceptions - intended to make the guidance more sensitive to conditions that might be faced within multi-occupancy residential buildings and more robust to the implications of such conditions.

This paper provides an overview of the approach adopted so far in the project – stopping short of final simulated results produced. This focuses on the integration between subject matter expertise across the multi-disciplinary team, the collection and application of survey results, and the modelling methodology developed. This methodology involves the application of two different evacuation tools and a means by which to investigate a wide range of scenarios with more refined simulation of key scenarios – including bounding cases and where step changes in results indicate the importance of the underlying factors. It is unusual for modelling applications to have dedicated data collection compilation and collection process associated with it, allowing a more informed and rigorous modelling process than might normally be the case.

This paper (and the project discussed) does not attempt to identify the root causes of the Grenfell Tower fire and no such inferences should be made from the results produced or the associated discussion.

INTRODUCTION

The Building Regulations in England are supported by Approved Documents which provide statutory guidance to meet the functional requirements expressed by the Building Regulations. Fire safety is specifically addressed in the two volumes of Approved Document B (AD B) guidance [1]. In response to the Grenfell Tower fire (and the tragic outcome of the fire spread and the prolonged resident evacuation), the government commissioned research to examine the technical guidance contained within AD B and how its future development might be affected by the Grenfell Tower case. Part of this research has been to examine the implications of resident evacuation from occupancies that follow the guidance in AD B and the implications for building design.

The authors have adopted several approaches to understand potential evacuee response and the factors that might affect it. The insights produced have value in themselves, but are also directly shaping simulation efforts to quantify the impact of design changes on evacuation performance. This has involved a review of current scientific understanding, examining engineering trends, conducting reviews of scientific literature, interviewing fire and rescue service personnel and surveying residents of multi-occupancy residential buildings. This last task was designed to assess projected responses to fire incidents and resident perception of building safety with respect to a 'stay-put' strategy post-Grenfell Tower – e.g. whether residents might stay put if advised to do so. Scenarios have been developed from this new understanding and modelling tools are being applied to identify potential benefits / disbenefits of proposed design changes. This work employs performance-based tools to test the 'prescriptive' guidance – supported by information on changing public perceptions – intended to make future guidance on building designs more sensitive and robust to conditions that might be faced within multi-occupancy residential buildings.

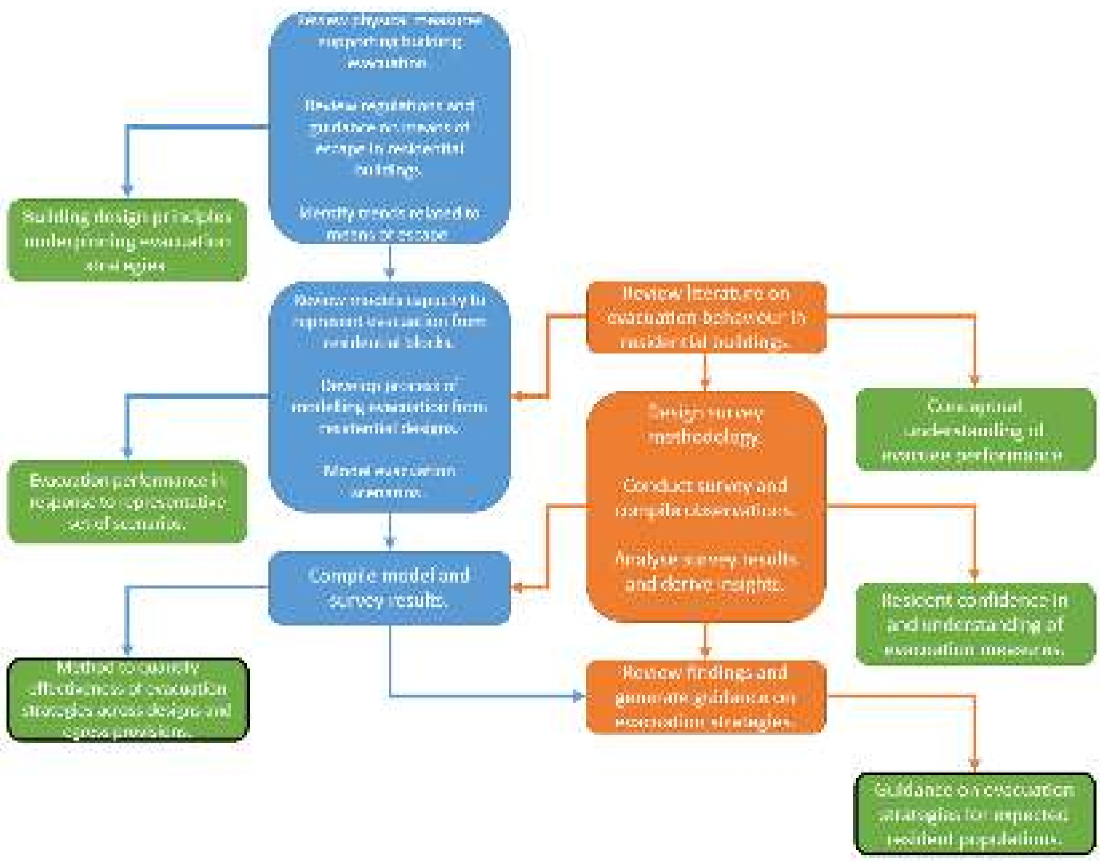


Figure 1: Method developed to generate key outcomes (indicated with black border).

This paper provides an overview of the approach adopted so far in the project (see Figure 1 for a simplified overview of the method adopted). This focuses on the integration of subject matter expertise, the collection and application of survey results, and the modelling methodology adopted. This modelling methodology involves two different evacuation tools and a means by which to investigate a wide range of scenarios with more refined simulation of key scenarios – including bounding cases and where step changes in results indicate the importance of the underlying factors.

The novelty of this work is to

- Build-off existing understanding of evacuation performance;
- Expand on our understanding resident perceptions of the guidance and fire incidents using surveys designed/conducted by social scientists; and
- Expand the scope and depth of the insights provided by simulating scenarios of interest across a representative set of both AD B compliant and non-compliant building designs subjected to the impact of fire scenarios.

METHOD

As is apparent in Figure 1, the work has required the management of several work streams focused on capturing information on physical factors/measures that affect performance, the resident decision-making response to these factors, the resident perception of current and planned guidance, and the strategy developed to simulate evacuation from representative building designs in order to quantify the relative impact of different factors on performance and the implications of this impact. The goal is to provide an evidence-based and transparent process by which models could be applied to a set of instructive scenarios (designed to provide direct insights to regulatory development), and also surveys conducted to provide standalone insights and inform the modelling effort. Several tasks were conducted to achieve this, and these are discussed below.

Task A: Identifying Physical Measures that Affect Evacuation Performance

A review was conducted to identify the physical measures and design variants that might affect building evacuation in the event of a fire. The review examined fire safety research literature and international fire safety guidance documents and standards. This process was used to produce a matrix of fire safety measures and their impact on evacuation performance. The goal was to link specific physical measures to evacuee performance.

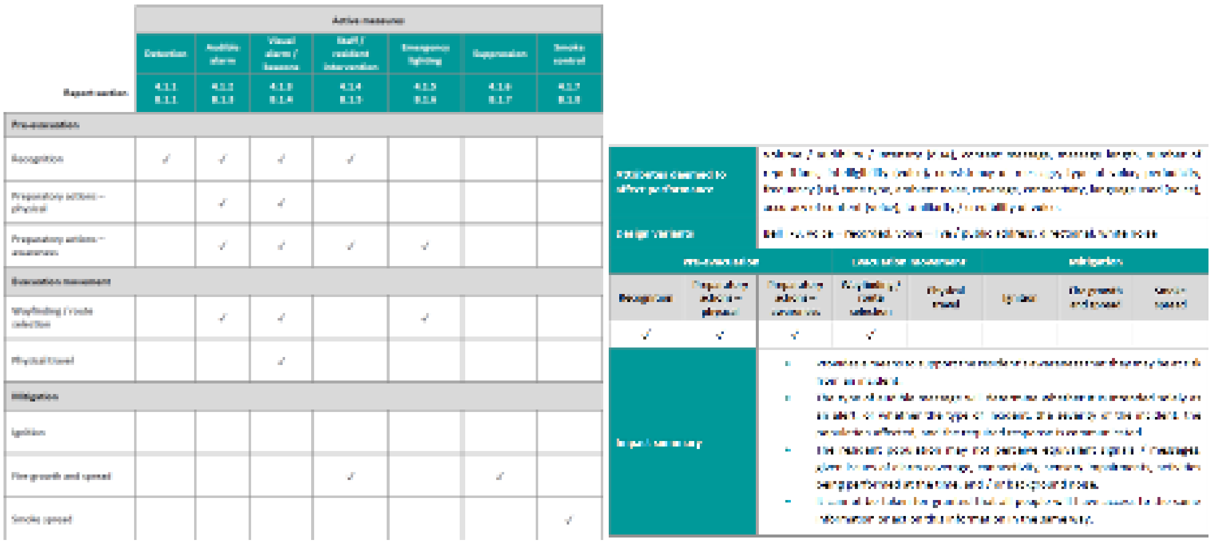
An informal review of commercial fire strategies for non-residential, residential and mixed-use buildings across multiple jurisdictions was initially conducted – as an indication of current practice. This was followed by a high-level review of international fire safety codes, guidance documents and standards. This included examining Approved Document B (AD B) [1], Building Standards Technical Handbook (STH) [2], British Standard BS 9991:2015 (BS 9991) [3], National Fire Protection Associate NFPA 101 Life Safety Code (NFPA 101) [4], New Zealand Acceptable Solutions for Buildings (C/AS2) [5], the International Building Code (IBC) [6], the National Building Code of Canada (NBC) [7] and the National Construction Code Volume One – Building Code of Australia (NCC) [8]. This first pass review helped identify the factors currently considered in practice.

A literature review of building evacuation and factors that affect performance has been used to form the 'deep review' process (digging into known areas of interest) from within the area of fire safety / life safety. An approach was adopted to combat gaps that might appear in more formal keyword searches of academic literature, that might ignore grey literature – that might form staple understanding within an engineering discipline. A more formal, broader review was then conducted using Google Scholar, adopting high-level keywords and Boolean logic to address synonymous terms.

The impact of physical provisions was compiled from the previous review steps allowing an impact summary table to be produced and attached to each measure identified. These included

- Attributes deemed to affect the performance;
- Key design variants;
- How the measure affects the evacuation process; and
- Key qualitative or quantitative results and insights identified in the review.

These allowed for the creation of a summary matrix depicting key factors and which aspects of evacuation performance they affected (Figure 2(a)), and separate tables related to each factor describing their impact in more detail (Figure 2(b)).



(a) (b)

Figure 2: (a) Section from the Review matrix which provides high level summary of active measures and how they affect evacuation; (b) Example from the Review matrix which provides summary of the material reviewed for each factor identified.

As a result, a description of the factors has been produced that are deemed to affect evacuation performance and how these factors relate to each other – forming a basis for the generation of scenarios to be simulated - to estimate evacuation performance.

Task B: Establishing the Evacuee Decision-Making Process

The goal of this task has been to develop a **conceptual understanding of expected resident performance during evacuation and the factors that might influence it.** This has been achieved by examining research literature and case studies on human behaviour during emergency evacuations that relate to high-rise residential buildings (building off the previous understanding of the physical measures that might influence performance). The following sources were reviewed to develop an understanding of relevant evacuee decision-making:

- **General material on evacuation from fire** (e.g. research literature, case studies, etc.). This has been used to identify key elements (behavioural statements) and develop a structure;
- **Existing conceptual models of evacuee behaviour.** This has been used to produce a structure applied to the resident decision-making process;
- **Material on resident evacuation from fire emergencies** (e.g. research literature, case studies, etc.); and
- **Material on resident evacuation from multi-occupancy structures involving fire emergencies** (e.g. research literature, case studies, etc.).

This has resulted in a simple conceptual model of resident decision-making (Figure 3) and example underlying factors associated with each stage of the decision-making process (Figure 4). The model therefore hosts several factors at each stage deemed to possible affect evacuee decision-making.

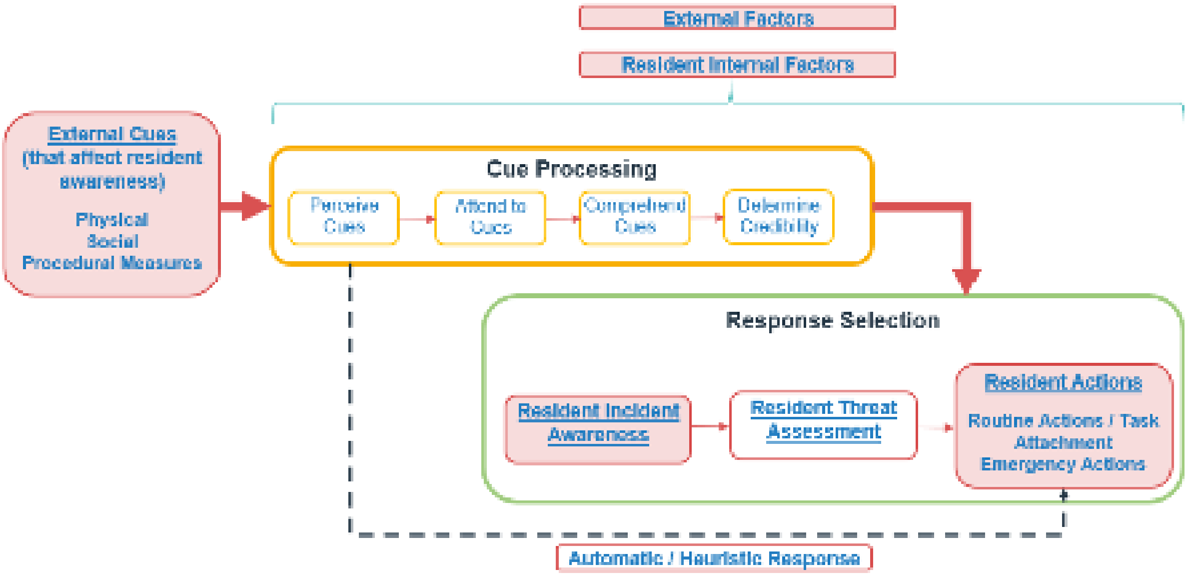


Figure 3: Simplified representation of decision-making process[9].

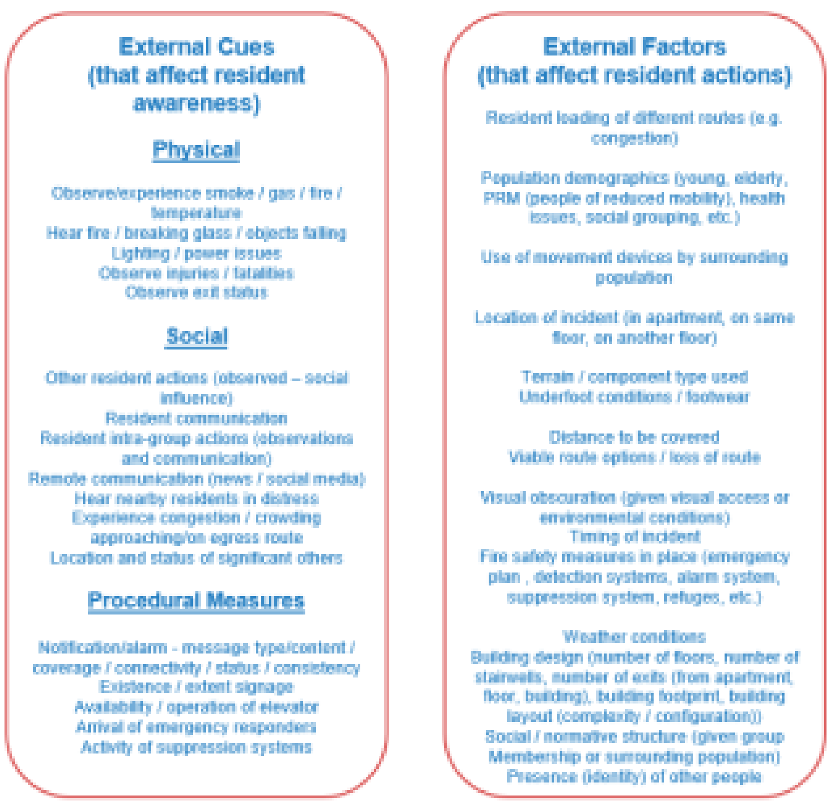


Figure 4: Example of detailed description of attributes that affect the elements captured in the resident decision-making process (External cues and factors).

Task C: Fire Rescue Service and Resident Surveys

The main aim of this task has been to interview fire and rescue service (FRS) personnel and residents of high- and medium-rise buildings to identify:

- FRS perceptions of public behaviour in high-rise residential buildings evacuations;
- FRS views on both evacuation guidance and guidance for residents regarding what to do the event of a fire;
- Resident understanding of evacuation strategies and fire safety measures; and
- Resident confidence in the fire safety guidance.

The review and survey work has helped to identify factors that influence evacuee performance, cluster them into suggested scenarios to modelled and assess the likelihood of resident response in these scenarios (e.g. the likelihood of evacuating), in sufficient detail such that they might be simulated. Example results from residents include:

- 90% of participants stated they understood what actions were expected of them in the event of a fire in their building;
- 59% believed 'staying put' would keep them safe; and
- 21% felt that staying put was safer than evacuating.

The results have informed the identification of the scenarios that need to be modelled and the expected take up of evacuation / stay put procedures that should be represented within the models (where required).

Task D: Modelling Selection and Assumptions

The previous analysis has produced a set of factors deemed to affect the performance of evacuating residents. These factors have informed the selection of models suitable for application to the scenarios of interest. The evacuation simulation work is using a two-stage process to examine these number of potential scenarios:

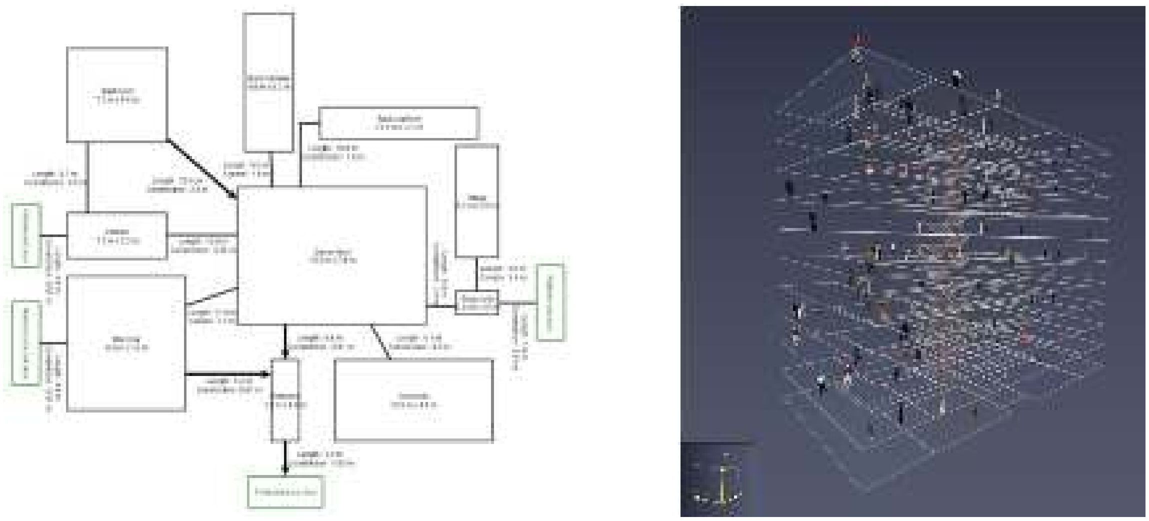
- High-level examination of all scenarios to capture key dynamics, rank outcomes and prioritize scenarios for more refined analysis. This provides a scoping study of key dynamics; and
- Refined examination of a sub-set scenarios. This produces a diagnostic investigation that will explore a wider array of underlying factors, interactions and examine a larger and more fundamental set of indicators of the simulated conditions.

These two stages require different modelling capabilities – in terms of scope, granularity and computational expense. Firstly, a model review was conducted to select suitable tools for these two tasks. Broadly speaking, the capabilities of the available models were reviewed to determine:

- Model availability (either to the public or to the authors);
- Representation of evacuee behaviours including route selection, pre-evacuation delays, variation in movement/flow rates that might be achieved, and evacuee objectives;
- Representation of different population types (including those with movement impairments);
- Representation of the scale and type of buildings (and their internal configuration);
- Representation of egress components / terrain and transitions present within and between such components (e.g. corridors, stairs, etc.);
- Representation of either global (flow) and individual evacuee perspectives (i.e., the two models selected adopt different perspectives);
- Generation of output on the performance of the population within locations of interest, floors, individual stairwells, building wide. This output reflects route use, arrival times, distances travelled, and congestion experienced; and

- Availability of model testing documentation to enhance confidence in model performance.

From reviewing the models identified by Kuligowski *et al*. (and from the tracking of recent model releases) [10,11], several candidate models were identified as meeting the requirements for the *scoping* and *diagnostic* activities identified. The models selected from these candidates for use were **Evacuationz** [12-16] for the scoping applications, and **Pathfinder** [17,18] for the diagnostic applications (Figure 5). Although adopting different modelling philosophies (with Evacuationz adopting a flow-based approach and Pathfinder adopting a genuinely individualistic approach to evacuee response) there is sufficient overlap between the models to allow them to both represent a sub-set of the scenarios examined. This triangulation has proved very useful - allowing comparisons between the model projections and building confidence in the inferences drawn from them.



(a) Evacuationz (b) Pathfinder

Figure 5: Example images from (a) Evacuationz and (b) Pathfinder indicating their different philosophies.

Task E: Scenario Definition and Model Application

The set of factors identified in the earlier reviews and surveys have been grouped into categories to define a set of scenarios to be examined:

- **Event parameters**: Time of day, weather conditions, fire location, fire impact;
- **Building parameters**: Building height, number of stairs, stair width, corridor length, amenity spaces;
- **Procedural parameters**: Means of warning, evacuation lift, evacuation strategy;
- **Resident parameters**: Number of residents, number of visitors, demographics, population location; and
- **FRS parameters**: FRS attendance.

Each of these have been identified to examine the impact they might have on a set of performance elements: *Pre-evacuation, travel speed, route availability, route use, resident tasks, achievable flow rate*.

The parameter sets have been examined to see what impact the settings might have on the assumed resident response. Table 1 shows the impact of different parameter settings (e.g. local sounder in an apartment, global building-wide sounder, global building-wide voice, no notification system) on the resident response (e.g. in the form of reduction in pre-evacuation (P-E) time, route availability (RA), route use (RU), the performance of other tasks (OT), etc.). These informed the selection of data-sets to characterize the combination of factors present in each scenario examined.

Table 1: Example impact on resident performance. Precise assumed impacts will evolve within the project lifetime.

Procedural parameters					
1p	Means of warning	Local sounder	Global sounder	Global voice	None
	Impact on Response	Baseline case P-E↑ (on same floor – not directly exposed to sounder) P-E↑↑ (elsewhere)	P-I ↓	P-I ↓↓ RU ↑	P-I ↑
2p	Evacuation lift	No	One	Two	
	Impact on Response	Baseline case	RA↑ RU↑ OT↑	RA↑↑ RU↑↑ OT↑	
3p	Evacuation strategy	Stay put	Clustered	Phased/ Cascade	Simultaneous
	Impact on Response	Baseline case P-E (FToC)	P-I (Representation of impact of notification system and incident cues on response by resident location)	P-I (1st phase – Preparation and Decision making) P-E (2nd phase – Decision-making) P-E derived from occupant communication	P-I = 0

The research literature already reviewed has been examined to quantify the extent of these impacts on the performance elements identified. In many situations, these factors interact in complex ways. It has not been possible to simply apply data independently within the scenarios; instead, the data-sets generated has had to reflect the interaction between factors within a particualr scenario. An example of this is shown in Table 2Table 2 illustrating how the notification type and population attribtes interact to generate pre-evacuation times mean values.

Table 2: Example values for mean pre-evacuation times type of cues present/notification system in place, given population attributes. These values are indicative and will likely evolve during the project lifetime.

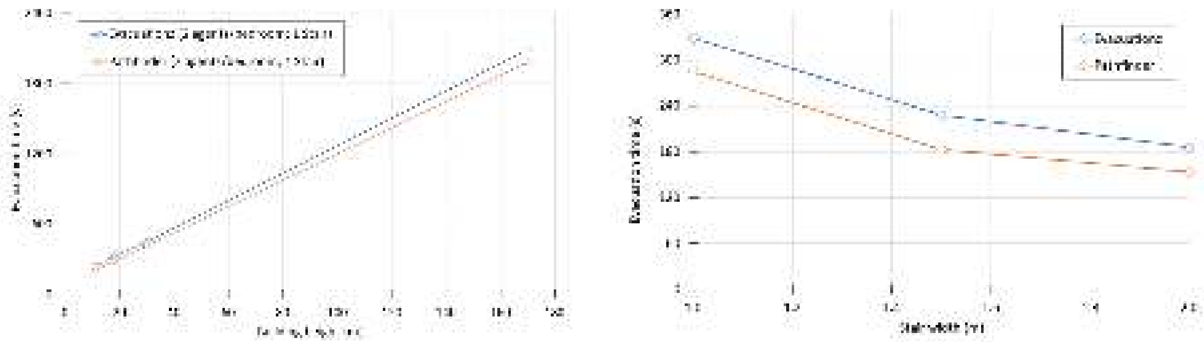
Level of Impairment	Status	Implied Pre-Evacuation Time (s)				
		Voice	Tone/Bell	Person	FRS	Smoke Cues
Impaired	Asleep	300	600	300	240	240
	Awake	180	300	180	120	120
Unimpaired	Asleep	180	360	180	120	120
	Awake	90	180	90	60	60

One challenge that has been observed during this work is that the same combination factors cannot be represented by precisely the same set of data within each model – given differences in the assumptions made and the impact that the data has upon modelled evacuation performance. Time has been spent deriving an approach to reduce the data to its constituent parts and then match it more closely to the behavioural parameters applied within the modelling tools used.

Results

As previously noted, Evacuationz and Pathfinder simulate the evacuation process from different perspectives so the models' performance was first compared using a series of basic test cases before being employed in the more complex analysis identified above. This testing has been conducted across several scenarios, generated by varying building height, number of stairs, stair width, corridor length, and number / distribution of occupants.

Although, as might be expected, there are differences in the results produced by the two models (Figure 6) the trends from the output produced are comparable as are the directional impact of introducing different factors on the results produced. This provides a level of confidence in the use of the two tools and also informs the suitability of the tools for certain types of scenarios to be examined.



(a) (b)

Figure 6: Comparison of simulated results by (a) building height and (b) stair width.

A set of scenarios have been simulated to examine the evacuation performance of a set of possible design options for residential blocks given resident response assumptions (derived from the research described previously). Example scenarios include:

- Impact of introducing different types of notification system (local tone alarm in apartment of fire origin, global building-wide tone, global building-wide voice, etc.);
- Impact of including one or two stairs;
- Impact of including stair / lift combinations;
- Impact of demographic changes, such that a sub-population has a movement impairment (whether they can self-evacuate or require assistance/elevator); and
- Impact of resident evacuation reliant on inter-agent communication.

The impact of these situations is to be examined across building designs (heights, footprints, etc.) enabling direct comparisons to be made across representative conditions.

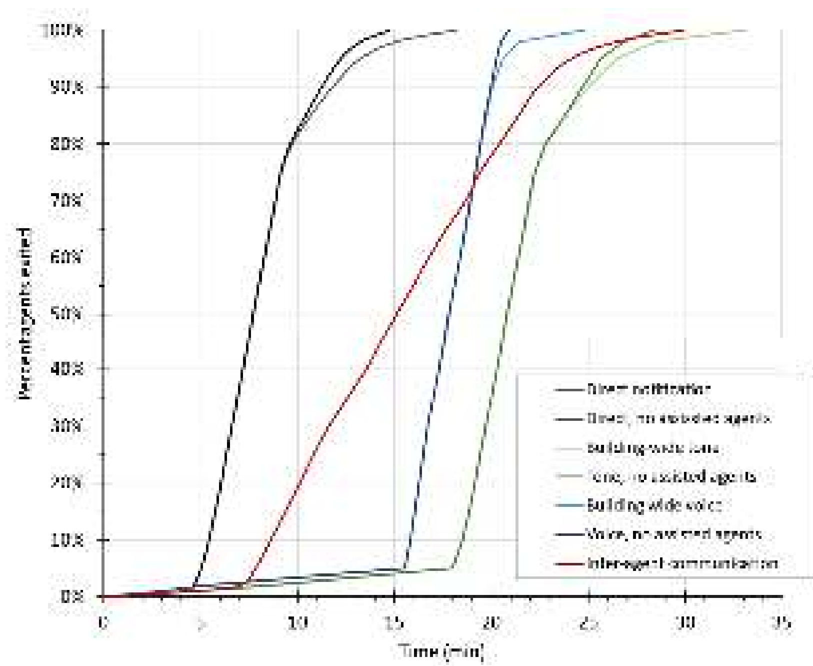


Figure 7: Impact of notification system and population type on evacuation performance compared with other evacuation strategies.

Figure 7 shows example results comparing the evacuation of a seven-storey single stair design, with two residents per apartment bedroom. The population make-up is varied:

- 80% of the residents are assumed to be ambulant without a movement impairment, 20% of residents are assumed ambulant but with an impairment (with assumed reduced movement rates), or
- 80% of the residents are assumed to be ambulant without a movement impairment, 15% of residents are assumed ambulant but with an impairment, while 5% are assumed sufficiently impaired to required assistance, with an assumed reduced movement rates reflecting the level of impairment and a wider body width to represent the need for assistance.

The scenario includes the initiation of a building-wide alert when smoke is detected in the common corridor adjacent to the flat of fire origin. In addition, the notification system available is varied between tone alarm and voice alarm – assumed to be audible from each apartment – and that agents all respond to the alarm by evacuating the building. The results are generated from which simple comparisons made to identify the potential benefits of design changes and the robustness of these benefits across different scenario conditions and demographic changes.

Table 3: Overall average evacuation times (min) given notification / population assumptions.

Movement Capabilities	Building configuration	Total evacuation time (min)			
		Direct agent notification	Building-wide tone	Building-wide voice	Reliant on inter-resident communication
No sub-population require assistance	Seven-stories, one stair	14.8	28.4	20.9	27.4
5% sub-population require assistance	Seven-stories, one stair	18.2	33.2	24.8	29.9

Table 3 compares the results from various evacuation strategies for the seven-storey building using Evacuationz Monte Carlo simulations. Due to space constraints, detailed descriptions of each scenario are not included herein. The simulation work is ongoing, and these findings only represent a small fraction of the results to be generated. They are presented simply to indicate the types of results produced and the questions that might then be examined.

CONCLUSION

The project described represents an effort to assess the impact of the physical provisions of current building guidelines on evacuation performance, and then project the impact of potential guideline modifications. This will provide evidence on the nature and scale of performance change given modifications to these physical provisions and accompanying procedural measures that might be introduced into the guidance. This involved a considerable effort (beyond that typically seen on modelling projects) to understand and quantify evacuee performance for the scenarios of interest and then collect additional data – to understand the impact of the Grenfell Tower fire on resident perceptions that might influence their evacuation behaviour.

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