SIMULATING HOSPITAL EVACUATION

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DECLARATION

I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others.

Signed…….. A. Hunt

Signed…… Prof. E. R. Galea

Signed…… Dr. P. J. Lawrence

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ABSTRACT

In hospitals, evacuation of those with severe movement impairments can be highly problematic – for the patients, for the staff and for the other evacuees. It is critical to understand the performance of horizontal and vertical evacuation strategies, including the means by which people with reduced mobility can be assisted in stair descent. The work presented herein quantifies the performance of trained hospital staff in evacuating people with reduced mobility and specifies algorithms to explicitly represent the dynamics of these devices within evacuation models. Data collected from 32 trials in which a test subject was evacuated through 11 floors of Ghent University Hospital using four commonly used movement assistance devices: stretcher, carry chair, evacuation chair and rescue sheet are presented and analysed. From this, performance results are calculated for both male and female assist teams that include device preparation time, horizontal speeds, vertical speeds and overtaking potential in stairwells. By deriving a device performance evaluation metric a direct comparison of the relative efficiency of each device is made. The performance results form the basis of integrating movement devices into evacuation models. To demonstrate this, the buildingEXODUS model is enhanced to represent movement devices in hospital evacuation. Moving objects, including evacuation devices, are explicitly specified in the existing model functionality. Algorithms are developed to calculate the movement of devices along corridors, through doorways and in stairway descent, including a method of geometric decomposition of the hospital geometry. This new functionality addresses the key evacuation components of repeated patient collection, and has numerous applications, both in simulating hospital evacuation and in representing evacuation of other premises that include people with reduced mobility. This is demonstrated by a series of systematic test cases designed to highlight both the validity and the predicting capability of this method. The latter can be used to significantly enhance planning and diagnostic capabilities related to the evacuation of hospital and other healthcare facilities. It should help ensure that the adoption of new procedural and structural designs are better informed and that risk assessments and evidence-based analyses are better supported by data, understanding and simulation tools in the future.

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1 INTRODUCTION

1.1 Rationale

There are approximately 1800 fires in UK hospitals each year, and relatively large amounts of non-fatal casualties in hospital and health care facilities: 107 non-fatal casualties per 1,000 fires [1]. Healthcare facility management teams are required to devise effective strategies for the safe evacuation of all hospital occupants in the event of fire [2]. This strategic planning for the evacuation process in a healthcare environment requires detailed consideration. Hospitals frequently have large and complex building structures, including portable furniture and equipment; hence there is great variability and dynamism in the pedestrian spaces. Wards have different uses (e.g. intensive care, outpatient clinics, etc.) and different staffing structures to accommodate these uses. There are specific security issues that may directly conflict with safety procedures; for example, there may be locked doors for medicine storage or in psychiatric units. Staff training can be problematic: live drills can be impractical, costly and arguably unethical. Specialist emergency training is required for some areas, for example in operating theatres. However, in a typical hospital environment, there is high staff turnover; therefore frequent training is required [3]. Areas will have unpredictable occupancy levels, for example accident and emergency (A&E) departments and maternity wards. Importantly, many people will require assistance to evacuate and therefore staff are vital to the evacuation strategy [4]. At any given time, a hospital may therefore contain a wide variety of occupants with a mixture of roles, i.e. staff, patients, and visitors, and varying physical, mental and ambulatory capabilities.

In hospitals, planning for the evacuation of People with Reduced Mobility (PRM) is particularly challenging, due to the large number of patients who are likely to require assistance to evacuate, the (potentially small) number of staff on duty to assist in the evacuation (e.g. during night shifts), the need to have multiple staff assisting single patients, the fatigue experienced by staff making repeated trips and

the possible blocking of stairs by the teams assisting patients leading to delayed evacuation of others.

Equality legislation requires that hospital evacuation strategy must consider the evacuation of people with disabilities, making reasonable adjustments to accommodate the needs of every individual in the building [5]. To address the needs of PRM, Hospital Fire Codes in the UK specify the strategy of progressive horizontal evacuation, where wards are allocated into compartments separated by fire resisting barriers. In the event of a fire, patients are progressively moved into adjacent compartments away from the fire while the situation is assessed. It is expected that horizontal evacuation will suffice, and that full hospital evacuation is unlikely to be required. However, in light of recent hospital fires, e.g. The Royal Marsden in London [6], the need for some revision of this hospital evacuation procedure has been highlighted. The evacuation of the Royal Marsden revealed that it might be necessary to not only undertake a progressive horizontal evacuation of patients to places of relative safety, but also to fully evacuate an entire hospital. The evacuation of the Royal Marsden revealed that a progressive horizontal evacuation of patients to places of relative safety can be insufficient and it might be necessary to fully evacuate an entire hospital. Furthermore, while lifts may be used in some hospitals, it is essential that provision is made for vertical (stairway) evacuation of patients. This requires the use of movement assist devices, for example hospital rescue sheets, to transport PRM down stairs.

Each healthcare facility management team is required to assess these factors and develop appropriate plans for safe, efficient and timely evacuation. While some of the evacuation process is likely to be undertaken by emergency services, the UK Regulatory Reform (Fire Safety) Order emphasises that in establishments such as health care facilities it is the management's responsibility to ensure that everyone can evacuate a building safely. It is not acceptable to rely solely on the Fire and Rescue Services' intervention to enable the safe evacuation of occupants [7]. This places an additional emphasis on the in-house emergency procedures: staff members are responsible for the safe evacuation of patients with a wide variety of physical impairments and medical requirements.

While the number of PRM is arguably the biggest complication in hospital evacuation, it is also an important consideration in other environments. In the UK, the second highest casualty rates in fires are in care homes for the elderly [8] where movement devices are also likely to be used. In addition, approximately 10% of people (6.5m) in the UK are classed as having a mobility disability [9], and according to the United Nations, in countries with life expectancies over 70 years, citizens spend on average approximately 8 years living with disabilities [10], which means that buildings used by the public must also consider mobility requirements.

Furthermore, an occupant's ambulatory capabilities may be variable, for instance elderly people or pregnant women may have conditionally reduced mobility if, for example, they are required to walk an extended distance. Indeed the incident that initiated the need to evacuate may have injured some fully mobile occupants, rendering them less mobile. Therefore, while termed as "hospital" throughout this thesis, this body of work is also relevant to the evacuation considerations of other healthcare facilities, by considering a wide range of occupant characteristics and the procedures employed by staff.

Many developed countries are now incorporating performance-based alternatives to increase design flexibility over previous prescriptive building codes and also enable safety performance levels to be established [3, 11, 12]. This represents an evidence-based approach of evaluating evacuation performance, where fire models are used to estimate the Available Safe Egress Time (ASET) and Evacuation Models are used to estimate the Required Safe Egress Time (RSET). This approach allows the performance of different designs to be compared according to given scenarios. The goal is to ensure that ASET>RSET plus a safety factor to incorporate a margin of error [13]. Performance based design requires fire safety engineering: a method of design that meets the requirements of regulations, but without necessarily adhering to prescriptive codes.

Simulation can support this fire safety engineering approach, and software developed to model the evacuation process is used internationally [14]. Simulation has the potential for quantifying evacuation performance. Agent based models, e.g.

STEPS [15], and buildingEXODUS [16], simulate the circulation and evacuation of individuals to gauge an expectation of a building's performance during egress. However, the application of these models to the hospital environment has proved problematic. Many models have recognised ambulatory differences between people and have incorporated mobility distributions. But those models that have included PRM have represented their ambulatory attributes by simply modifying their walking speeds, not the devices used to transport them. Furthermore, the reduction in walking speeds used in these analyses are generally based on data associated with PRM who are able to move assisted by personal assist devices such as wheel chairs or walking sticks [17]. Some models can represent wheelchair users [15, 18, 19, 20], however these models are not able to represent the shape and increased footprint of such a device, particularly in vertical movement, and the impact that it might have – on navigation, manoeuvrability, speed, and on the movement of the adjacent population. Understanding this impact has been shown to be key in assessing the effectiveness of a procedure (or a device) in moving vulnerable populations to safety [17]. Currently, evacuation models cannot effectively represent the horizontal and vertical evacuation of patients and staff within hospital environments as they are largely focused on modelling individuals who can move unaided. Therefore, although current models can quantify performance, the validity of this quantification is diminished through the exclusion of the key factors highlighted.

A number of commercially available devices can be used to assist in evacuating PRM. However, there are only a few data-sets that can be used to quantify the performance of these devices. The use of track-type evacuation chairs has been investigated in a number of studies [21, 22, 23], however the speeds observed varied significantly, ranging from 0.21 m/s to 1.1 m/s. This may indicate the importance of handler training, with the fastest times recorded by trained manual handlers and firefighters.

This brief discussion has highlighted several points:

- This combination of structural, procedural and occupant issues make planning safety strategies for health care facilities particularly challenging. The array of

interacting factors mean that analytically (or intuitively) identifying the effectiveness of procedural strategies becomes highly problematic.

- Recent legislation requires equivalent (if not identical) safety practices for all occupants. This, coupled with expected demographic changes, means that a growing population of people with movement impairments need to be accounted for in evacuation strategies (in healthcare facilities and beyond).
- Historical safety procedures may not be sufficient given the evidence provided by recent incidents.
- Recent regulatory practices have spawned a generation of engineering tools designed to quantify evacuation performance. These are typically generic in nature.
- Engineering/simulation tools that can quantify performance are of particular value in a healthcare environment. However, such tools require dedicated functionality to represent the peculiarities of the hospital environment (e.g. PRM movement) and require data on which to build these functionalities.
- There is a paucity of such developments and such data.

The work presented here addresses shortfalls in the relevant data on PRM use of egress devices through the collection of new data and then uses the data collected to inform the development of dedicated functionality within an existing egress simulation tool. This represents a significant advance – in the understanding of PRM movement in evacuation devices, in the quantification of this movement, and the representation of this movement within a simulated environment. This advance will allow practitioners to quantify the effectiveness of their procedural strategies and building designs in getting a hospital population to a place of safety in the time available.

A key objective of this research is to enable the evacuation of patients (PRM occupants) using assist devices to be credibly modelled within evacuation software in order to simulate hospital evacuation – and therefore quantify the effectiveness of different evacuation strategies. This functionality will enable model users to develop and test evacuation procedures while avoiding the impracticalities of live evacuation drills. Such drills would be enormously problematic in a hospital with

such a vulnerable population. A software tool with appropriate functionality could contribute to the design of personal emergency evacuation plans for patients and in demonstrating the overall effectiveness of the evacuation strategy (e.g. as part of a performance-based design of hospital evacuation strategy or the building design).

The data, analysis, and development of evacuation simulation tools presented in this work are applicable to other health care facilities such as the evacuation of residential and care homes for the elderly in which there are a high proportion of fires, in comparison to other building types [1]. This is becoming an issue of increasing importance as worldwide demographics indicate a significantly larger proportion of elderly people in the future: in the UK, the number of people aged 70 and older is projected to rise to 12.8 million by 2035, accounting for 17.5% of the population [24].

This developed functionality will be useful in other applications; the ability to model the full scale of mobility requirements is a useful function when considering the performance of individuals evacuating any type of building. Furthermore, the separate components of the theoretical model and the working simulation tools may apply to the modelling of other phenomena. However, the models presented here must be calibrated to directly apply to any given scenario, whether modelling a traditional hospital or otherwise.

To evaluate the performance of commonly used operator controlled movement assist devices in the evacuation of PRM, and to represent the use of these devices within computer simulations, data are required to quantify the performance of these devices.

1.2 Methodology

This thesis describes work undertaken to quantify the performance of movement devices in the evacuation of patients: data collection, the subsequent analysis and

evaluation of data, and the development of an evacuation model to simulate hospital evacuation.

A series of trials are conducted where four operator-controlled movement assist devices are tested in evacuating PRM through 11 floors of Ghent University Hospital [25]. In total 32 trials are conducted involving four common types of operator controlled movement assist devices: a stretcher, a carry chair, an evacuation chair and a rescue sheet. These are operated by male and female teams of trained hospital staff. Detailed video analysis is undertaken to document and quantify the performance of each device.

These data, alongside those collected from a questionnaire completed by the trial participants, form the basis of the device performance evaluation. By combining the performance factors in a transparent, flexible and meaningful manner a metric is presented based on the weighted sum of each performance factor. The metric offers a simple approach to gauge the overall performance advantage of one device over another, allowing user-based priorities and user-specific performance factors to be considered. In addition, the data are incorporated within the buildingEXODUS evacuation model [16] to demonstrate the use of the trial data in order to implicitly represent the evacuation of a hypothetical hospital ward using available day and night shift staff. This was achieved using the existing itinerary and group functionality of the evacuation model and highlighted the necessary developments in order to explicitly represent the movement of the assist devices.

As a result, the buildingEXODUS model was developed to represent movement devices. The ability to simulate moving objects (e.g. evacuation devices) is explicitly specified in existing model functionality. In this way, the process of evacuating PRM within hospitals can inform, and be influenced by, the features of people movement already represented. A method of geometric decomposition of the hospital geometry is developed to assess the viability of egress routes for evacuation devices; i.e. establishing whether a particular device can physically be navigated along a particular route. A set of algorithms are developed in order to calculate the movement of devices along corridors, through doorways and in

stairway descent. A stoppage model is also introduced in order to represent the periodic stops devices make during their vertical descent, in accordance with the behaviour observed during the Ghent trials. The algorithms enable other agents to evacuate alongside devices, their routes appropriately obstructed in the corridor and in the stairwells. Agent-device interaction is also implemented to represent agents preparing patients for movement within devices, evacuating patients and returning to assist the evacuation of other patients. As such, the functionality addresses the key evacuation components of conveying PRM on an evacuation device, and has numerous applications, both in simulating hospital evacuation and in representing evacuation of other premises that include PRM, as demonstrated in the test cases presented in this thesis.

Outlined below are the five research questions addressed in this thesis, initially to establish the scope of the problem, and then specifically to delineate the proposed approach. These represent the specific objectives of this work.

1) What influences the outcome of hospital evacuations? (Section 2.1)

- What regulatory frameworks constrain hospital design?
- What happened during previous hospital evacuations?
- What factors influence hospital evacuation?

2) What developments are required in order to improve hospital evacuation simulation? (Sections 2.2-2.4)

- What supporting data are available quantifying performance in hospital evacuation?
- What data requirements are proposed to advance hospital evacuation modelling?
- How do models currently represent hospital evacuation and how appropriate is this representation?
- What model enhancements are proposed to advance hospital evacuation simulation?

Given the conclusions from this initial investigation (Q1-2), the following research questions are proposed to address the previously identified requirements:

3) How do movement assist devices perform in the horizontal and vertical evacuation of people with reduced mobility? (Chapters 3 and 4)

- How long does it take to prepare PRM for assisted evacuation?
- What are the horizontal travel speeds for assisted evacuation?
- How long does it take to open and traverse doors during assisted evacuation?
- What are the vertical travel speeds for assisted evacuation?
- Do handlers experience fatigue from assisted evacuation?
- Can other people evacuate alongside vertical stair devices?
- What factors influence the performance of assisted evacuation?

4) How can these data be used to compare the performance of movement devices in evacuation? (Chapter 5)

- How can the data for movement devices be combined to compare the performance of different devices and in different scenarios?
- How can performance data be used to numerically simulate hospital evacuation outcomes?
- What are the limitations in using an implicit (data-only) model to compare devices?

5) How can movement devices be explicitly modelled? (Chapters 6-7)

- How can movement devices be specified and geometrically represented in an evacuation model?
- How can a hospital building be assessed for the accessibility of devices?
- How can agent-device interactions be represented in an evacuation model?
- How can the horizontal movement of devices be represented in an evacuation model?
- How can the vertical movement of devices be represented in an evacuation model?
- How can the functionality implemented be tested and verified?
- How can the model implemented provide insight into hospital evacuations?

Chapter 2 provides an initial investigation to establish what influences the outcome of hospital evacuation, how egress models represent hospital evacuation, and what data are available to quantify evacuation performance in hospitals. Model enhancements and data requirements are proposed to advance the quantification and modelling representation of hospital evacuation performance.

The data requirements established in Chapter 2 are addressed in Chapters 3 and 4, where work is undertaken to establish the performance of four movement devices. This work investigates: the preparation of PRM to proceed with assisted evacuation in a movement device; the horizontal movement of PRM in devices in corridors and through doors; the vertical movement of PRM in devices; and any indication of handler fatigue that may impact the performance of assisted evacuation.

The modelling requirements established in Chapter 2 are addressed in Chapters 5 and 6 where methods of performance comparison are presented, along with a theoretical model comprising algorithms derived to represent the use of movement devices within evacuation modelling software buildingEXODUS [26].

Chapter 7 tests the implementation of the algorithms presented in Chapter 6, using the results of the data analysis in Chapter 4 to quantitatively and qualitatively verify the model.

Chapter 8 presents a discussion of the work undertaken by addressing each of the research questions established here, and Chapter 9 concludes this thesis and identifies threads of future work required to advance the body of work presented.

2 LITERATURE REVIEW

This chapter reviews the current understanding of evacuee performance during hospital evacuations, the tools available to assess performance and the regulatory frameworks within which such assessment takes place. This current understanding of evacuee performance is represented by an examination of egress models designed to forecast evacuee performance and data collected in support of the development and application of such models, with evidence from experimental trials and real incidents. These form the basic subject matter examined during this work. The examination of this material provides a statement of the current state-of-art subject matter understanding and practice, outlines factors that influence the outcome of hospital evacuations and where these factors are not represented within existing tools. This discussion then forms the foundation of the subject matter understanding presented here and a roadmap indicating required data collection and model development.

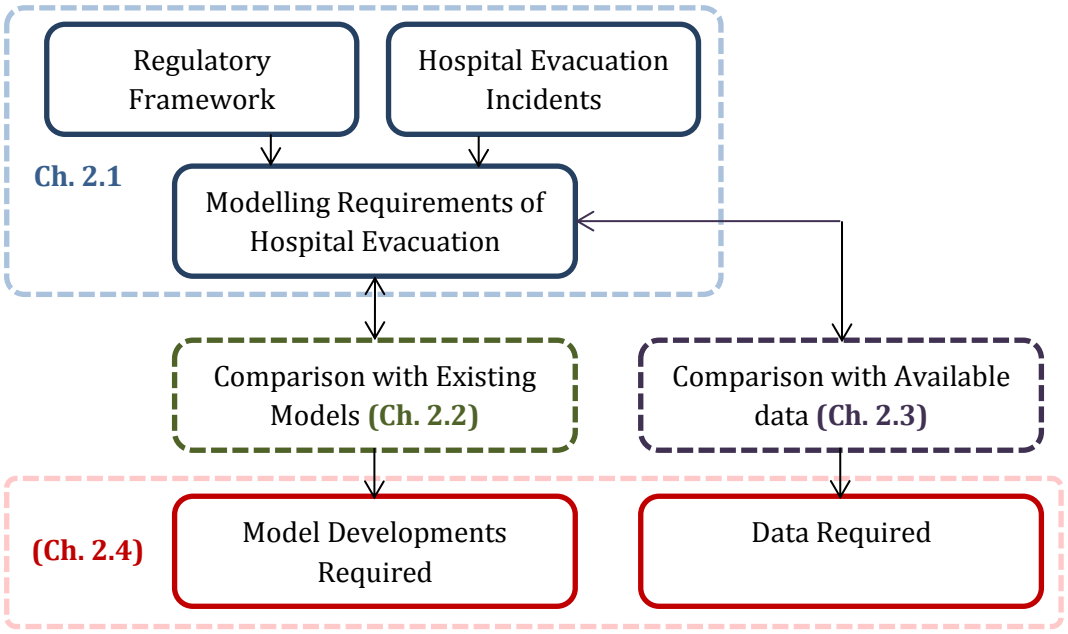


Figure 2-1: Literature Review Structure

As depicted in Figure 2-1, this literature review is divided into four key sections: section 2.1 provides an overview of the current regularly framework, a discussion

about real life hospital evacuation incidents and outlines the modelling requirements for hospital evacuation. This is then compared, in section 2.2 to the capabilities of the current models and compared, in section 2.3 to the data available for hospital evacuaiton modelling. Finally, section 2.4 describes the concluding proposition of model developments and data collection requirements in order to progress body of knowledge in this area and to improve the current ability to model hospital evacaution. As such, this chapter attempts to answer the following research questions:

1) What influences the outcome of hospital evacuations? (Section 2.1)

- What regulatory frameworks constrain hospital design?
- What happened during previous hospital evacuations?
- What factors influence hospital evacuation?

2) What developments are required in order to improve hospital evacuation simulation? (Sections 2.2-2.4)

- What supporting data are available quantifying performance in hospital evacuation?
- What data requirements are proposed to advance hospital evacuation modelling?
- How do models currently represent hospital evacuation and how appropriate is this representation?
- What model enhancements are proposed to advance hospital evacuation simulation?

2.1 Hospital Evacuation Overview

Initially outlined in this section is the regulatory framework that governs the design of emergency provisions and procedures in hospitals. This framework constrains design practice and also codifies much previous research understanding. There are a number of approaches adopted internationally, such as prescriptive codes, performance based codes and objective based codes. This description focuses on the hospital fire codes for the UK.

A series of case studies are discussed outlining hospital fire incidents and the factors that influenced their outcome. Although not exhaustive, the discussion identifies a number of high profile and instructive cases. This discussion is critical in identifying the underlying factors that influence the outcome in real incidents and therefore the factors that need to be understood and modelled to ensure that the tools employed (during the design process constrained by the regulatory frameworks employed) are credible and representative.

2.1.1 Regulatory Framework

The construction and operation of hospitals are regulated by building and fire codes. Currently, there are three types of building codes that can regulate hospital design: prescriptive codes, performance based codes, and objective based codes. Each represents different measures taken to prepare hospitals for emergency evacuation of occupants. Although the approaches adopted differ, the intent is to ensure that the safety of a hospital population is maintained during a fire incident.

Prescriptive codes (e.g. UK Building Regulations [27]), delineate a set of rules which form the minimum standards that buildings must comply with. If the design of a building is produced in accordance with the prescriptive code, then it is deemed to be safe. These codes rely on subject matter expertise being embedded within the code (in the form of a large number of rules that need to be followed) to ensure that the practitioner following the code produces a design that is sensitive to the real world factors that might influence the outcome. Performance based codes (e.g. Australia's National Construction Code [12]) specify the performance objectives of a building, and then require the practitioner to demonstrate that these objectives have been met. Performance based design requires fire safety engineering: a method of design that meets the requirements of regulations, but without necessarily adhering to prescriptive codes. Although guidance is provided on the techniques that can be employed and the assumptions that can be made, this approach provides practitioners with a great deal of flexibility in the designs produced and the methods adopted to demonstrate performance. An evidence-based approach is used to demonstrate compliance; engineers quantify performance to ascertain safety levels. For fire safety analysis, this quantification

depends on the comparison between the amount of time required for escape after an incident occurring (Required Safe Escape Time: RSET) and the time available in which to escape, i.e. the time until the incident has eliminated tenability (Available Safe Escape Time: ASET) [13]. In this way, the practitioner establishes that the design facilitates evacuation in the time available. Objective based codes (e.g. Canada's National Building Code [11]) specify a set of objectives to be achieved (e.g. safety, structural protection) and a set of provisions that meet these objectives. However, the code can be met in a number of ways: alternative solutions can be used instead of the specified technical requirements that achieve the same level of performance and objectives. Therefore, in this approach, both prescriptive and performance requirements can be utilised. This represented a provisional move from prescriptive codes towards performance-based design. The practitioner is still provided with a set of prescriptive requirements to follow; however, the function of each requirement is linked to a specific objective allowing the intent and expected outcome of each requirement to be understood.

Performance based design has become more commonplace in the building codes of developed countries given the flexibility that it affords and its ability to compare the performance of different designs allowing risk analysis and cost-effectiveness analysis to be conducted. Thus, fire safety engineering is regularly used in the UK, where prescriptive requirements are stipulated, but the legal requirements can also be met with performance analysis [28]. This is especially useful for large or complex buildings, where the interaction of prescriptive rules becomes difficult to ascertain, and may offer cost effective solutions. Many practitioners utilise fire modelling simulation and evacuation simulation to assist in estimating the ASET and RSET respectively; i.e. to quantify fire and evacuee performance. However, while the use of simulation software is regulated in the maritime environment [29] there are no current regulations governing its use in hospitals and other buildings, for example its necessary functionality and the methods required for its verification and validation. This means that the tools used vary in the assumptions made, the methods employed and the scope of the factors included. This then directly influences the credibility of the forecasts made.

In the UK there are a range of legislative considerations for hospital evacuation planning, including Equality Legislation [30, 31, 32], Hospital Fire Safety Legislation [33, 34] and Building Codes [2, 27, 35]. These are briefly outlined in the following sections. These considerations influence the requirements for hospital occupants in the broader sense that then indirectly influences the conditions produced during a fire incident.

2.1.1.1 Equality Legislation

Healthcare facilities are among the most likely buildings to house a high proportion of people with temporary or long-term disabilities. When planning the evacuation of building populations that include many disabled occupants, it is imperative that relevant equality legislation is applied. Under the 1948 Universal Declaration of Human Rights [30], everyone has the right to security of person, and everyone is entitled to equal protection against discrimination. In 2006, the United Nations Convention on the Rights of Persons with Disabilities [31] outlined measures for governments to ensure that buildings, including medical facilities, consider all aspects of accessibility for people with disabilities. Most countries in the developed world have legislation to this effect.

In the UK, there have been recent developments in equality legislation that impact hospital evacuation planning. The Disability Discrimination Act (DDA) 1995 [32] stated that in all buildings "reasonable adjustments" must be made to practices, policies and procedures ensuring that people with disabilities are not discriminated against. In the context of evacuation, this requires building management to ensure that the emergency evacuation procedures developed specifically consider whether disabled people are disadvantaged in comparison to non-disabled evacuees. Amended in 2005, the DDA introduced the Disability Equality Duty (DED), which emphasised the specific duties of public sector bodies (including healthcare providers) in promoting equality for people with disabilities [36]. As part of this duty, hospitals are required to produce a Disability Equality Scheme in collaboration with disabled people and publish their action plan to address disability equality issues. This legislation is now incorporated into the Equality Act of 2010 [5], with disability named as a protected characteristic. In this

act, PRM with a disability are defined as those with a physical impairment that has a "substantial and long-term adverse effect on their ability to carry out normal day-to-day duties." As a result of this, locally and nationally commissioned services must promote equal access and consideration for health and safety for disabled people and non-disabled people when making functional strategies, including evacuation planning. Failure to provide a fit-for-purpose evacuation strategy for disabled people may be interpreted as indirect discrimination under this act. To meet these requirements, the independent regulatory body, the Commission for Equality and Human Rights (CEHR) [37] recommend adjustments that take into account the needs of every individual in the building. For the evacuation of people with physical disabilities, guidance includes the use of buddy systems and refuge areas from which these is a safe route to a final exit. It is emphasised by the CEHR that staff should be aware of evacuation procedures for disabled building occupants and the plans should be tested regularly. However, studies have shown that many people with disabilities are not aware of the use of refuge areas and may not be comfortable with waiting for rescue in this way [38].

Therefore, legislation requires that hospital evacuation strategy must consider the evacuation of people with disabilities, making reasonable adjustments to accommodate the needs of every individual in the building [5, 37]. This does not mean that every individual should follow the same evacuation plan; rather, as described in the concept of Equal Egressibility [39], that there is "equivalent opportunity of life safety for everyone".

2.1.1.2 Fire Safety Legislation

In the UK, the enforcement of Regulatory Reform (Fire Safety) Order in 2005 [33] means that it is no longer compulsory for building management to have fire certificates, but they are instead legally required to conduct and document comprehensive fire risk assessments. The onus is placed on those in charge of a building to ensure the safety of all building occupants. Therefore, where there is the potential for disabled workers or visitors in any non-domestic building, those responsible for the premises must provide them safe means of escape in the event of fire. This includes establishments such as health care facilities, where there are

likely to be many disabled occupants. It is then important to understand and be able to demonstrate (as part of the risk assessment) the safety performance of the structure during an emergency evacuation. It is the Fire Authority's duty to enforce these requirements, but it is not acceptable for evacuation strategies to rely on the intervention of the Fire and Rescue Services to enable the safe evacuation of occupants [7]. Guidance provided on this fire risk assessment strategy [34] emphasises the specific consideration of those with disabilities: 'personal emergency evacuation plans' (PEEPs) may be required in consultation with disabled occupants, and general PEEPs prepared in advance of disabled visitors. Furthermore, in complex buildings advice from a professional consultant or from disability organisations may be useful in devising more elaborate plans for escape.

The fire risk assessment must include all matters relating to fire precautions and training. Detailed records must be kept in order to document the risk assessment, considering those who are at risk and developing evacuation procedures, including safety drills and nominated staff to implement them. Fire safety training should be provided continuously, commencing on the appointment of new staff and then be repeated at least once a year. Special training must be provided to those with nominated fire safety responsibilities, and those in unique environments, such as operating theatres [40]. However, where there is a high turnover of staff and a higher risk of fire (as are both typical in healthcare environments), the training should be more frequent than once a year [3].

2.1.1.3 Hospital Regulations

In the UK, building regulations for non-dwellings [27] classifies hospitals as institutional residential buildings (purpose group 2a). In 2010, amendments were made to these regulations which specified a separate Firecode [2] for the design of hospitals and similar heath care premises. This provides prescriptive guidance to mitigate against internal and external fire spread and specific guidance for evacuation. This includes required dimensions for the hospital structure and the standard of evacuation strategy required. Where there are patients that cannot evacuate unassisted (dependent patients), the key features of the fire evacuation strategy are outlined here.

2.1.1.4 Progressive Horizontal Evacuation

Evacuating an entire multi-storey hospital may place dependent patients (e.g. those with severe medical conditions) at risk and compromise the functionality of the hospital; therefore, evacuation could be conducted horizontally and in stages to limit exposure and reduce the distress that might be caused to vulnerable patients. Premises are divided into compartments and sub-compartments, constructed to provide required levels of fire safety. The concept of horizontal evacuation reduces the number of patients to be fully evacuated, as long as fire compartmentation is effective. This approach is based on a three stage procedure. PRM in the fire sub-compartment are initially moved in beds or wheelchairs to an adjoining compartment or sub-compartment. If a second stage is necessary, patients are then moved from the entire fire compartment to an adjoining compartment. Additional horizontal evacuation may be required in this stage, to provide additional fire resistance before the third stage: vertical evacuation to a lower floor, or to the outside. In adopting this approach, those most intimate with (and most exposed to) the incident are given priority, while attempting to minimize the distress caused to the patients involved.

2.1.1.5 Vertical Evacuation

Vertical evacuation requires the movement of evacuating patients between floors. This is typically conducted using stairways and, to a lesser extent, elevators. Given the nature of stair movement, it represents a more challenging and time consuming endeavour.

All stairways must be designed as escape stairways, and all stairways that service areas of dependent patients must be designed to accommodate the evacuation of patients on mattresses, or other similar methods. The width of these stairs should allow the manoeuvrability of these mattresses; otherwise, vertical evacuation using this method becomes impractical. Appendix B depicts the landing dimensions required for assisted evacuations on stairways. On upper levels, stairways are required in two of the three sub-compartments. The maximum distance between stairways should not exceed 60m and the distance from a compartment exit to a stairway should not exceed 30m. On the ground floor, the

exit from a stairway should lead to a final exit within 60m. When patient beds on any floor exceed 100, an extra staircase is required per 100 patient beds. All staircases should be positioned to provide alternative means from every compartment and sub-compartment. Although evacuation lifts may provide benefits in stage three (vertical) evacuation, they are not required by the code. It is highlighted that escape stairways will always be required as the total evacuation of occupants from multi-storey hospitals cannot be realistically achieved solely by lifts. To accommodate beds and associated equipment, the clear car size of lifts must be 2700mmx1800mm.

2.1.1.6 Planning

Management must ensure that an evacuation procedure is produced, that there is sufficient staff to implement it, and that staff are adequately trained [2]. The design of the hospital should ensure that fires are detected at the earliest possible opportunity, utilising staff and automatic detection, and that suitable warning is communicated to patients, staff and emergency services. Extra fire protection must be provided for specialist areas, such as intensive care and operating theatres, where there is a great risk to life.

2.1.1.7 Space

Each compartment must be able to hold the designed occupancy of the largest adjacent compartment in addition to its maximum capacity. Each sub-compartment and compartment must have at least two exits for horizontal escape. Exit from compartments should be to and from a circulation space. Floors smaller than 1000 m^2, that are below 12m from ground level, should have at least two compartments and no more than 30 patients. Floors larger than 1000 m^2 that are below 12m from ground level should have a minimum of three compartments. All floors above 12m from ground level should be divided into four compartments, each of which is larger than 500 m^2, unless a compartment is a hospital street (a large corridor), in which case its area may be smaller. A compartment must be sub-compartmented if it has a floor area greater than 750 m^2,(or greater than 1000 m^2 for out-patient departments), or a potential occupancy of more than 30 patients. Hospital streets should be treated as compartments, with a clear width of 3m and a minimum of three sub-compartments. As depicted in Appendix A, the expected bed

dimensions for assessing evacuation routes is 1000mm-1080mm width x 2370mm-2440mm length (depending on whether a pump is attached to end). A trolley of 450x450 is also anticipated. To permit bed evacuation the effective width of corridors should be at least 2150mm and doors 1550mm.

2.1.1.8 Procedure

In an "extreme emergency" [2], people in immediate danger should be evacuated first, followed by ambulant patients and then non-ambulant patients. Patients are considered to be independent if they can self-evacuate or if they require minimal assistance from another person for minor mobility impairments (i.e. they do not need to be assisted by staff to evacuate). Dependent patients require staff assistance, and highly dependent patients rely entirely on staff members, for example those in intensive care areas, or in operating theatres [40]. These patients require more time for evacuation due to the treatment associated, as well as their equipment requirements. Travel distances should be limited to ensure that occupants can escape horizontally within a reasonable amount of time. For in-patient accommodation the maximum travel distance before these is a choice of escape routes should be no more than 15m for in-patient accommodation and 18m for other parts of the facility. Longer distances may be required in exceptional areas (for example aseptic prep units, operating departments and linac rooms), but these must be justified explicitly in the strategy document. In reality, the time to reach safety is dependent on the time taken to cover the distance, not the distance itself. The total travel distance in each phase of horizontal evacuation should be less than 60m for compartments and 30m for sub-compartments. For very high dependency patients, extra consideration must be given to the distance of travel that may be necessary during evacuation.

2.1.1.9 Security Issues

In-patient units that have hospital beds for patients with learning disabilities, those receiving mental health services or those detained under the Mental Health Act may be secured with locked doors and controlled [41]. Horizontal evacuation remains the strategy here, but external escape should be a last resort. To maintain security in this case, control is placed with the staff in these areas (who should be

highly trained) to open the final exit on confirmation of the fire signal and these routes should lead to secure external assembly points. Any delay incurred by a non-automatic door release should be countered by the availability of sufficient numbers of well-trained staff.

The previous sections outline some of the physical and procedural considerations for hospital design. These are designed to ensure the safety of patients and staff. However, hospital evacuations are complex and highly dependent upon the actions of a number of parties – designers, responders, staff, patients, safety managers, contractors – all of whom might influence the outcome. In addition, the outcome of an incident might be influenced by factors before the event (e.g. design requirements, design choices, technological resources in place, training levels, etc.) and those during the event (e.g. the nature of the incident, staff actions, etc.). Several case studies are now presented, outlining the outcome of the incidents and the relative importance of these factors.

2.1.2 Hospital Evacuation Incidents

There are a variety of emergency situations that can prompt hospital evacuation. *Internal emergencies* are those with an origin inside the hospital building, including: fire, explosion, smoke and the release of hazardous fumes; loss of services such as electricity, water and communications; loss of medical gases; and violent acts by occupant(s) [42]. *External emergencies* are those with an origin outside the hospital building including: natural hazards such as earthquakes, hurricanes, floods and tornados; local power outage; civil disturbance; terrorism; transportation accidents; and the release of hazardous materials and radiation [42]. As hospitals have a duty of care to their patients, as well as any externally injured persons, their effective response to emergencies is crucial. An evacuation of patients and staff may be required as part of this response; either in isolated areas of a hospital building, or of a whole hospital building.

The incident prompting the decision to evacuate dictates the level of preparedness, the time available for the evacuation, and the resulting requirements for patient care. In the case of natural disasters, information can pre-empt the arrival of the

incident, allowing a hospital to evacuate its occupants before conditions begin to deteriorate. Management may have time to assess expert predictions of disasters such as floods [43], hurricanes [44] and earthquakes [45] and decide whether evacuation is necessary. Sometimes it is not until the event unfolds that the decision to evacuate is taken, and defend-in-place strategies may be taken in the interim. Regardless of the timing, after an evacuation, hospitals may need to continue functioning medically for the needs of the surrounding population in disasters such as these: the hospital may go from being the subject of an evacuation to a resource to cope with other evacuations. Where there is no warning, for example in the case of sudden natural hazards, building fires, and purposeful attacks, spontaneous evacuation is required. These immediate and emergency evacuations are more prevalent than those with prior warning and, as in the case of natural disasters; they may require some or all of the hospital staff to remain in medical service due to the incident at hand. Off-duty staff may also be summoned to the scene to assist as part of a facility's major incident strategy.

The most common type of hospital evacuation is in an unplanned evacuation in response to a fire threat; i.e. an incident with little or no prior warning. Since 2000, there have been an average of approximately 1800 hospital fires each year in the United Kingdom [8, 46, 47, 48, 49]. This number has been gradually decreasing since previous records of fires in the UK at the end of the last century, which documented large numbers of hospital fires: approximately 2800 in 1998 and 3100 in 1999 [8]. The most recent data in the UK show that hospital buildings account for approximately 1-1.5% of all building fires [1, 49]. This aligns with international trends in developed countries: for instance, there are approximately 6240 yearly fires in health care facilities in the US [50], which represents 1.3% of all structural fires [51], and approximately 194 in new Zealand, which represents 1% of all structural fires [52].

Historically, severe hospital fires have produced a large number of casualties. For example in the US alone: 125 people died in an Ohio hospital in 1929, 74 died in an Illinois Hospital in 1949, and 41 died in an Iowa hospital in 1950 [53]. While effective emergency response planning has generally decreased the number of

incidents and the number of casualties resulting from incidents in the last century, developing countries and countries with a poor safety record still report incidents with large casualties. In 2005, 39 patients were killed in a city hospital fire in Liaoyuan, China [54]. It took more than five hours to suppress the fire and 152 patients were transferred to hospitals in that time. This year, 38 residents were killed in a care home fire in Pingdingshan city in Henan province, China [55], where poorly designed fire escape routes and insufficient fire proofing were reported [56].

Despite the provision of comprehensive standards [11, 27, 35], tragic fire incidents still occur, even in countries with good safety records. Training standards are not always met; for example, management of a retirement home in Orillia, Canada, were convicted in 2010 of violating the law after four elderly residents died in a fire in 2009. Staff were found to have not been instructed in the emergency procedures, and training drills had not been conducted [57].

Injury, death and property damage are more likely in buildings with elderly occupants than in those with a younger population [58], particularly in nursing homes [50]. In the UK more than half of the fatalities from fire in all building were people aged 65 years or older and, according to the most recent analysis, people who are 80 or older have more than four times the risk of dying in a fire than the average person [1]. Also reported are the relatively large amounts of non-fatal casualties in hospital and health care facilities: 107 non-fatal casualties per 1,000 fires.

Hospital evacuations then present a particular challenge to fire safety. They are typically relatively complex spaces; with a large vulnerable population who are dependent on others to provide assistance; a fluctuating population of staff depending on the time of day; hazardous materials; and multiple functions. These challenges are evident in the cases described below.

Presented here are a number of incidents that highlight the particular challenges posed by these varying hospital evacuation situations. These incidents include case

studies of recent fire evacuations in hospitals/care homes, pre-emptive disaster evacuations, and evacuations from secured psychiatric facilities. Also included are incidents that required the provision of on-going patient care. The purpose of this section is to demonstrate the susceptibility of hospital environments to different emergency incidents, the impact of preparedness and of varying evacuation procedures on the outcomes. Although not exhaustive, this review identifies a number of characteristics and omissions that have contributed to these real evacuation processes. These characteristics and omissions are suggestive of research required to better understand and quantify the behavioural factors that influence evacuation performance.

2.1.2.1 Emergency hospital evacuations

Healthcare institutions and fire services routinely record fire and evacuation incidents. However, these reports vary in detail and content. Several of the highest profile and most instructive cases are discussed here. The National Health Service in the UK reviewed the management of five London hospital fires between 2008-2009 [59], identified as those "with the greatest amount to offer in terms of experiences and lessons". In adapting a benchmarking tool that assessed hospital response to the Northridge Earthquake in California [60] to create a general tool to categorise the process and characteristics of each incident, a summary of lessons learned was presented. Of these, this review reports the Northwick Park Hospital (that was partially evacuated in 2009), the Great Ormond Street Hospital and the Chase Farm Hospital (that both conducted full building, but not full-site, evacuations in 2008), and the Royal Marsden Hospital (that conducted a full-site evacuation in 2008).

Furthermore, a tragic psychiatric hospital evacuation in Russia is reported [61], as well as two care home fires, based on recent findings about their evacuation processes by Purser [62]. These represent the two key types of care home (nursing and residential) and included fatalities. These incidents are representative of the different hospital facilities that can be involved during an evacuation (e.g. paediatric and psychiatric hospitals, surgical and intensive care units, high rise hospitals, and care homes) and the challenges that they pose.

2.1.2.1.1 Northwick Park Hospital Fire (London, UK), Wednesday 11th February 2009: partial building evacuation [59].

This hospital had a 600 patient capacity, and was at 95% bed occupancy at the time of the incident. A fire broke out in an electrical plant room under the main wing of the hospital, and an alarm sounded at 14.35. Smoke spread quickly through the ten-storey building and a major incident response declared 15 minutes later. There were numerous issues with communication between agencies and individual staff members (e.g. out-of-date telephone numbers), and the decision regarding a full evacuation was taken after an hour of deliberation. Some of the evacuation routes were found to be cluttered. The fire brigade made it clear that their role was only to fight the fire, not to aid in evacuations or make procedural decisions, however management took the decision to partially evacuate based on the advice of the brigade who were struggling to contain the fire. 123 patients were evacuated in 23 minutes, including immobile patients. The evacuation effort successfully transported those in the fire vicinity away from danger, and there were no casualties. It was fortunate that the fire brigade gained control of the fire shortly afterwards, as the report highlighted a lack of preparation for a full scale evacuation. There was a lack of essential equipment, for example, there was not a ski sheet under every bed. It is not clear whether the staff were adequately trained in the use of such devices, but it is highlighted that the first time that a staff member uses emergency equipment should not be in an emergency itself. It is likely that, had a full-scale evacuation been necessary, this hospital would have faced a range of challenges because of the lack of equipment and training.

Key evacuation issues identified:

- Issues with internal and external communication channels
- Egress pathways were not clear
- Lack of evacuation equipment
- Lack of staff training.

2.1.2.1.2 Great Ormond Street Hospital Fire (London, UK), Monday 29th September 2008: full building evacuation [59].

This high-rise hospital site accommodates 335 paediatric patients in medical units as well as various lodging for families. A smoke alarm in the 5th floor cardiac wing was activated at 8.30am, and the spread of smoke meant that within two minutes 23 children with cardiac or respiratory were evacuated from neighbouring wards. The progressive horizontal evacuation [2] procedure was used, where these children were moved to alternative safe sites, away from the fire, and eventually to other buildings in the hospital site. At 8.40am, an oxygen cylinder exploded as a result of the fire, and this caused the ceiling on the 5th floor to collapse. Water also began to leak throughout the building because of the firefighting, and these conditions prompted a full building evacuation. The timing of the event meant that the hospital could be effectively locked down; parents and staff entering in the morning were kept away and therefore effective assessment and control of the incident was possible. Control centres and email communication was effectively used. But, the progressive horizontal evacuation plan proved to be insufficient in this case, because of the necessity to vertically evacuate patients. It was fortunate that the patients with cardiac and respiratory conditions had been moved to other buildings prior to the ceiling collapse, as the report identified the potential challenges of moving patients with complex needs vertically. This evacuation did not result in any casualties, and as such was successful. However, the planning for vertical evacuation was deemed insufficient. As a result of this incident, a vertical evacuation plan has been developed and more comprehensive training (including walk-arounds) has been introduced.

The quick horizontal evacuation of critical patients proved to be highly effective in the first few minutes of the incident. Had the ceiling collapsed before this time, it is likely that there would have been a greater risk to the patients, and a more challenging vertical evacuation would have ensued. Furthermore, the success of the vertical evacuation may have been in part due to the very high staff to patient ratio in the hospital: many staff could stay with one patient and care for them for prolonged periods of time. This ensured the swift movement of patients as well as

on-going care. Because the patients were children they typically weighed less for those carrying them. Furthermore, there were parents on site who helped carry children down stairs. Therefore the unplanned vertical evacuation was unusually straightforward in that equipment was not necessary to transport patients, particularly as the most critical patients had already been moved to another building.

Key evacuation issues identified:

- Escalation of incident requiring unplanned full evacuation
- Horizontal evacuation not sufficient
- Children can be carried in vertical escape, but emergency equipment is needed if they are critically ill
- The time of the incident contributed to evacuation success: a high staff ratio, and parents were available to help

2.1.2.1.3 The Royal Marsden Hospital fire (London, UK), Wednesday 2nd January 2008: complete site evacuation [59].

There were 78 inpatients and approximately 120 outpatients in this cancer care hospital at the time a fire broke out on the hospital roof (1pm). At this time, three patients were in operating theatres, and six were in intensive care unit (ICU). A major incident plan was conducted (although not announced until after the incident), and culminated in the full evacuation of the hospital. The decision to evacuate was made very quickly, within minutes of the fire starting. Even though the telephone system was disabled as a result of the incident, internal communication was good due to the use of mobile phones. There were some issues in relaying information to external hospitals given the immediacy of the evacuation. Patients in ICU were among the first to evacuate, and clinical staff made the decisions about what equipment it was necessary to take. Fortunately, there was a nearby hospital to move critically ill patients to, and St Paul's church provided a triage centre for other patients evacuated from the building. Bed-bound patients were evacuated using ski sheets that were available under every mattress. However, there were issues with the revolving doors at the entrance/exit to the

hospital. These doors did not have the effective width to allow these mattresses through. According to the report [59] this highlights "the importance of real exercises, and simulated patient evacuations to allow the identification and correction of similar practical problems before a real incident." Despite these issues, the full evacuation took just 28 minutes; with outstanding leadership and teamwork cited as the reasons for the speed of evacuation. However, incident plans have now been updated to account for full-scale hospital evacuations to remove the previous assumption that a horizontal evacuation procedure alone would suffice.

Key evacuation issues identified:

- A full evacuation was required despite planning for horizontal compartmentation
- Communication issues with external agencies
- Difficulties negotiating routes with egress devices – exit consisted of revolving doors that could not allow mattresses through.

2.1.2.1.4 Rosepark Nursing Home Fire (South Lanarkshire, UK), 31st January 2004: complete building evacuation [62].

A fire broke out at 4.27am on the ground floor of this custom-built nursing home. There were four members of staff on duty; this is consistent with night staffing guidance – one per two occupants in each compartment up to a maximum of nine. There were 40 residents, typically aged 80-90: 21 on the ground floor and 19 on the lower ground floor, where there were two external exits. Some were able to walk with mobility aids, some with assistance from staff, and others were confined to beds. All of the 14 occupants that died required some assistance from staff to move. While drills and training were conducted at the home, none of the staff on duty that night had participated in a drill, nor received training since the commencement of their employment. The staff misinterpreted the information from the alarm panel and searched in the wrong area for the fire for nine minutes before discovering the incident and calling the emergency services. At this point the smoke was too intense in the corridor of origin for the staff to enter, and so

they evacuated residents from all other parts of the building with the assistance of fire fighters. It took four nurses and two fire fighters 27 minutes to evacuate 23 patients (the fire fighters arrived 13 minutes into this evacuation effort). Meanwhile other fire fighters rescued survivors from the smoke filled area (the fire had self-extinguished at this point). There were 14 fatalities, all of which had open doors to their bedrooms in the fire area. This demonstrates the risks of defend-in-place strategies where fires are not adequately contained. Where progressive horizontal evacuation is the primary procedure in an evacuation, it is imperative that self-closing doors are used or that staff are trained to always shut doors.

Key evacuation issues identified:

- Staff availability given incident scenario
- Issues with situation awareness
- Issues with reaching and evacuating patients
- Patient fatalities involved those with mobility issues
- Insufficient staff training
- Procedural issues

2.1.2.1.5 Lincolnshire Residential Home Fire (Lincolnshire, UK), 11th July1994: complete building evacuation [62].

A fire broke out on the first floor of this three storey residential home at 10.16pm. There were three members of staff on duty and 18 elderly residents. The staff had completed yearly fire training, but it is not clear what the training entailed. 15 residents were on the fire floor, of which approximately half required mobility assistance to evacuate. The fire began in a bedroom, and immediately after the alarm was raised a staff member attempted to extinguish the fire. The attempt was unsuccessful so they isolated the fire by closing the door. The emergency services were then called. Fire doors were effectively used, and so there were only three other residents in the fire compartment. One, a wheelchair user was brought to the top of the stairs and they "bumped" themselves to the bottom, while the other two occupants were left in their closed room because they required assistance to evacuate. There were two adjoining compartment where residents were relatively

agile and slowly evacuated themselves down the protected stairs, helping each other as necessary. One resident resisted the evacuation efforts and had to be "dragged" to the bottom of the stairs where she was left by the staff. The evacuation of ambulant residents took 4 minutes, and the rescue services then evacuated the two remaining residents that required mobility assistance.

The success of this evacuation was helped by the containment of the fire. The only open fire door was at the source, and this was closed by staff. The onus was on the staff to alert the emergency services, but the staff investigated first.

The staff did not attempt to evacuate non-ambulant people, even though they were positioned in the fire compartment. This was not an issue in this case, but should the fire services have been delayed, or the level of compartmentation provided a shorter tenability, then the delayed evacuation of these patients may have contributed to the seriousness of the incident.
Key evacuation issues identified:

- Presence of mobility impaired patients
- Different procedures employed regarding patient movement
- Patients were moved or self-evacuated

2.1.2.1.6 Chase Farm Hospital Site Fire (London, UK), Wednesday 15th October 2008: full building evacuation [59].

This hospital site hosts a variety of trusts and services, but the area affected by the fire was a medium secure psychiatric service where 70 patients suffering from mental illnesses were detained because they are subject to criminal justice processes. Fire alarms sounded at 18.35pm and patients were quickly moved to the opposite end of the three-storey building once the fire was discovered. The fire brigade arrived after ten minutes, but a major incident was declared after an hour, and a full evacuation completed in 1.5 hours. Evacuating the patients was a complex task as the major incident plans primarily consider horizontal evacuation as the standard procedure. There was no prescribed process for determining

placement of patients in the case of a full building evacuation, so staff began telephoning other secure facilities. For any kind of transferral of patients in these types of incidents, permissions must be gained from appropriate justice authorities, or patients could be placed in custody temporarily. In this case, nearby facilities were used to shelter the patients and were secured by police officers. Reportedly [59] staff felt that there was little chance of a full scale evacuation prior to the fire. This incident has prompted all other medium secure units in the country to run table top exercises to determine full scale evacuation procedure.

Key evacuation issues identified:

- Unplanned full evacuation
- Security and legal additional procedures
- External resources / permission required to evacuate facility

2.1.2.1.7 Psychiatric Hospital No 14 (Ramenskoye, Moscow, Russia), 26th April 2013: fatal building fire

In 2013, a psychiatric hospital in Russia caught fire [63] in the early hours of the morning. The hospital was a secure facility, with 38 patients locked inside, and 3 staff members presiding overnight. 36 of the patients and two doctors died in the incident. Reportedly [64], there were secure bars on the windows, and patients died in the corridors while looking for an exit. The only surviving nurse was reported to have tried to tackle the fire upon hearing the alarm, but could not suppress it and therefore exited the building, taking two patients with her. A high proportion of wooden materials in the building structure rapidly spread the fire and it was extinguished by emergency services three hours after its estimated ignition (2am). Fire fighters said the poor condition of the roads meant the 32 mile drive to the village in the Moscow suburb took an hour. In this case, sedation was potentially an issue.

Key evacuation issues identified:

- Low staff-patient ratio
- Ineffective fire resistance
- Insufficient evacuation planning

2.1.2.2 Evacuation as a result of natural disasters

Prior warning is available for some emergency incidents; for example, floods [43], hurricanes [44] and earthquakes [45, 65]. This allows emergency measures to be enacted before conditions deteriorate. Several examples are now presented to demonstrate that cases allowing pre-emptive evacuation still face challenges relating to the prioritization and execution of patient movement and are particularly reliant on the accuracy of the arrival time and severity of the incident to ensure that the procedures employed are appropriate. Importantly, there is an impact on on-going patient care. These recent disasters have shown the intricacy of these requirements (i.e. managing an evacuation while maintaining patient care), and in particular the need to take a bespoke approach to planning a full hospital evacuation.

2.1.2.2.1 New Orleans hospital evacuations after Hurricane Katrina, August 23rd 2005

In countries such as the USA, prior warnings of natural disasters are often available and then inform the decision to evacuate hospitals before local conditions deteriorate. Often, only a portion of occupants are evacuated ahead of a disaster, for example when Hurricane Katrina hit hospitals in the New Orleans area [44] many hospitals had discharged ambulatory and stable patients in advance. Hospital officials opted for defend-in-place strategies for the remaining occupants as the logistics of evacuating critically ill patients were challenging and potentially placed patients at undue risk [66]. While the buildings themselves successfully survived the disaster, 11 hospitals (with approximately 1749 patients remaining) were surrounded by floodwater and ceased to be operational. This result of unforeseen levels of flooding included loss of power and water/sewage systems. Communication was impeded, as well as resupply channels for food, medicine etc. Thousands of other people resided in the hospitals including staff and those who self-admitted in anticipation of the storm. Basic medical support was compromised, for example, staff were unable to sterilise equipment without power. In desperate conditions, some hospitals required full evacuations [67]. Hundreds of people died in these hospitals as a result of this disaster, prompting

questions about whether evacuation planning was sufficient. As well as highlighting improvements to emergency facilities (e.g. protection for electricity generators), the incident led to a re-evaluation of the speed and coordination of evacuation decision making at local, state and federal levels [68].

Key evacuation issues identified:

- Defend-in-place strategies were not sufficient in the developing conditions
- Communication and planning issues at local, state and federal levels

2.1.2.2.2 Hospital evacuations as a result of an earthquake in Northridge, California, 17th January 1994 [45]

An earthquake in Northridge, California, led to partial or full evacuations in eight out of their 91 hospitals, due to varying degrees of structural damage, water damage and loss of electrical power [45]. The decision to evacuate was based on the emerging conditions in each hospital. The four hospitals that fully evacuated within the first day following the earthquake all took many hours to complete the process of moving patients to an alternative facility (320 patients were moved in 9 hours; 125 patients in 19 hours; 270 patients in 9 hours; and 76 patients in 13 hours). In the multiple storey buildings, lifts were used as well as available equipment (blankets, backboards and gurneys). No specialised emergency equipment (e.g. evacuation assist devices) were used for evacuation. The majority evacuating in non-emergency conditions chose to evacuate the most critically ill patients first, as their on-going care required the most resources, and those resources were depleting as a result of the earthquake. One Veteran's Affairs Hospital considered their patients in immediate risk, and therefore adopted an emergency strategy of evacuating the ambulant patients first, followed by those that were self-sufficient (transported in wheelchairs and in mattresses), then the intensive care unit and finally people who were trapped in the building. Manual ventilation was used when transporting intensive care patients, and to evacuate this unit alone it took two hours.

This incident highlights the key differences between emergency and non-emergency hospital evacuation strategy. Where patients are not in immediate risk, the non-ambulant and critically ill patients are typically evacuated first, whereas emergency procedures prioritise the speed of evacuation, and thus the order is reversed, enabling the greatest number of people to evacuate in the first instance. This kind of utilitarian approach is widely adopted in emergency procedures that include PRM.

Key evacuation issues identified:

- No specialised emergency equipment was used
- Defend-in-place strategies worked for some, but in one case led to a full evacuation
- Critically ill patients were typically evacuated first, but the process took a long time

2.1.2.2.3 Memorial Hermann hospital evacuations after tropical storm Allison (Houston, Texas, USA), 4th June 2001

In 2001, tropical storm Allison caused flooding in Houston, Texas, prompting the evacuation of the Memorial Hermann hospitals: one building housing 450 adult patients and one housing 150 child patients [43]. In total, there were 199 beds for intensive care patients (including neonatal). Overnight, the flood caused a loss of all power to the hospital buildings. Some intensive care patients had ventilation equipment with back-up power of two hours, but others required manual ventilation support. The nature of the back-up ventilation systems meant an increased use of oxygen, and therefore supplies were quickly depleting once the power was gone (and no more oxygen deliveries were possible because of the flood). Hospital staff charged battery units in their personal residences.

The order of evacuation was determined by the needs of the patients and the facilities that they would be transferred to (i.e. careful consideration was made not to overwhelm any other facilities resources), therefore a triage system was introduced. A centre of command was established in the ambulance bay. ICU

managers evaluated their own patients and determined an evacuation order, and similarly paediatric triage was conducted by paediatric experts. Other organisational roles were established; for example administrators were responsible for communicating with outside hospital facilities, and a medical director scheduled the ground and air ambulance evacuation. Senior management then coordinated the full effort liaising with all parties. The order of evacuation was logged by placing identification stickers on patients. Staff and equipment were sent with patients as needed, if, for example, a hospital had beds but not enough resources. According to post-incident analysis [43], patient transportation was conducted by teams of people:

"Teams of physicians, nurses, ancillary staff, and volunteers transported patients to the waiting ambulances and helicopters down as many as 10 flights of stairs without benefit of elevators, overhead lights, or air conditioning. Patients were secured to backboards for transit. In the pediatric unit, as many as 5 infants were secured to 1 backboard. Adults were more difficult to maneuver and required multiple persons to carry each patient. A manual census was continuously taken to assess patient location and condition."

The full evacuation reportedly took 31 hours: 169 patients discharged, 406 patients were transferred to 29 hospitals, and six patients died (but the coroner did not attribute the deaths to the conditions cause by the flooding). This is an exemplary case of effective emergency response and shows outstanding planning, but in this case, there was ample time to prepare for the evacuation. Given that it took 31 hours for the successful evacuation under these circumstances, it may be argued that it would not be feasible to conduct the same calibre of response during emergency situations and that the level of preparedness and on-going care would be compromised in an emergency situation.

Key evacuation issues identified:

- Backboards were used to transport non-ambulant patients down as many as 10 flights of stairs, sometimes with 5 infants strapped to a backboard.
- While the evacuation process ran smoothly, it took 31 hours

2.1.2.3 Discussion

Section 2.1.2 examined a diverse set of cases that present different evacuation challenges. A number of factors can be identified from these incidents:

- Insufficient fire protection and/or evacuation planning. *The time available and the appropriateness of the response may not be as expected.*
- Ad hoc plans and equipment used to compensate for shortfalls in dedicated resources to cope with the presence of those with movement impairments.
- Incidents can escalate quickly – requiring emergency procedures to adapt ensure occupant safety.
- *Horizontal evacuation is often not sufficient.*
- Given the need for vertical evacuation, *movement assist devices are frequently required to evacuate PRM*.
- Accurate information and communication (internal and external) of the incident is important. Inaccurate information can mean that the procedural response is quickly out of date with the current situation.
- Egress paths are not always in the required condition to allow emergency use.
- Emergency equipment is not always available. *Moving patients then faces numerous challenges.*
- Staff training is important and not always sufficient. Staff levels fluctuate given the time of the scenario. *The performance of staff then varies significantly between incidents.*

These point to a number of common threads in the hospital evacuation incidents:

1) Emergency procedures do not adequately facilitate full-site evacuations;
2) Defend in place strategies are not always sufficient in natural disasters– developing conditions may mean that even critically ill patients are required to evacuate;
3) Staff are required to assist all patients without relying on the help of emergency services;
4) Movement assist devices are required to evacuate PRM;

Here, each of these findings are discussed in turn.

2.1.2.3.1 Emergency procedures do not adequately facilitate full-site evacuations

The incidents reviewed here highlight the need for hospital and care facilities to plan for, and assess the effectiveness of the proposed plan, the event of full hospital evacuation. The progressive horizontal evacuation [2] approach is commonly specified in healthcare incident planning where those that are in immediate danger are moved to a safer area and other occupants stay in place until the fire is successfully suppressed [69]. As determined in the examples explored in this section, for example the full evacuation of the Royal Marsden [59], clearly there is a need to prepare for vertical evacuation as well. As is evident, healthcare management do not typically consider this as a likely scenario in their incident planning and, as a result of recent incidents, NHS London have highlighted that it is imperative to plan and test full site evacuation plans in every hospital [59]. Therefore, investigation into the process of vertical evacuation of patients (particularly PRM and those in critical condition) is vital in developing effective evacuation plans for hospitals and care-homes.

However, new procedures are very difficult to test in hospital environments as full-scale drills are clearly unfeasible with critically ill patients, and therefore estimates of evacuation time may not be realistic. It is proposed in this thesis that the use of evacuation simulation tools may therefore be able to provide valuable insight into the feasibility of potential evacuation procedures.

An integral part when redeveloping of hospital evacuation procedures, is an effective programme of staff training. Incidents presented in this section have highlighted cases where staff were not adequately trained. As a result of the NHS fires, there have been some redevelopment of staff training programmes in London, including: table top exercises, training in specialised emergency equipment, and evacuation walk-throughs. However, as full-site evacuation testing is not feasible in a healthcare environment, the scope of this training is limited.

2.1.2.3.2 Defend in place strategies are not always sufficient in natural disasters– developing conditions may mean that even critically ill patients are required to evacuate

A key element identified in this section is the difference in procedural responses between pre-emptive evacuation (before an incident), contingent evacuation (shortly after an incident, as a result of emerging conditions) and emergency evacuation (responding immediately to the incident). If there is time before an incident occurs, triage principles can be applied. Pre-emptive evacuations can carefully plan and staff the necessary transit and care of patients within a relatively large timeframe. Contingent evacuations may also have increased time available, but the procedures are more reliant on available resources because they are subject to developing conditions. For these reasons, it is likely that people with the least mobility will be evacuated first, and those who are fully ambulant evacuate later. This is in contrast to emergency evacuations, where typically people in immediate danger should be evacuated first, followed by ambulant patients and then by non-ambulant patients. In natural disasters, most plans include defend-in-place (DIP) strategies for critically ill patients. This strategy requires an on-going assessment of risk as any evacuation is contingent on the emerging conditions resulting from the incident. As is evident from the incidents presented in this section, structural damage to hospitals after a natural disaster may develop over time, and therefore a defend-in-place pre-emptive strategy may prove unfeasible as a situation develops. Furthermore, emergency planning is not just essential for large-scale catastrophes. Even in countries not regularly exposed to severe weather conditions, flood risks may result in impromptu patient evacuations. For example, an accident and emergency department in Ireland was recently evacuated due to heavy rain [70], prompting criticism that flood planning was not incorporated into a brand new unit.

There are clear differences between the processes of planned and unplanned evacuations. However, regardless of the schedule of evacuation (i.e. critically ill patients being moved first or last), the need for the evacuation of PRM is a potential factor for any type of healthcare building, and any type of emergency incident. Their evacuation must still be undertaken within the time available, and

the time required for these procedures are not yet well understood. It is proposed here that computer simulation may aid the calculation of required egress time, actual egress time, and the implications of imposing a number of different procedures.

2.1.2.3.3 Staff are required to assist all patients without relying on the help of emergency services

All hospital evacuations rely heavily (often exclusively) on hospital staff conducting the evacuation. In the UK, the hospital fire codes [2] state that hospital management are responsible for the evacuation of every person in a hospital building and that the fire services are not to be relied on for evacuation assistance. The incidents in this section show the necessity for staff to be fully prepared to conduct a full-scale evacuation of a hospital building unassisted by the fire services. In this respect, hospitals and care homes are unique environments for evacuations. Unlike other buildings where occupants evacuate themselves, studies show that in healthcare facilities patients will wait for staff instruction before proceeding with evacuations [71].

Similarly, the onus is on the staff in the first instance to alert the emergency services. The incidents presented in this section indicate that this is not well-known, that staff are not sufficiently trained, or that the procedure is unrealistic as it has been found that this process is often delayed where staff choose to investigate the incident prior to alerting the fire services [72].

These requirements present more complex issues in mental health facilities where staff are also responsible for maintaining security. Approximately one in five (21%) of healthcare fires in the US are in mental health facilities [50] and in these situations the staff present must solely organise and evacuate the patients. Unlike most building types, additional time is spent assessing the situation before unlocking doors. Planning for the retention of patients after evacuation is also a critical factor, particularly where patients are sectioned under the Mental Health Act [41], i.e. involuntarily detained as they are a danger to themselves or others, as

there are potentially serious consequences of their unsupervised release. Furthermore, the range of mental competencies of the patients poses difficulty in emergency preparedness. Procedures cannot rely on occupants necessarily following or understanding instructions. It may also be harder to convey the reality of the emergency, or the danger associated, to psychiatric patients. Consequently, pre-incident training for the occupants, including practise drills, may be unfeasible. There are also potential issues with responder safety that can further complicate the processes.

2.1.2.3.4 Movement assist devices are required to evacuate PRM

It is evident from the incidents presented in this section that the challenge of assisting the evacuation of a large number of PRM is arguably the principal complication in hospital evacuation. Given the demographic shift approaching with the ageing population [73, 74], this is likely to be become a larger factor still, particularly in care homes for the elderly. The use of mobility assistance equipment is therefore vital in an emergency; it is evident that without sufficient mobility aids, staff can only improvise, for example by strapping a number of children to one backboard [43], or by giving "piggy backs" [67]. It is critical to understand how effective these devices are in the specific scenario and quantify their impact on overall evacuation performance. This would assist in hospital design, planning emergency procedures and risk assessment.

When only considering horizontal evacuation, the necessity of evacuation devices and key elements, such as the size of the external exit, may be overlooked. In the case of the Royal Marsden evacuation [59], full evacuation drills, emergency equipment testing, or computer simulation would have highlighted the issue with the revolving exit doors. Risk assessments must include the egress for PRM in movement devices in order to identify these issues and to ensure compliance with fire codes, which in the UK specify the effective width of hospital doors as 1550mm [2] for England and Wales and, similarly, 1500mm in Scotland [75]. Indeed, there is a precedent against the use of revolving doors and they have historically

contributed to fatalities in tragic fire incidents because they can cause serious crushing conditions [76].

Furthermore, these incidents reveal that currently the availability and training in the use of emergency equipment is not sufficient. In London hospitals, members of staff were using mattresses for evacuation for the first time in real incidents and have since recommended evacuation chairs at every floor [59]. However, there is no indication of how many chairs are required per patient population, nor the programme of training that will sufficiently prepare staff to use them for vertical evacuation.

The next section collates the lessons learned from these real evacuation incidents, as well as guidance provided for evacuations to identify the most influential factors to be considered in the planning of hospital evacuations.

2.1.3 Modelling Requirements of Hospital Evacuation

The previous sections have highlighted the unique set of issues that hospitals face in evacuations. Numerical and stochastic models can yield valuable insights into evacuation processes [77] and are used as part of fire safety engineering calculations to establish required safe egress times [78]. As highlighted previously, the quantification of evacuation performance is a key component of risk assessment and of egress analysis as part of performance-based design. To model (and therefore quantify) hospital evacuation, consideration must be made of the behavioural and procedural factors that influence real world performance. This was clearly borne out in the analysis of the case studies in section 2.1.2.

A number of previous reviews [14, 79], have categorized modelling requirements into the following: population, procedural, behavioural, and environmental factors. The approach adopted here is to identify these key requirements for the representation of hospital evacuations within egress models.

2.1.3.1 Population Factors

Inherently, occupants of hospitals and other health care facilities present medical needs. As a result, a wide range of conditions and capabilities can be found in these populations; clearly, the extent of individual mobility is a crucial element to evacuation strategies where movement to a place of safety is required. It is therefore critical that egress models reflect a population with diverse attributes, including those relating to movement.

The capabilities of an evacuating population are highly dependent on the type of facility they reside in. In hospitals and nursing homes, a proportion of occupants are likely to have severe physical and mental disabilities and will require the assistance of staff in order to evacuate, whereas residential homes are more likely to present age-related disabilities, and therefore will have a range of physical ability. Like hospitals, any type of residential care homes will require staff-led evacuation [62]. Staff are duty-bound to the care of their patients and the process of evacuation can be traumatic and dangerous for critically ill patients. Even evacuating patients with minor disabilities can result in significant personal consequences. For example, in 2015 more than 1000 care home residents in Cologne, Germany, were recently evacuated due to the discovery of an unexploded bomb. Management reported a "physical and emotional burden" on its residents as a result of the evacuation [80].

Patients' ability to move is dependent on their condition as well as any assistance that might be required. There are patients whose mobility is not affected by their condition, for example, outpatients visiting clinics for routine appointments are likely to mobilise as normal within a hospital setting. However, for those patients who have reduced mobility, there are a number of conditions and factors that may inform their evacuation performance. Broadly identified in this section are some categories of ambulatory capabilities and assistance requirements for PRM in hospitals, firstly differentiating between the mobility of unassisted patients and assisted patients, and then between the varying methods of assistance: manual and electric wheelchairs; one or two crutches; walking sticks and walking frames; and patients that are fully immobile.

It is noted that patients may not have a constant level of mobility (i.e. they may not fit into one distinct category). For instance, elderly people or pregnant women may have conditionally reduced mobility if, for example, they are required to walk a certain distance. Furthermore, occupants may become injured during the evacuation process, rendering them with less mobility.

The examples presented here are based on personal communication with a manager of nursing staff [81], but it is recognised that these categories represent a generalisation of the extensive range of medical conditions that can contribute to mobility impairment. The reference codes applied are for ease of comparison when associated data are investigated in section 2.2.

2.1.3.1.1 Unassisted Patients (UA) and Patients with Visual Impairments (VI)

Elderly patients and those with mobility impairments may be able to walk short distances without being assisted by physical aids or by other people. However, their walking speed will be significantly reduced in comparison to the typical adult population. For example, in elderly patients there may be a range of underlying and chronic conditions, for example heart failure, and chronic obstructive pulmonary disease (COPD), that means that they cannot overly exert themselves physically and therefore their walking speeds and distance travelled will be reduced. Patients awaiting treatment, for example those in A&E with fractures or traumas, may be able to self-evacuate in the same manner in which they arrived, but they may not achieve normal ambulant walking speeds.

Patients with an upper body injury may have otherwise normal mobility, but may be adverse to moving quickly in a crowd (for example if they had a painful injury in a sling) and may be more likely to lose balance on stairwells if they cannot use the hand rails. Other patients may have visual impairments that do not directly impede their mobility, but reduce their speeds because of wayfinding issues [82], and may be accompanied by a guide dog [82].

2.1.3.1.2 Assisted Patients (A)

Currently, 10% of people (6.5m) in the UK are classed as having a mobility disability [9], and this proportion is certainly higher in the majority of hospitals. In an evacuation, patients may use aids that they are familiar with (e.g. their own canes, crutches and wheelchairs) or those that are unfamiliar (e.g. hospital wheelchairs and evacuation devices). Some patients are assisted by another person; for example a member of staff or a visitor may assist those with mobility or cognitive impairments. For those patients that can move unassisted but with reduced speed for a certain distance, assistance by another person may improve their speed by providing minimal stability support, for example an arm to hold on to. For some evacuees, (for instance, elderly patients with chronic respiratory conditions), a sudden evacuation situation can induce anxiety that exacerbates their condition, and therefore assistance by another person may improve their evacuation performance because of encouragement.

There may also be a need for patients to be carried, for example children and babies may be carried by parents and/or hospital staff, and adults may be carried using the "fireman's lift" by emergency responders. An individual's walking speeds are reduced when carrying another person. Pedestrians walking at their own pace with additional load weights of 10%-40% of their body weight have been found to decrease their walking speed to compensate for a heavier load, therefore carrying babies, children and adults will all likely reduce an individual's walking speed [83].

2.1.3.1.3 Patients with manual wheelchairs (WC)

For patients using wheelchairs, their level of experience with wheelchair equipment is an important factor. People who regularly use a self-operated wheelchair may be able to transport themselves at their normal speeds if unimpeded by other evacuees. However, there are additional conditions (for example, respiratory or heart problems) that would significantly reduce the speed which wheelchair-users would be able to achieve. Indeed, hospital staff may prevent such patients attempting self-operated wheelchair escape.

Typically, patients that require hospital wheelchairs, but who are not regular wheelchair users, will be transported in chairs operated by hospital porters. There are a number of patients with emergency and non-emergency conditions that would require this mobility assistance; including transporting patients with broken limbs, with heart failure, in advanced labour, and those who have recently had an operation. In an evacuation, some patients may be able to self-operate the hospital wheelchair for short distances and staff members or relatives may push those that are unable to operate a wheelchair themselves.

2.1.3.1.4 Patients with electric wheelchairs (EWC)

Patients with their own electric wheelchair, for example those with paralysis, neurological conditions or amputations, may proceed with evacuation independently. These wheelchairs can be very fast while travelling on the horizontal, particularly when unimpeded. However, unless there is a specific attachment to enable vertical transportation, a further device is required to descend stairs.

2.1.3.1.5 Patients with one crutch (CR1) or two crutches (CR2)

Patients may require crutches to walk, for example after a joint replacement operation or broken limb. With sufficient physiotherapy, a patient may be adept on their crutches, but their speed depends on their experience of using them as well as their physical capability. Younger patients may be more quickly adjusted to the crutches than older patients and patients with conditions that impede their ability for physical exertion.

For patients with one crutch, the crutch is positioned on the side of the injury. Their speed when descending stairs would be reduced, and may depend on whether or not they can use the 'ideal' handrail: for example, with an injury on the right leg, the left hand rail would be ideal. For patients with two crutches, who cannot bear weight on the injured side, their walking speeds are slower still. They typically only use one crutch on the stairs, relying heavily on the handrail. Their

speed may be further impeded by carrying their second crutch at the same time, for use at the bottom of the staircase.

2.1.3.1.6 Patients with a walking stick (WS) or walking frame (WF)

Patients with a walking stick are likely to have brought it to hospital with them, and therefore may be adept with its use, although will have decreased walking speeds in both horizontal and vertical evacuation. Patients provided with walking frames, however, are likely to have less experience in using them compared to those with walking sticks.

Walking frames are given to patients if, for example, they are frail or prone to falls. Those using frames can be expected to travel slowly and perhaps in stages. There are two types of frame: one with four feet, and one with two wheels at the front and two legs at the back. Neither type of frame is deemed safe to use on stairs, and are potentially more dangerous for patients to try to use on stairs than to attempt to use the handrail alone. Patients using frames can therefore self-evacuate on the horizontal, for short distances, but will require assistance for long journeys and when descending stairs.

2.1.3.1.7 Patients who are immobile

Patients who are unconscious, seriously injured or paralysed, or mid-operation at the time of evacuation are considered immobile. They require full assistance to evacuate. It may be appropriate for some of these patients to be transferred into a wheelchair for evacuation, but some will require to be prone; for example unconscious patients and patients with multiple fractures or head injuries. For critically ill patients, there is often associated equipment that must travel with them during their evacuation. For their on-going care, staff will be required to attend to them throughout the evacuation, until they can be handed over to another medical service. The evacuation devices that can be used to transport PRM are described in the next section.

2.1.3.2 Procedural Factors

This section addresses procedural factors for consideration when modelling hospital evacuations. Although fire safety codes and associated guidance recommend evacuation procedures, in most developed countries hospital management are required to develop customised incident plans for their facilities. This is a critical aspect to the success of emergency procedures as it is evident that healthcare organisations with comprehensive evacuation plans have a significantly improved emergency response [59]. It is therefore critical that egress models can reflect the processes stipulated by emergency procedures, in order to gauge their effectiveness.

The managerial structure is an important consideration: those evacuations with explicit command structures, clear channels of communication, and identification of decision-makers conduct more efficient fire safety procedures. In addition, management should establish back-up channels of communication in advance to enable efficient cascading of information, for example: email, handheld radios, text messages to mobile phones, and websites. Crucially, management must realise that it is not the responsibility of the emergency services to decide whether to evacuate [7].

After an incident, methods of "wait and reassess" may be considered, where a hospital waits for more information before pre-emptively evacuating (e.g. after a bomb threat [84]). Horizontal evacuation is typical a staged approach adopted by hospitals while situation assessment is underway. There may be defend in place strategies for non-ambulatory/critically ill [44] until conditions deteriorate and a full evacuation is conducted [44, 67], or a procedure of delayed evacuation (including refuge [85]) may be adopted to transport PRM. It has been found that stay in place strategies are safer for occupants in high-rise evacuations as corridors and stairwells, as well as the area containing the fire, are the most dangerous during the incident [86].

For evacuating PRM, procedures can take a "micro" approach, by developing procedures specifically for PRM, or a "macro" approach in which the procedures

can be followed by all occupants [39]. The micro approach may be applicable in facilities with few PRM, for example a residential building where a buddy system can be used [87], and in a hospital to the extent that each patient is evacuated according their needs. However, the overarching plan must consider the majority of patients as PRM (or certainly, people with medical needs) and, unlike residential buildings, cannot presume occupants have been trained in their evacuation procedures.

The World Health Organisation has recently published an emergency response checklist that advocates extensive evacuation planning for hospitals, with a focus on safeguarding the continuation of patient care [88]. Therefore, management can apply triage principles (categorising and prioritising patients to provide the best care to the greatest number of patients [89]) when devising the procedure [4]. Despite careful planning in advance, deciding the sequence of an evacuation may still require a flexible approach in response to a given situation [90]; i.e. even the best preparation may need to be adapted when faced with a specific emergency scenario. There is general consensus [2, 42, 90] that in extreme emergencies the order of evacuation should be: those in immediate danger, ambulatory patients, then non-ambulatory patients. But real incidents have had varying approaches, for example, in many recent hospital evacuations, the patients evacuated first were those that require the most resources (medically, and in terms of mobility) [43, 45, 91].

Regardless of the approach adopted, arguably the greatest logistical challenge is the evacuation of PRM [85, 92] and therefore the following sections address the equipment and training challenges involved in procedures involving PRM.

2.1.3.2.1 Evacuation Equipment

Once management has developed an evacuation plan, hospitals must ensure that there is sufficient equipment in which to conduct their plan, particularly in the transportation of patients – without this, vertical evacuation would not be practical. There are a number of established means in which to transport PRM

down stairs. As categorised by Hedman [93, 94], innovative technologies have been developed, including electric wheelchairs with stair travel wheels for independent evacuation, as well as stair travel attachments that can be added to wheelchairs, and wheelchair carriers that can be used to manually transport wheelchairs and users. Other solutions include the use of lifts and inclined chairlifts. However, while some hospital occupants may have their own wheelchair for horizontal travel, it is uncommon for PRM to possess their own equipment to enable travel down stairs; therefore hospitals must provide enough evacuation equipment to facilitate vertical evacuation for these individuals. Furthermore, even if there are lifts suitable for use in emergencies in a hospital, the escape stairways must be equipped for full evacuations as the exclusive use of lifts is not sufficient for a full evacuation of a multi-storey hospital [2].

As outlined in UK hospital evacuation guidance (see Section 2.1.1.3), the stair descent devices that healthcare facilities will typically use are rescue sheets or sliders [95, 96, 97]: devices that have either a mattress or a solid board with fastening straps attached to secure a PRM and are pulled down the stairs. The former are designed to be stored under a patient's mattress for ease of access. Also encouraged in hospital evacuation regulations [2] are the use of purpose-designed evacuation chairs that have track / belt systems [98, 99, 100]. The system of continuous belts controls the chair's stair descent, working in proportion to the load it is bearing.

Rescue sheets and evacuation chairs make direct contact with the stair and are therefore either pushed or pulled by operators. Other devices that do not make contact with the stairs are designed to be carried, such as carry chairs [101, 102] and stretchers [103, 104]. For these devices, the full load is borne by the operators, which can be physically demanding, depending on the weight of the patient. Most devices are designed to bear weight up to 150kg, but specialist devices can also accommodate a maximum user weight of up to 228kg [94]. Lavender *et al.* evaluated the ergonomics of manual carried and track type devices [23] and found that compared to other carrying devices, there is a physical advantage to using an extended handle carry chair. Track type devices, such as evacuation chairs reduced

the demands on back muscles but may increase the demands on arms and shoulders. However, the fastest stair speeds were achieved with stair track devices. There are few data quantifying the performance of these devices (as discussed in section 2.3). This is a crucial issue, as the speed of movement is clearly a significant factor in an evacuation situation.

The American National Standards Institute (ANSI) and the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) published performance standards for wheelchairs in 1988 [105]. However, there are currently no equivalent standards for emergency stair travel devices. RESNA and ANSI, have begun development of a performance standard [106, 107] that will be based on devices weights, capacity, their stability for both horizontal and vertical travel, and manoeuvrability. Also specified will be the training instructions provided on the device itself. The National Institute of Standards and Technology have issued extensive guidance on the selection and use of track-type evacuation chairs [108], however performance factors of varying device types, such as speed, are not yet considered. Therefore, the literature does not effectively document the relative evacuation performance of varying designs and manufacturers.

Some procedures do not require specialist equipment: for example, the use of sheets to transport patients while lining the stairwell with mattresses [92]. However, the safety and efficiency of these methods are also not sufficiently tested.

2.1.3.2.2 Training

Staff training is a crucial performance factor in evacuations [109]. Full evacuation drills are unfeasible in healthcare facilities due to the risk to patients; therefore training must be conducted in components of evacuations, such as table top exercises, and evacuation walk-throughs. Little is known about the effectiveness of fire safety training in healthcare environments, apart from the case studies highlighting inefficiencies in practice [59, 62]. A 2008 study of hospital staff in Shiraz, Iran, [110] showed a relationship between fire safety knowledge and level of education. The same study also found a link between “job tenure” and fire safety

knowledge, although it is not clear whether this refers to total length of service, length of service in a particular facility, or some scale of seniority or job permanence.

A key component of training is in the use of evacuation equipment. Little is known about the required frequency for this training to be effective, or the ideal method of training itself. As an example, consider the experience of a handler from the WTC 9/11 evacuation: account WTC1/069/0002 [111]. The interviewee and nine other colleagues assisted a 130 kg quadriplegic male down from the 69th floor of the North Tower of the WTC using an evacuation chair. It was reported that most of the handlers had seen an instructional video on how to use the device some time prior to the event, but most had forgotten the details. It took four handlers approximately 15 minutes to transfer the PRM from the wheelchair into the device. Furthermore, four handlers were required to control the chair during the descent, two at the rear of the device and two at the front of the device. The device handlers were changed approximately every two floors making for a very slow descent. While successful, it is suggested that better training would have made this process significantly quicker and easier [111]. There is research into the types of printed signage that may encourage untrained individuals in activities such as manual lifting (i.e. a series of symbols showing sequential steps are more effective than diagrams incorporating text); however, this has not been effectively tested in a manual handling scenario for evacuation [112].

There are great advancements in technology that can potentially be applied to provide in wide-reaching and cost-effective training. Virtual reality (VR) in computer games are already being developed to provide task specific cognitive training for elderly people [113]. This kind of task-oriented training could also be used to convey evacuation procedures, and walk participants through an evacuation process without needing an actual drill. This approach could be applied to effective existing programs of fire education; for example, those tailored to the elderly [114]. Gaming and instructional videos have proven effective in nursing staff training [115] and so this type of VR training may be applied in the future to provide valuable insight into a real life simulation and highlight areas of risk [116].

Hospital staff have a large number of clinical training requirements in addition to training in emergency procedures, and limited training time [115]. This is further compounded by high staff turn-around in hospital environments [117]. More research is required to investigate whether real-life or computer training is appropriate for hospital staff, and how frequently training is required to optimise the evacuation process.

2.1.3.2.3 Simulating Evacuation Procedures

The time taken to transport patients and the time taken to evacuate the full building should be estimated, irrespective of whether the decision is based on guidance [118] or risk criteria [119]. This will enable an informed evacuation decision. This decision should take into account the available staff, exit routes, transportation, and location of care sites to send patients to [90]. Engineering hand-calculations have proven effective in some straightforward evacuations [120], but may not be as effective as computational tools in incorporating the effect of individual and emergent group behaviours, for example as a result of social influence [121].

In order to simulate specific evacuation scenarios, computational tools are calibrated to model the key factors that may affect a specific scenario. Different types of evacuations yield different evacuation phenomena; for example, people in hospitals may exhibit different behavioural patterns and walking speeds to the same people in an office building or in their homes. Simulating hospital evacuation procedures may provide insight into the effectiveness of incident planning and may support training by enabling visualisation of procedures. Crucially, models are needed to substantiate the current ideas that the evacuation sequence should either begin or end with the most critical patients [4].

2.1.3.3 Behavioural Factors

This section addresses behavioural factors for consideration when modelling hospital evacuations. While procedures may guide the process of a hospital evacuation, as with any type of evacuation outcomes depend highly on the

behaviours exhibited by individuals [122]. As such, it is an important consideration for evacuation model developers.

The behaviour of individuals in response to a fire threat is varied, and subject to complex decision-making practices. A number of studies have categorised individual decision-making processes, for example as phases of "Recognition", "Validation", Definition", "Evaluation", "Commitment", and "Reassessment" [123]; or as "Perceive Cue(s)", "Interpret Situation and Risk", "Make Decision about Action", and "Perform Action" [124]. Behaviours from real life and experimental observations can inform the development of models such as these, but the field is still in its infancy and as such the need for comprehensive behavioural theory in evacuation modelling has been highlighted [125] as our current understanding of behaviour in emergency situations is still limited [126].

Pre-evacuation time is known to influence evacuation outcomes; it is classified as the time spent by the occupant before starting to evacuate, given that the alarm has been raised. According to Gwynne *et al.* [71], behavioural factors in pre-movement times typically include the perception of the incident; the perception of the seriousness of the incident; the disengagement of the individual from their current activity; the collection of goods; the investigation of the incident; and the fleeing from the scene. However, during an unannounced hospital evacuation drill all patients waited for instruction before evacuating [71]. This accords with real life fire incidents that find that, in a hospital setting, patients are highly reliant on staff to evacuate [39, 61]. Additionally, unlike those in residential buildings, hospital occupants may not have previous building knowledge so the behaviours of those perceived to be "leaders" will be particularly important [127] . While much human behaviour literature points to peoples' use of familiar exits or time-dependant information [128], it has been found that in public areas, people will be highly influenced by the staff directing them [129]. Therefore, the behaviour of nursing staff has a vital impact on the responses of outpatients before an evacuation occurs. This makes the design, training, and adherence to procedure important factors. Studies of human behaviour in health care facilities indicate that

evacuation roles are performed by staff regardless of high degrees of personal risk [123].

In addition to pre-evacuation behaviours observed in evacuations from buildings, for example: investigating the incident, finishing phone calls, putting on coats, finding relatives, and gathering belongings [123]; there are a number of further behavioural issues in healthcare environments. For example, there are evacuation issues perceived by those with disabilities: Bengston *et al.* [130] found that a focus group of wheelchair users have experienced issues with evacuation pre-planning, staff training and the communication of information before and during evacuations. There are also a number of conditions, for example dementia or learning disabilities, that restrict the decision-making capabilities of patients [61, 131]. While these patients may be able to move freely, they require instruction and assistance.

Unlike most other public buildings, there is the consideration of clothing in pre-evacuation times, compounded by the effects of illness, sedation, and injury. There may be further implications for more specific clothing requirements; for example, Almejmaj *et al.* [132] are investigating the potential extra time required for Saudi Arabian women to construct their abaya before evacuating.

Notification is also a key issue. Notification can affect their evacuee performance, particularly in their perception of the seriousness of a situation [133]. In a hospital staff are typically responsible for notifying their patients of the procedures during an incident, but various automated systems can be also used to alert visually and auditory-impaired people [39]. Standardised sounds and temporal patterns across healthcare institutions may increase the patients understanding in these settings [134]

Evacuee behaviour is typically seen in relation to a social collective [127]. In hospitals there are key staff-patient interactions as well as patient-patient and staff-staff interactions that underpin the collective. Cooperative behaviours, for example those that are undertaken in groups, can therefore affect the performance

of an evacuation. Indeed, the movement of family units and the movement of children are likely to have an impact on performance [135, 136]. While staff may be engaged in urgent medical tasks to complete before evacuation, patient evacuees will need to be prepared to ensure their safe evacuation, and may also pursue personal objectives; for example, gathering belongings or using the toilets. Some types of activities (e.g. getting dressed) may be more prevalent at night-time. Certainly, lower staffing levels at night may prolong the detection phase and staff ability to ready and evacuate patients [137]. The number of staff will also impact individual staff members' levels of fatigue as repeated collection of patients is undertaken, although the physical impact of repeated patient collection is not well understood [25, 85].

2.1.3.4 Environmental Factors

This section addresses environmental factors for consideration when modelling hospital evacuations. Health care facilities and care homes have a proportionally high number of fire incidents per year [48]. For fire safety engineering considerations, these buildings can be particularly complex due to: varying combinations of building types (e.g. legacy and modern); ignition sources such as lasers and cautery units; oxygen rich environments that can promote the spread of fire; and sterile environments (such as intensive care) that require specialist fire equipment [137].

The Fire Protection Research Foundation found that the expected increase in the proportion of disabled people requires an increase in fire protection over the next 25 years [138]. The use of sprinklers may be increased in buildings with PRM; for example, recent incidents in Ontario, Canada, [57] have led to discussions about making automatic sprinklers mandatory in buildings of this nature [139]. However, in critical healthcare environments, this is a complex engineering decision because of areas with sensitive equipment [137].

The environment has a number of implications for evacuation. Firstly, there are areas with very different functions [40, 42]: laboratories, mechanical rooms,

operating rooms, emergency department, clinics and patient rooms, facility services and maintenance areas. Other staff areas, such as the administration department and pharmacy should be able to self-evacuate, but may have patients in there with them, or disabled staff. Furthermore, the structure may have a series of locked doors for security, or bars on windows [61, 140]. Investigation has begun on building environment improvements to aid evacuation [85], for example: evacuation elevators may be useful for those with disabilities, as would sky-bridges (horizontal egress at height) and refuge floors, although there are concerns that these may not be used as designed, or be cost effective.

The use of emergency lifts may become a key part of hospital evacuation. New innovations in lift machinery (without counterweights) enable larger lift carriages and therefore improve access for beds and other devices [141]. However, work must be undertaken to ensure that the historical view of elevators being unsafe in a fire is overturned for lift strategies to become effective, and that information provided must be carefully considered, particularly for those with disabilities [142].

Also included in the environment are beds, trolleys, specialist equipment and other obstacles. It has been demonstrated that these kind of obstacles can impact evacuation flow [143], therefore, to model these types of environments, a flexible approach is required, including the functionality to specify the layout and furniture in the setting; the ability to represent an incident developing, the inclusion of locked and unlocked doors; and the ability to specify evacuation devices.

2.1.3.5 Summary of factors

This section has demonstrated how the population, procedural, behavioural and environmental factors influence real world hospital evacuation performance. In order for a model to reflect these specified considerations for hospital evacuation, it is proposed that functionality is required as presented in Table 2-1.

Table 2-1: Required model functionality for hospital evacuations

Hospital Evacuation Consideration	Required model functionality
Population (section 2.1.3.1): Hospitals contain a diverse range of people with varying attributes, conditions and capabilities.	• The ability to represent a varied population, including: staff, assisted and unassisted patients, elderly people and children. • The ability to represent individual attributes such as age, height, weight, walking speeds and stair speeds.
Procedural (section 2.1.3.2): Hospitals employ complex procedures that are conditional on the extent of the danger present, as well as the needs of the occupants. The use of emergency equipment is critical to the success of an evacuation.	• The ability to construct scenarios to represent evacuation procedures, including the time taken to prepare patients. • The ability to represent repeated patient collection. • The ability to closely scrutinise scenarios and the individual actions of agents in order to analyse and compare the effectiveness of different procedures. • The ability to model the emergency equipment used in hospital evacuations.
Behavioural (section 2.1.3.3): As part of an evacuation, staff engage in a number of activities including patient preparation and repeated collection and triage. Patient-staff interaction and group behaviours are exhibited.	• The ability to represent individual behaviours • The ability to represent group behaviours. • The ability to assign tasks to staff members, including the time taken to prepare patients for evacuation. • The ability to represent fatigue as staff repeatedly evacuate patients.
Environmental (2.1.3.4): Hospitals have a complex layout with many beds, furniture and equipment. An incident may develop over time prompting full evacuation. There may be locked doors, and emergency lifts.	• The functionality to specify the layout and furniture in the hospital setting. • The ability to represent an incident developing. • The inclusion of locked and unlocked doors. • The ability to represent the use of evacuation lifts.

The following sections reviews current evacuation models and their ability to simulate the requirements outlined in Table 2-1; i.e. to determine whether they have sufficient functionality to represent hospital evacuations without considerable user intervention.

2.2 Hospital Evacuation Simulation Review

This section discusses evacuation simulation methodology and the models currently available, comparing them with the modelling requirements of hospital evacuations. 27 computational models are reviewed according to categories

established in model reviews [14], and their suitability to the task of simulation hospital evacuation is discussed.

In the past 40 years, a number of computational evacuation models have been developed in order to quantify egress performance. Their methodologies range greatly and the selection of these methodologies were largely informed by their modelling objectives. For example, “ball-bearing” non-behavioural models may be useful for measuring the optimal evacuation of premises; whereas agent based models that simulate some individual agency, can enable a more realistic and detailed investigation of the impact of behaviour on evacuation processes [144]. Models can be crudely categorised into macroscopic and microscopic models. Macroscopic models simplify underlying factors (population, geometry description, etc.) to focus on the eventual outcome of a simulation; e.g. the overall evacuation time. Microscopic models represent the underlying factors in more detail attempting to represent the intermediate and eventual outcomes and their relationship with the underlying factors; e.g. the time for individual agents to evacuate, the interaction between evacuees and the structure, etc.

A key consideration in all models is the decomposition of space, i.e. the geometric environment that governs route selection and availability. So-called ‘macroscopic’ models typically decompose space coarsely (grouping agents or areas together within a large grid), whereas ‘microscopic’ models typically decompose space finely (agents are represented individually on a small grid) or continuously (agents move individually on a continuous plane). Within the microscopic models, the complexity of the rules that govern agent movement and behaviour vary: some represent basic cellular automata, where agents select paths based on a single goal [145]; whereas others incorporate sophisticated behavioural models [16, 146].

The extent to which evacuating agents have been represented in models (i.e. microscopic or macroscopic; behavioural or non-behavioural) has been informed to an extent by computational speed and power, and for this reason some models apply more than one approach [147], adopting a hybrid approach. In recent years, escalating computational capability (e.g. parallel processing [148]) alongside key

developments in models using microscopic approaches (i.e. more efficient movement algorithms used in conjunction with fine and continuous networks), have enabled the more intricate representation of agent behaviour in evacuation models.

Studies have shown considerable differences between the performances of various models [149, 150, 151], and it has been found that different egress scenarios have different determining factors that contribute to their evacuation performance [152]. In any case, assumptions made by model developers can significantly change the outcomes of the simulations; for example, the shape of assumed travel path can significantly influence any subsequent speed calculations [153]. Sophisticated models are unlikely to be appropriately applied "out-of-the-box" [154], and so reputable model developers provide extensive instruction and training in their software to engage users in appropriate use [16, 146]. This required level of understanding is likely to be one of the reasons why professional model users tend to stick to one piece of software [155].

While formal regulation does not currently govern these computational models, systematic reviews have begun to categorise them. Gwynne *et al.* [79, 156] conducted the first systematic review in 1997, where 22 models were classified according to their methodology. Those models that primarily considered evacuation as a homogenous, efficient flow were termed as "Optimization" models; those that in some way represented individual decision-making in evacuations were termed as "Simulation" models; and those that quantify the risk of emergency incidents by identifying the likelihood of hazards were termed as "Risk Assessment" models. Also categorised in this review was each models' decomposition of space into fine and coarse networks, and the global or individual perception of agents. Models were also considered in terms of their behavioural representation, based on agent-agent , the agent-environment and the agent-structure interactions.

Building upon the original review, a number of subsequent reviews incorporated new methodologies and new evacuation software. Santos and Aguirre [157]

reviewed models in 2004 within broad categories: “flow”, “cellular automata”, “agent-based” and “activity based”. The final category was introduced for models such as EXODUS [158] that had developed itinerary functionality to enable agents to engage in task-driven behaviours before and during evacuations. Castle [159] produced guidelines in 2007 for assessing models based on: availability, purpose, nature, geometric representations, perspective, movement, behaviour, validation, and support. Incorporating each of these considerations, Kuligowski *et al.* [14] reviewed 26 egress models in 2010, categorising them according to their features, purposes and capabilities. This represents the most current review of models used to date and this established comparative criteria between egress models and has formed the basis of the most recent guide for users when selecting an egress model depending on scenario [160].

It is evident from the latest literature that work undertaken to validate models is not consistent among the fire safety community. In the field of maritime evacuation, projects such as SAFEGUARD [161] have provided data and methodology for systematic validation in the maritime environment. However, no definitive standards have been agreed in the built environment, although guidance documents provide examples and address the associated issues (e.g. ISO/TR 16730-5:2013 [162]). Therefore, work is underway to standardise the validation criteria for building evacuation models. In 2013 NIST [163] proposed a set of tests for verification of models, alongside suggestions for validation methodology. This proposed that model functionality is assessed in terms of pre-evacuation time; movement and navigation; exit usage; route availability; and flow constraints. Following this report Lubaś *et al.* [164] proposed extensions to some of the NIST verification tests and suggested that differentiation be made between basic tests and extended tests. This implies a hierarchy in the importance of certain factors which, for example, categorizes test for representation of disabled evacuation as an extension to the basic tests for evacuation models. This is discussed further in section 2.2.4.

For hospital evacuation, a range of factors, as identified in the previous section, can influence the evacuation process. It is therefore essential, when simulating

evacuation from hospital, that the model used has certain characteristics (e.g. the ability to identify and modify agents walking speed based on their mobility is required to model those with reduced mobility [156]). Evacuation modellers have noted the importance of including PRM, e.g. EvacuationNZ [165] and STEPS [20] are investigating the inclusion of wheelchair users. However, the use of movement devices in hospitals is not yet explicitly represented.

The following section investigates the current model types based on the latest criteria proposed by Kuligowski and Peacock [14], updating to include new models [166]. It then explores the characteristics required in order to simulate hospital evacuation, and reviews the current capabilities and limitations of computational egress tools for this purpose.

2.2.1 Typology

This section looks at the model features required to simulate hospital evacuation, based on the factors identified in the previous section. The models included in this review are those with peer-reviewed methodology, which can simulate building evacuations, i.e. transport-only models are omitted. Furthermore, models with currently limited methodological discussion in the literature are discussed separately: Christensen and Sasaki [18], Brunnhuber *et al.* [167], Johnson [137], Taaffe *et al.* [168], Uehara and Takenaka [169], and Notake *et al.* [170].

The 27 models considered for review are: ALLSAFE [171], ASERI [172], buildingEXODUS [26], DBES [166], EPT [173], EVACNET 4 [171], CRISP [174, 175], EGRESS [176], EvacuationNZ [165, 177], EXIT89 [178], FDS+Evac [179], GridFlow [180], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], Pathfinder [184], PedGo [185], PEDFLOW [186], PEDROUTE [187], Simulex [146], Wayout [188], SGEM [189], Simwalk [190], SpaceSensor [191], and STEPS [20].

These models are considered for their suitability in simulating hospital evacuation according to the following criteria proposed by Kuligowski and Peacock [14]: the grid and structure; the perspective of the model and occupant; the behavioural

model employed; the ability for evacuation counterflow; the representation of group behaviours; the representation of disabled/slow occupants; the delays and pre-evacuation times used; and the use of lifts. As presented in Table 2-2, these categories map to the required functionality established in section 2.1.3.5, with the exception of a category for vertical evacuation equipment. A category for this has therefore been added to those explored in this section, as its inclusion in a hospital evacuation model is an important aspect to represent.

Table 2-2: Categories of evacuation model functionality and required hospital evacuation model functionality

Kuligowski [14] ***Categories***	***Required hospital evacuation model functionality***
Grid Structure	→ The functionality to specify the layout and furniture in the hospital setting. → The ability to represent an incident developing. → The inclusion of locked and unlocked doors.
Perspective of Model/Occupant	→ The ability to closely scrutinise scenarios and the individual actions of agents in order to analyse and compare the effectiveness of different procedures.
Behaviour	→ The ability to represent individual behaviours → The ability to represent individual attributes such as age, height, weight, walking speeds and stair speeds. → The ability to assign tasks to staff members, including the time taken to prepare patients for evacuation. → The ability to represent fatigue as staff repeatedly evacuate patients.
Counterflow	→ The ability to represent repeated patient collection.
Groups	→ The ability to represent group behaviours.
Disabled/Slow Occupants	→ The ability to represent a varied population, including: staff, assisted and unassisted patients, elderly people and children.
Delays/Pre-evacuation Times	→ The ability to construct scenarios to represent evacuation procedures, including the time taken to prepare patients.
Use of Lifts	→ The ability to represent the use of evacuation lifts.
Additional category	***Required hospital evacuation model functionality***
Vertical Evacuation Equipment	→ The ability to model the emergency equipment used in hospital evacuations.

2.2.1.1 Grid/Structure

There are approaches to modelling the building structure: fine grid networks in which individual agents move from node to node; coarse networks where larger

portions of the geometry, for example rooms and corridors, are occupied by multiple agents at the same time; and continuous networks in which agents move on a continuous, e.g. Cartesian, plane. Some models adopt a combination of these modes. It is proposed here that models that can only represent coarse networks are not appropriate for modelling hospital evacuation. As established in section 2.1.3.5, the dynamics in a hospital are highly reliant on staff-patient interactions and complex procedures. The actions of individuals are crucial to the progression of an evacuation in this environment, and thus require explicit representation in a model. Those models that utilise a course grid therefore may not be suitable for complex individual actions present in hospital evacuations: ALLSAFE [171], DBES [166], EVACNET 4 [171], EvacuationNZ [177], EXIT89 [178], PEDROUTE [187], and Wayout [188]. Models that have a fine or continuous grid have the potential to more explicitly represent individual actions: ASERI [172], buildingEXODUS [26], EPT [173], CRISP [174, 175], EGRESS [176], FDS+Evac [179], GridFlow [180], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], Pathfinder [184], PedGo [185], PEDFLOW [186], Simulex [146], SGEM [189], Simwalk [190], SpaceSensor [191], STEPS [20].

2.2.1.2 Perspective of the Model/Occupant

This category describes the representation of the occupant population. Models that have an individual perspective identify the movement and actions of individual agents in the evacuation simulation; models that have a global perspective do not track individual movement, but rather focus on global outcomes. It is proposed that the models with individual perspective will satisfactorily enable users to scrutinise scenario outcomes based on individual actions. It was also shown in section 2.1.3 that there is considerable variety in the building knowledge of evacuees in hospitals, given their personal attributes and role; therefore, individual behaviours and tasks are key to the process of hospital evacuation. Models that assume global knowledge (i.e. a shared knowledge of exits) are therefore not ideal for modelling the various movements resulting from individuals' varying hospital knowledge, i.e. ALLSAFE [171], EVACNET 4 [171], PEDROUTE [187], and Wayout [188]. Those models that specify individual

perspectives have the potential to simulate hospital evacuations: i.e. ASERI [172], buildingEXODUS [26], DBES [166], EPT [173], CRISP [174, 175], EGRESS [176], EvacuationNZ [165, 177], EXIT89 [178], FDS+Evac [179], GridFlow [180], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], Pathfinder [184], PedGo [185], PEDFLOW [186], Simulex [146], SGEM [189], Simwalk [190], SpaceSensor [191], and STEPS [20].

2.2.1.3 Behaviour

The behaviours of occupants within hospitals in response to emergencies are key to the outcome of evacuations. Behavioural responses are diverse and not uniform across the building or compartments. Therefore, assuming a uniform response excludes a previously identified factor in the outcome of hospital evacuations. The ability to forecast or assign tasks to occupants (for example, for repeated assisted patient collection), is therefore essential in modelling the evacuation process in hospitals. Models should be able to incorporate the complex staff and patient interactions and associated behaviours in order to simulate hospital evacuation. The following evacuation models do not currently have the functionality to model these types of task-led behaviour: EVACNET 4 [171], Pathfinder [184], Wayout [188]. The models that do have the potential to represent these types of behaviours: ALLSAFE [171], ASERI [172],buildingEXODUS [26], DBES [166], EPT [173], CRISP [174, 175], EGRESS [176] EvacuationNZ [165, 177], EXIT89 [178], FDS+Evac [179], GridFlow [180], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], PedGo [185], PEDFLOW [186], PEDROUTE [187], Simulex [146], SGEM [189], Simwalk [190], SpaceSensor [191], and STEPS [20].

2.2.1.4 Counterflow

Some models have the facility for agents to be able to move against the flow of evacuating populations. In hospital evacuation, staff must be able to repeatedly assist patients and this process of collection and return requires the model functionality to allow travel against the flow of evacuations if necessary. Furthermore, scenarios including emergency services entering the building require the ability for new agents to access, and move within, the building contra

to the evacuating agents. Models that preclude the representation of this movement include: ALLSAFE [171], EVACNET 4 [171], EvacuationNZ [177], Pathfinder [184], PEDROUTE [187], SpaceSensor [191], and Wayout [188]. Those models have the potential to represent counterflow are: ASERI [172], buildingEXODUS [26], DBES [166], EPT [173], CRISP [174, 175], EGRESS [176], EXIT89 [178], FDS+Evac [179], GridFlow [180], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], PedGo [185], PEDFLOW [186], Simulex [146], SGEM [189], Simwalk [190], and STEPS [20].

2.2.1.5 Groups

Some models are able to represent the sensitivity of evacuating agents to those around them. The representation of hospital-assisted evacuation requires the ability for agents to group with other agents for some duration during the simulation. Furthermore, patients and families are likely to form groups during an evacuation [192]. Models that cannot represent group movement, and which may not be appropriate for modelling assisted evacuation, include: (EVACNET 4 [171], EXIT89 [178], FDS+Evac [179], GridFlow [180], Pathfinder [184], SGEM [189], SpaceSensor [191], and Wayout [188]). Those models that have the potential to represent group behaviours include: ALLSAFE [171], ASERI [172], buildingEXODUS [26], DBES [166], EPT [173], CRISP [174, 175], EGRESS [176], EvacuationNZ [165, 177], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], PedGo [185], PEDFLOW [186], PEDROUTE [187], Simulex [146], Simwalk [190], and STEPS [20].

2.2.1.6 Disabled/Slow Occupants

This category represents the ability for a model to represent disabled or slow agents, typically set by the user at the beginning of the simulation. Given hospital demographics, it is essential that models can represent those with a wide range of mobility impairments. Also included is the representation of wheelchairs, as they may be represented by reduction in agent speed. Models that are not able to represent such varied occupant movement: ALLSAFE [171], EVACNET 4 [171], Pathfinder [184], SpaceSensor [191], and Wayout [188]. Those that may represent

disabled occupants include: ASERI [172], buildingEXODUS [26], DBES [166], EPT [173], CRISP [174, 175], EGRESS [176], EvacuationNZ [165, 177], EXIT89 [178], FDS+Evac [179], GridFlow [180], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], PedGo [185], PEDFLOW [186], PEDROUTE [187], Simulex [146], SGEM [189], Simwalk [190], and STEPS [20].

2.2.1.7 Delays/Pre-evacuation Times

Pre-evacuation times have been shown to be an important factor in the evacuation process. This is as true in hospital evacuations as in other types of occupancy. Therefore, the ability to assign this as a delay is an important factor in simulating hospital evacuation. For patients that must be evacuated with an assist device, it is also important that a delay is assigned to represent the time taken to secure a patient into the device. Furthermore, other delays associated with medical interventions may be required during the evacuation process. Therefore, hospital evacuation models must be able to designate delays as part of a simulation. Those models that do not have delay functionality include: EVACNET 4 [171], Pathfinder [184], and SpaceSensor [191]. Those models that can represent a delay to some extent include: ALLSAFE [171], ASERI [172], buildingEXODUS [26], DBES [166], EPT [173], CRISP [174, 175], EGRESS [176], EvacuationNZ [165, 177], EXIT89 [178], FDS+Evac [179], GridFlow [180], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], PedGo [185], PEDFLOW [186], PEDROUTE [187], Simulex [146], Wayout [188], SGEM [189], Simwalk [190], and STEPS [20].

2.2.1.8 Use of lifts

High-rise hospitals are increasingly using lifts as part of their procedures in line with recent and expected changes in governing regulations. While many procedures can be modelled on the horizontal, to fully capture the process of high-rise hospital evacuations, a lift model within the simulation is required, in addition to vertical evacuation methods. Most models do not include lifts functionality: ALLSAFE [171], ASERI [172], CRISP [174, 175], EGRESS [176], EvacuationNZ [177], EXIT89 [178], FDS+Evac [179], GridFlow [180], MassEgress [182], Pathfinder [184], PedGo [185], PEDROUTE [187], Simulex [146], and Wayout [188]. The

following models can simulate lifts: buildingEXODUS [26], DBES [166], EPT [173], EVACNET 4 [171], Legion [181], MassMotion [183], Myriad II [123], PEDFLOW [186], SGEM [189], Simwalk [190], SpaceSensor [191], and STEPS [20].

2.2.1.9 Vertical Evacuation Equipment

Among the most important factors that clearly differentiate hospital evacuation from other types of building evacuation are the complex physical and medical requirements of the evacuating occupants. Staff members are required to ensure the safe evacuation of patients with reduced mobility, and therefore the use of assist devices is necessary for movement along horizontal routes, as well as in the instance of stair evacuation. Currently, one model contains an explicit representation of a chair device: ASERI [172]. The other models are yet to develop such functionality: ALLSAFE [171], buildingEXODUS [26], DBES [166], EPT [173], EVACNET 4 [171], CRISP [174, 175], EGRESS [176], EvacuationNZ [165, 177], EXIT89 [178], FDS+Evac [179], GridFlow [180], Legion [181], MassEgress [182], MassMotion [183], Myriad II [123], Pathfinder [184], PedGo [185], PEDFLOW [186], PEDROUTE [187], Simulex [146], Wayout [188], SGEM [189], Simwalk [190], SpaceSensor [191], and STEPS [20].

2.2.1.10 Other factors

Kuligowski [14] identified a number of other features in which to categorise evacuation models that are not included in this analysis. These represent important model attributes; however, unlike those explored previously in this section, they do not directly enable or inhibit the modelling of hospital evacuations. These include: model availability, inclusion of fire models, CAD enabled, and visualisation attributes.

2.2.2 Review of simulation models

There are a growing number of evacuation models available today that may be used to simulate evacuation from hospitals and comparable structures. Using comparative methods, fitness for purpose can be established for such an

application [14, 79]. Considering the factors outlined in the previous section as criteria for hospital evacuation modelling, Table 2-3 presents those models that do fulfil the required features at the time of publication.

Table 2-3: Evacuation model functionality for simulating hospital evacuations

	Grid/ Structure	Perspective	Behaviour	Counterflow	Groups	Disabled Occupants	Delays	Lifts	Evacuation Devices
ALLSAFE [171]			✓		✓		✓		
ASERI [172]	✓	✓	✓	✓	✓	✓	✓		✓
buildingEXODUS [26]	✓	✓	✓	✓	✓	✓	✓	✓	
CRISP [174, 175]	✓	✓	✓	✓	✓	✓	✓		
DBES [166]		✓	✓	✓	✓	✓	✓	✓	
EGRESS [176]	✓	✓	✓	✓	✓	✓	✓		
EPT [173]	✓	✓	✓	✓	✓	✓	✓	✓	
EVACNET 4 [171]								✓	
EvacuationNZ [177]		✓	✓		✓	✓	✓		
EXIT89 [178]		✓	✓	✓		✓	✓		
FDS+Evac [179]	✓	✓	✓	✓		✓	✓		
GridFlow [180]	✓	✓	✓	✓		✓	✓		
Legion [181]	✓	✓	✓	✓	✓	✓	✓	✓	
MassEgress [182]	✓	✓	✓	✓	✓	✓	✓		
MassMotion [183]	✓	✓	✓	✓	✓	✓	✓	✓	
Myriad II [123]	✓	✓	✓	✓	✓	✓	✓	✓	
Pathfinder [184]	✓	✓							
PedGo [185]	✓	✓	✓	✓	✓	✓	✓		
PEDROUTE [187]			✓		✓	✓	✓		
PEDFLOW [186]	✓	✓	✓	✓	✓	✓	✓	✓	
SGEM [189]	✓	✓	✓	✓		✓	✓	✓	
Simulex [146]	✓	✓	✓	✓	✓	✓	✓		
Simwalk [190]	✓	✓	✓	✓	✓	✓	✓	✓	
SpaceSensor [191]	✓	✓	✓					✓	
STEPS [15]	✓	✓	✓	✓	✓	✓	✓	✓	
Wayout [188]							✓		

Clearly, a number of models have the majority of functionality to represent the basics of hospital evacuation: they have a fine or continuous grid; represent individual agents; have representative behavioural models; can reflect varied travel speeds, pre-evacuation and delay times; and have rudimentary lift models. These include buildingEXODUS [26], EPT [173], Legion [181], Myriad II [123],

PEDFLOW [186], Simwalk [190], and STEPS [20]. A number of these models have taken steps to represent the assistance of PRM, as discussed in the next section.

2.2.3 Simulating hospital evacuation processes: current work and limitations

Discussed in this section are models that have attempted to represent hospital evacuation processes, particularly patient collection. As identified in Table 2-1, several models (e.g. FDS+evac [193]), reduce the speeds of their elderly agents, those with reduced mobility, and wheelchair users, based on data [17] in the literature. However, the larger footprint of the horizontal devices are typically not reflected and subsequently nor is their impact on the performance of those around the device.

buildingEXODUS [26] functionality was used to represent horizontal evacuation – picking up patients and moving them to muster locations and the progressively out of the building [194]. However, it did not include the preparation time required for the patients or reliable data concerning transport speeds for the staff-patient combinations, or staff fatigue functions, etc. These features would contribute to a more realistic simulation [194].

STEPS [15, 20, 195, 196] software decomposes space into planes and unidirectional paths. Individual agents move towards target points (e.g. towards exits, or areas in which they will be fulfilling a task). Stochastic decision making is employed for conflict resolution, for example when two agents are competing for the same space. Pre-evacuation times can be utilised as well as attributes such as patience, age and gender (and associated speeds), and group association. Agents have an individual view, i.e. they are aware of local checkpoints and exits, but do not have a global view of the system. STEPS has a 3D representation of wheelchair, people with backpacks and trolleys etc. However, this larger space and shape is not represented within the model beyond a reduction in speeds.

SimWalk [19, 190] applies a social force model to impose targets and minimum distances. This kind of model [197] subscribes to the notion that pedestrian movement can be simulated by measuring changing social motivations within

individual agents. Three forces are typically considered: agents' acceleration towards a velocity of motion based upon their personal attributes, agents' distance from boundaries and other agents based on external conditions and personal attributes; and the attractive and repulsive effects of social stimuli according to an individual's motivation. Vectors are used to represent the direction and magnitude of these forces and therefore emergent crowd behaviour can be observed from this Newtonian approach [198]. However, complex behaviour in evacuation is not well represented in this way. Staff/patient interaction, for example, in hospitals and other care facilities is an integral factor in the evacuation dynamics. Social force modelling has begun to account for group behaviours (e.g. the empirical formations of groups of two and three can be modelled using social forces determined by the density surrounding a group [199]) but cannot represent the cyclic and continuous patterns of patient collection. It can represent a number of "handicaps and accessories": backpack, cane, crutches, handcart, shopping bag, suitcase, and wheelchair. No stair device or bed is defined, and it is not clear from published literature whether the physical size of the additional accessories are represented explicitly.

Microscopic evacuation model ASERI [200] depicts wheelchair users as circular objects (larger agents) with a max speed of 0.9m/s horizontally and 0.3 m/s vertically assisted. Pushed wheelchairs are represented by two circles, and the assistance on the stairs is three circles, unlike the human shaped representation of other agents. The model demonstrates the ability to model a wheelchair being carried down the stairs, modelled as a series of three circles. The shapes are static; i.e. surrounding agents have no interactive properties with the wheelchair in the evacuation flow. While a circular representation of a device may reasonably occupy the space required for a wheelchair, the circular shape specification significantly restricts the ability to represent different devices. For example, a wheelchair and an evacuation chair may have similar width but differing depth and therefore their comparative size may not be well represented by a collection of circular shapes. Furthermore, large devices such as beds or stretchers have an elongated shape: therefore a circular shape may take up the required area, but the rectangular shape itself is not fully represented.

NIST [163] suggested a verification test for models that include disabled people in which a wheelchair user is represented. This is only deemed appropriate in models that allow agents of non-uniform sizes (i.e. they can be specified as occupying larger areas to represent movement devices such as wheelchairs). In the test (Verif2.10), the path to an exit is defined as two rooms connected by a ramp that is 1.5m wide. A scenario is devised where a wheelchair user is among the evacuating population, travelling at reduced speeds and the larger area of the wheelchair will block the ramp. This is compared to a scenario with no disabled occupants to verify the impact of the slower speed and the ramp blockage. In their analysis of the NIST verification tests Lubaś *et al.* [164] proposed that the disabled movement test should be specified more precisely and that it should not be included as part of the basic verification tests, but instead should be categorized under "extended tests for specialized models". This implies models should be verifiable without demonstrable capabilities to represent disabled population. Given the projected population demographics that include greatly increased numbers of elderly and disabled building occupants, this recommendation is not consistent with the expected requirements for future evacuation simulation. Crucially there are no equivalent standards for the representation of evacuation stair devices.

2.2.3.1 Other models

The following models have been developed in recent years and as such the literature does not detail enough methodology for a category-based review as per the last section. Outlined here is an overview of their capabilities according to the latest literature.

BUMMPEE [18] is an agent-based model that specifically addresses the need to include a heterogeneous population in an evacuation simulation. Included are seven categories of individual impairments and includes both a motorised wheelchair and manual wheelchair users. Impairments are represented by a reduction in speeds, and the size of these larger devices are accounted for in the model. Exitus [201] is another agent-based model, based on BUMMPEE [202], that

can represent disabilities, and assisted evacuation, but not the presence of vertical stair devices.

As part of the MASIMO project [167] work has been undertaken to model the cognitive process of elderly and handicapped people in wayfinding, asserting that extant evacuation tools have not yet adequately represented these specific cognitive functions. Using trials in which people talked through live decision-making, wayfinding data were collected for one station environment and reproduced in a 3D environment. Future work plans to couple an agent-based pedestrian model with the visual/cognitive model, however stair descent devices are not included.

A numerical model was developed by Taaffe *et al.* [168] to derive approximate evacuation time in hospitals by aggregating into a stochastic delay the time to prepare patients for movement, processing paperwork for moving them to another facility, and movement to a first floor staging area. Focussing more on the planned, not emergency, movement of patients to sheltering facilities in the area, this model numerically approximated the times taken. Later versions incorporated the time taken to transport patients to sheltering facilities, using buses, vans and an ambulance [203]. Duanmu *et al.* [204] also modelled the traffic interaction between hospital evacuation and communitywide evacuation, finding that the travel times are subject to congestion during an external incident, i.e. a hurricane. There are also optimisation-based models [205] that measure the effectiveness of evacuations in terms of cost, clearance time and patient risk. However, these are deterministic approaches and do not represent the evacuation explicitly.

Uehara and Takenaka [169] and Notake *et al.* [170] have recently developed assisted evacuation systems in which wheelchair users, stretchers, and person-led assistance of patients are represented on the horizontal, or on the vertical in lifts. Reduced speeds were used for those evacuating with assistance, but it is not clear whether the devices were explicitly represented in the model, i.e. if they occupied the associated space.

The Glasgow Hospital Evacuation Simulator [137] used Monte Carlo techniques to calculate the time taken to horizontally evacuate a hospital. Using reports and experimental data, the developers allocated speed and delay distributions to individual patients and nurses. The evacuation process followed a pre-described order, and the associated time of each patient collection on the horizontal summed to the total evacuation time. Beds and wheelchairs are explicitly represented, although it is not clear how any conflict resolution occurs in multiple evacuation of the same path, nor whether the results are validated against data. No vertical evacuation of PRM was explored in this study.

2.2.4 Summary

As described in this section, a number of model developers have included valuable functionality toward hospital evacuation. Several current models provide sufficient functionality to directly represent a simplified hospital evacuation or allow the user to manually configure agent performance to indirectly represent a simplified hospital evacuation. However, none of the current models are capable of representing all of the key factors that directly and significantly influence the outcome of a hospital evacuation. A key shortfall in current model functionality is the ability to explicitly represent the use of stair evacuation devices during hospital evacuations. Several models now include wheelchair devices [15, 18, 19, 20], using current data; i.e. the models represent the reduced travel speed adopted by someone using a wheelchair [17]. However, these models are not able to represent the shape and increased footprint of such a device, and the impact that it might have on navigation, manoeuvrability, speed, and on the movement of the adjacent population. Although several models may allow the user to approximate the reduction in travel speed of evacuees using movement devices or directly represent the reduction in travel speed once the device has been assumed, no model is able to fully represent the impact that such devices might have on the evacuation. Understanding this impact has been shown to be key in assessing the effectiveness of a procedure (or a device) in moving vulnerable populations to safety.

An extensive and explicit stair device model is required to fully represent the use of these devices in evacuation simulations. To support the development of models to include movement devices such as stretcher, evacuation chairs, carry chairs and rescue sheets, more data are required. The next section explores the current data available to support these model developments.

2.3 Available Data

As investigated in section 2.1.2, real incident reports outline the key timings of emergency events, but do not typically detail sufficient evacuation data to determine how long it took individuals or groups to evacuate. Without intricate detail, it is not clear why there are great differences between the time taken to evacuate various premises. For example, in the Royal Marsden incident, it took 28 minutes to evacuate 78 inpatients, and in Northwick Park 123 patients were evacuated in 23 minutes, but again it is not clear about the number of staff, the number of PRM, the distances travelled, or the starting positions [59]. In Rosepark Nursing home, it took two nurses and four fire fighters to evacuate 23 elderly patients in 27 minutes [62]. After the tropical storm Allison, it took 31 hours for the transfer of 406 patients from a ten storey hospital with flood damage and in the Veteran's Affairs Hospital, Northridge California, [45] it took two hours to evacuate just the intensive care patients. However, the detail of reporting is not sufficient to establish individual performance, nor the effectiveness of transporting PRM.

In the relatively recent field of pedestrian and evacuation dynamics, research has typically focussed on the movement of ambulant people. Data from seminal research, for example walking speeds documented by Predtechenskii and Milinskii in 1987 [206] and Pauls in 1995 [207] are seminal sources of data for evacuation calculations and simulations. Currently, there is discussion on the disparity between data use within the field, and the appropriateness of the applications in which movement data are utilised [208]. Given this, and the on-going requirement for new statistics to inform engineering practice [209], data are being collected and collated to deliver a broader picture of modern evacuation dynamics. For

example, experiments are being designed to explore the impacts of social issues [132] and of culture on evacuation behaviour [210], and researchers are investigating the expected behaviours of specific groups of pedestrians, e.g. children [211, 212]. As part of this on-going collection of data, more data collection efforts have been conducted to investigate the evacuation performance of people with disabilities, including PRM [17, 22]. This is important in establishing a broader view of evacuation dynamics, as mobility impairments are expected to increase with an ageing population [73, 74], and in the context of recent equality legislation investigating the impact of these impairments, and sufficiently planning for the evacuation of PRM, is a topic of great consideration at the moment. These data are crucial to the simulation of hospital evacuation based on the large proportion of PRM within care environments, because of the limitations in hospital incident reporting, and the issues with executing live evacuation drills in hospital settings [137].

As per Table 2-1, the required functionality for a hospital evacuation model includes the ability to represent the speeds of a wide population including assisted and unassisted PRM. The preparation time to ready patients for evacuation is also required, as is the impact of fatigue on repeated collection of patients. This section explores the current data available that can be applied to evacuating PRM in a hospital setting.

2.3.1 Vertical and Horizontal Movement of PRM

As established in the previous section, a significant complication in hospital evacuation is the potentially high proportion of occupants of PRM expected within the building. PRM typically walk at significantly lower speeds than ambulant people when unassisted, and may require aids (e.g. walking sticks and frames) in order to evacuate. Some PRM may be able to travel unassisted for a short distance before requiring assistance, for example elderly people, pregnant women, and those on crutches. Others will require full assistance for the whole evacuation procedure. An important consideration is that PRM are likely to require assistance in vertical stair descent. As outlined in section 2.1.1.5, escape stairways must be

incorporated into evacuation planning as the total evacuation of occupants from multi-storey hospitals cannot be realistically achieved solely by lifts [2], but are likely to require the use of evacuation mattresses or other methods. While some PRM may be able to travel along corridors using walking aids, these may not be effective on stairwells. Categorised in Table 2-4 are some of the assisted evacuated means that have been supported by data.

Table 2-4: Data categories for evacuating PRM

Label	Description
A	PRM was assisted
UA	PRM was unassisted
NA	No aid was used
VI	PRM was visually impaired
CR1	PRM used one crutch
CR2	PRM used two crutches
WC	PRM used a manual wheelchair
EWC	PRM used an electric wheelchair
WF	PRM used a walking frame
WS	PRM used a walking stick
F	Fire fighters assisted PRM in evacuation
CWC	A carried wheelchair was used to transport PRM down stairs
EC	An evacuation chair (2 wheeled) was used to transport PRM down stairs
ST	A stretcher was used to transport PRM down stairs
CC3/4	The PRM was carried down the stairs in a Carry Chair by three or four handlers
RS	A drag sheet was used to transport the PRM down stairs
EC4	An evacuation chair (4 wheeled) was used to transport PRM down stairs
ECL	A long track evacuation chair was used to transport PRM down stairs
ECR	A rear-facing evacuation chair was used to transport PRM down stairs
ECN	A narrow evacuation chair (2 wheeled) was used to transport PRM down stairs
MC	The PRM was manually carried down the stairs by two handlers
CC2	The PRM was carried down the stairs in a Carry Chair by two handlers.
FS	The PRM was carried down the stairs in a Fabric Seat by two handlers.
ECC	The PRM was carried down the stairs in an Extended Handle Carry Chair by two handlers.

Establishing a full and informative data set is an onerous task as there is a continuous range of mobility impairments. Categorising changing conditions and measuring associated performance is a also challenging task. A number of studies have been undertaken to measure the speeds at which PRM travel to quantify assisted and unassisted evacuation performance horizontally and vertically. In Table 2-5, the average (mean) speeds of current data sets are presented, alphabetically per author, and in the categories outlined in the previous Table 2-4. Further notes on methodologies and data from each publication are presented in the Appendix C.

Table 2-5: Average (mean) speeds in m/s recorded for assisted and unassisted movement of PRM, by lead author.

	[213] Adams (2010)	[17] Boyce (1999)	[214] Brand (2001)	[215] Fujiyama (2004)	[216] Jiang (2012)	[22] Kuligowski (2012)	[23] Lavender (2012)	[217] Proulx (1995)	[21] Sano (2004)	[218], [219] Shields (1997)	[82] Sørensen (2012)
HORIZONTAL TRAVEL											
UA-NA		0.95	1.00	1.31	1.27						
UA-CR1					0.87						
UA-CR2		0.94			0.78						
UA-WS		0.81									
UA-WF		0.57									
UA-WC		0.69	1.35							0.72	
UA-EWC		0.89	1.85								
UA-VI											0.98
A-NA		0.78									
A-WC		1.30								1.10	
A-EC	1.5										
A-ST	1.1										
A-CC3/4	1.5										
A-RS	0.9										
VERTICAL (STAIR) DESCENT											
UA-NA		0.36		0.60-0.91	0.85	0.41		0.56-0.88			
UA-CR1		0.22			0.43						
UA-CR2					0.33						
UA-WS		0.32				0.23					
UA-WF		0.16									
UA-VI											0.73
A-CWC		0.13				0.25				0.32	
AF-NA						0.18	0.32*				
A-VI		0.19									
A-EC	0.81					0.21	0.86*		0.26-1.11*		
A-ST	0.55										
A-CC3/4	0.57										
A-RS	0.62										
AF-CC							0.34*				
AF-FS							0.45*				
AF-ECC							0.75*				
AF-EC4							0.66*				
AF-ECL							0.67*				
AF-ECR							0.69*				
AF-ECN							0.82*				

***Data inferred from graphs. Please refer to Appendix C for further notes and working where applicable.**

Boyce *et al.* [17] conducted an extensive experimental trial including 107 male and female participants in Northern Ireland to assess the movement performance of those with various disabilities in horizontal travel, stairways and ramps. Jiang *et al.*

[216] conducted an experimental trial including 117 male and female participants on the horizontal and on the stairways of a Chinese subway station, where data were collected for PRM moving unassisted and with crutches. Sørensen and Dederichs [82] conducted evacuation trials in four New Zealand buildings and collated data relating to the unassisted movement of 46 people with visual impairments in corridors and descending stairs. Fujiyama and Tyler [215] conducted evacuation trials to investigate elderly persons movement ascending and descending four flights of stairs and a short flat surface. Speeds were shown to be faster than Fruin's data for elderly people in 1971 [220]. As part of the exercise, participants were requested to use normal and fast speeds. Several staircases were used, providing a comparison between varying degrees. Brand *et al.* [214] conducted trials on ramps and the horizontal with 48 unassisted PRM, and wheelchair users – both manual and electric. Lavender *et al.* [23] conducted trials over 2-3 flights of stairs to assess the ergonomic implications of using various methods in which to transport PRM down stairs. It was suggested that the performance on the landing may significantly inform the speed of the device. However, the faster speed achieved in this trial may have been because of the use of fire fighters.

Shields [218] found speeds for four manual wheelchair users in an unannounced hotel evacuation. Kuligowski *et al.* [22] analysed video footage from an announced evacuation drill of an assisted living building in the USA. This study is particularly valuable as it was conducted over 13 flights of stairs. However, no significant fatigue was noted, and this analysis was conducted with data collated from various starting points meaning the comparison between local speeds is not necessarily accurate. Again, the participants were fire fighters which may have impacted the speeds they achieved. Proulx *et al.* [217] analysed video footage from three evacuation drills in high-rise (12-14 floors) apartment buildings in Canada. Those with movement limitations evacuated slower than other occupants, although wheelchair bound people stayed in place to be rescued. Older people were found to achieve slower speeds as expected. Shields *et al.* [219] conducted an unannounced evacuation drill where a wheelchair user was assisted by two people down the stairs. The PRM and assistors had pre-knowledge of the evacuation. They

evacuated in a flow of people, but the other evacuees did not overtake and were therefore impeded in their evacuation resulting in congestion on the stairs.

Sano *et al.* [21] conducted experimental trials where 20 participants used an evacuation chair to descend up to 20 floors of a staircase. Data presented in Sano *et al.* [21] are depicted in diagrams and graphs, not in tables, therefore the figures quoteds here are extrapolated from graphs. For all handlers that repeated the experiment, the time taken to traverse the initial floor was decreased the second time around. This effect was greater for untrained handlers than for trained handlers. Furthermore, for each handler the average speed recorded was faster the second time they conducted the trial. As expected, speeds are generally faster for trained participants. A wide range of speeds are reported over five, ten and 20 storeys. In two separate experiments, it is reported that untrained participants travelled at 0.26 m/s and 1.11m/s, however it is not clear in which the order of trials were conducted, therefore participants that have repeated the experiment up to five times may no longer be properly classed as untrained. Participants speed did not decrease as they traversed each floor; the graphs indicate that speeds remained either constant or increased during each trial. From questionnaires, participants felt that on-site training must be conducted for the use of the devices, and that the most difficult manoeuvre was the transition from stair to landing. Most participants felt that they could travel at least 20 stories with an evacuation chair.

Adams and Galea [213] conducted trials over 11 floors with trained handlers evacuating PRM in four devices: evacuation chair, carry chair, stretcher, and drag sheet. Average data were presented for device speeds along the horizontal and vertical. This analysis did not investigate the floor-by floor speeds of the handling teams in order to establish any reduction in speed or stopping behaviours indicating the need to rest, nor the impact of gender on the evacuation performance. It did not closely scrutinise the devices' progress in terms of the corners and turns present in the evacuation paths, nor the times taken in which to ready a PRM for evacuation.

A key issue in the comparison of evacuation speeds is the methodology used. For example, there are different methods of measuring the paths taken on a stairwell. The horizontal "birds-eye" path can be measured, without considering the depth of the stairs [220]. There is also the diagonal path measurement, using a Pythagorean calculation of the slope of a stairwell: Pauls [221], Peacock *et al.* [222], and Predtechenskii and Milinskii [223] all used this method for widely accepted pedestrian calculations and this is becoming the more common method. These yield varying results which can significantly affect the speeds calculated [224], as well as the (elliptical or otherwise) path taken on the landing [153], and any photoluminescent stairwell installations that may impact movement [225]. Future data therefore requires detailed reporting, and raw data and methodologies must be published in order to make meaningful comparisons [78].

As is evidenced by the variety of speeds noted and the varying trial conditions and methodologies used, more data are required to better understand the evacuation of PRM. Some high quality data have been established for walking speeds for people with disabilities [17, 219], and these have been applied to evacuation models, although recent reports show that applying reduced speed variables alone may not reduce the evacuation times of mixed ability populations as required by experimental results [226]. In particular, there is great variability in the speeds found for evacuation chairs: speeds ranged from 0.21m/s to 0.86 m/s. This may reflect the effect of training and of participant strength, or the distance travelled. No fatigue has yet been observed in the repeated use of these devices.

2.3.2 Availability of other data

When considering the performance of evacuees from hospitals, much of the existing data may be applicable for the representation of movement speeds of occupants and staff who are ambulant, for example pre-movement times [71], the behaviour of groups and of children [211] have shown great variability in horizontal and vertical speeds when evacuating in drills [212].

This synopsis of the current data for hospital evacuations demonstrates a significant gap in the current knowledge, particularly for the performance of emergency evacuation equipment. In order to better plan for and model hospital evacuation, more data are required in the use of emergency devices. In addition to the speeds of these devices on the horizontal and in vertical descent, there are facets to hospital evacuation dynamics that require quantification to be understood and collated meaningfully for performance analysis, modelling and simulation. These include the impact of fatigue [85]; evaluation of the ergonomics of manual handling in evacuation situations has shown that repeatedly evacuating PRM from buildings can be a physically strenuous task [227], but there are insufficient data on this over an evacuation of many floors. It is expected that many repeat collections of patients must result in handler fatigue, and potentially that the gender of the operators of a device may significantly affect the physical responses of repeated evacuation but little is known about the difference in speeds when assisting a PRM in vertical evacuation for example.

While research has begun to be conducted in the effect of devices in a horizontal flow of people [228], little is known about the effects of evacuation devices in an evacuation flow. The staff-patient dynamic also requires specific representation in evacuation modelling, particularly the pre-evacuation time of patients and staff. This must incorporate all of the actions required to inform and prepare patients for their evacuation [229]. It is therefore vital that more data are collected to quantify performance in order to better model hospital evacuation [78, 230].

2.4 Summary and Proposed Developments

This chapter has attempted to identify the factors that influence the outcome of hospital evacuations, clarify the current supporting data available to quantify evacuee performance, and establish the current means in which computational egress models can simulate hospital evacuation. As a result of this review and the outcomes identified, a series of proposed developments are suggested.

Section 2.1 described the key factors that influence a hospital evacuation. It demonstrated that such evacuations were sensitive to a range of structural,

procedural and behavioural factors: insufficient fire protection and/or evacuation planning; the use of ad hoc plans and equipment; the rapid escalation of incidents; the insufficiency of horizontal evacuation; the critical importance and frequent use of movement assist devices; the importance of accurate information and communication; the inappropriateness of egress paths for emergency use; the availability of emergency equipment; and the importance of staff training. The identification of these considerations provided a set of factors that appear to have a significant impact on the outcome of hospital evacuations and would then need to be represented in egress models to more comprehensively simulate them.

Section 2.2 reviewed the currently available egress models to determine their suitability for use in simulating hospital evacuations. It was found that the many of these models were inappropriate given the methods employed to represent key egress components: their grid/structure, the perspective of the model and the occupant, the behavioural model employed, the ability to represent repeated evacuation through counterflow, the representation of the disabled population, the allocation of pre-evacuation times and medical related delays, the use of lifts, and the representation of vertical evacuation equipment. It was then possible to determine models as candidates for further development. In addition, it was possible to identify those aspects of evacuee performance that were ripe for development and, in accordance with the review of key factors in hospital evacuations, where these developments might have the biggest impact on the accuracy of the model in question. In alignment with the data review, it was established that there is a need to develop models to include movement assist devices.

Section 2.3 categorised the attempts have been made to better quantify the evacuation performance of PRM. This includes the work conducted by Adams and Galea (2010) [213], Boyce *et al.* (1999) [17], Brand *et al.* (2001) [214], Fujiyama and Tyler (2004) [215], Jiang *et al.* (2012) [216], Kuligowski *et al.* (2012) [22], Lavender *et al.* (2012) [23], Proulx *et al.* (1995) [217], Sano *et al.* (2004) [21], Shields *et al.* (1997) [218, 219], and Sørensen and Dederichs (2012) [82], that address a range of evacuee performance, some including the use of horizontal

movement devices. However, several key omissions in the data currently available was identified by comparing the current data with the factors deemed key in influencing hospital evacuation in section 2.1.3. It was found that more data are required, primarily in the performance of assisted evacuation. A number of devices have been designed to vertically evacuate PRM, however little is currently known about their performance in hospital evacuation.

This thesis aims to address some of the issues identified in this section, towards a better understanding of behaviours in hospital evacuations and the creation of a model to represent the phenomena. As such, the following have been identified as requirements necessarily to progress this area of research: in terms of the data required and the model development required.

2.4.1 Data requirements

To address the question of evacuation performance for assisting PRM, it is proposed that data are required to address the following requirements:

[DR1] How long does it take to prepare a PRM for assisted evacuation?

[DR2] What are the horizontal travel speeds for assisted evacuation?

[DR3] How long does it take to open and traverse doors during assisted evacuation?

[DR4] What are the vertical travel speeds for assisted evacuation?

[DR5] Do handlers experience fatigue from assisted evacuation?

[DR6] Can other people evacuate alongside vertical stair devices?

[DR7] What factors influence the performance of assisted evacuation?

These data requirements are addressed in Chapters 3 and 4, where work is undertaken to establish the performance of four movement devices. This work investigates: the preparation of PRM to proceed assisted evacuation in a movement device; the horizontal movement of PRM in devices in corridors and through doors; the vertical movement of PRM in devices; and any indication of handler fatigue that may impact the performance of assisted evacuation.

2.4.2 Modelling requirements

Similarly, the following modelling requirements have been identified in order to represent the evacuation of PRM within hospitals:

[MR1] How can these data be used to compare the performance of movement devices in evacuation?

[MR2} How can movement devices be specified and geometrically represented in an evacuation model?

[MR3] How can a hospital building be assessed for the accessibility of devices?

[MR4] How can agent-device interactions be represented in an evacuation model?

[MR5] How can the horizontal movement of devices be represented in an evacuation model?

[MR6] How can the vertical movement of devices be represented in an evacuation model?

These modelling requirements are addressed in Chapters 5, 6 and 7, where methods of performance comparison are presented, along with algorithms derived to represent the use of movement devices within evacuation modelling software buildingEXODUS [26]. This software was selected for practical reasons (i.e. the author had access to the model), and because of its suitability according to the model review in section 2.2.2: it was one of a number of models that fulfils the other requirements of simulation hospital evacuation albeit without the functionality required to explicitly represent movement devices. Chapter 8 then presents a discussion of the key findings from this literature review, and from the subsequent work undertaken.

3 DATA COLLECTION

As established in the literature review (2.4.1), a vital component for the development of hospital evacuation software is the acquisition of data to evaluate the performance of assisted evacuation. PRM require the use of specialist devices in order to evacuate. These movement devices are designed to enable both horizontal and vertical evacuation, although there is little data quantifying their performance. Extant procedures rely on the assisted movement of patients who require hospital staff to evacuate them. Therefore, in order to progress an evidence-based approach to hospital evacuation planning, more empirical data are required to establish the performance of movement devices.

An experiment was designed to establish the performance of movement devices in hospital evacuation, according to the methodology outlined in this section. The University of Greenwich collaborated with Ghent University Hospital to test the use of movement devices in 32 evacuation trials in September 2008 [231]. Trained staff evacuated a test subject through 11 floors of Ghent University Hospital using four commonly used movement assist devices. Analysis of the experiment videos delivered data on the performance of each device for both male and female handling teams. This chapter describes this data collection process in three sections: before, during and after the Ghent Experiment. Figure 3-1 outlines these sections and the structure of the Greenwich and Ghent collaboration.

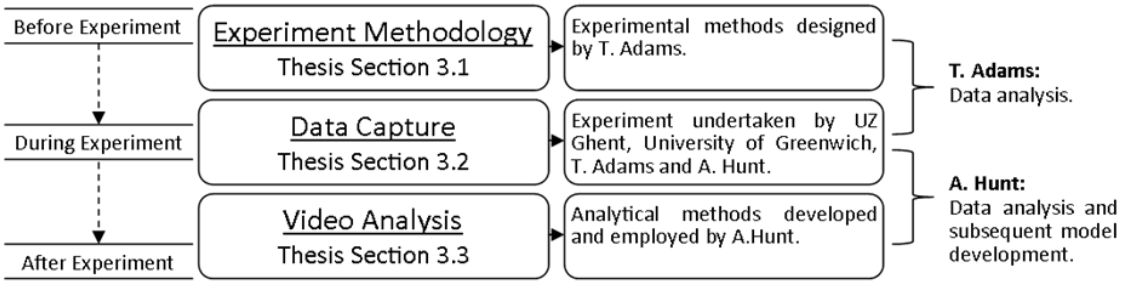


Figure 3-1: Data collection collaboration structure.

The experiment was designed by Ton Adams towards a Masters project [213] under the supervision of Professor Edwin Galea from the University of Greenwich. This aspect is described in the first section of this chapter. The second section presents methods employed during the trial in order to capture the full process of the experiment. Participants from the host organisations undertook these procedures, with assistance from the author, during the live experiment. The final section describes the author's development of analytical methodology in order to derive data sets from the trial video footage. There are significant differences between the depth of analysis undertaken in this thesis to the initial work undertaken by Adams [213] in which broad averages were taken between starting and finishing points of the evacuation. This work presents comprehensive video analysis to address the specific objectives outlined in the literature review (2.4.1): DR1 – DR7.

3.1 Experiment Methodology

The collaborating institutions designed the procedures employed in this egress trial to quantify, compare and model the performance of various movement devices in the horizontal and vertical evacuation of PRM. This section describes methodology used to conduct the experiment, given the resources available: the Ghent University Hospital premises, time allowance, trial organisers and participants.

3.1.1 Premises

The building in which the trials were conducted was part of Ghent University Hospital. It consisted of 14 floors with a system of stairs and lifts employed in the normal running of the hospital with an additional evacuation stairwell spanning the height of the building. These evacuation stairs were used for the trials in question. The utilization of this stairwell was not only conducive to the study of emergency egress, but also allowed the hospital facility to operate with little disruption while the experiment was being conducted. One lift was designated for the sole use of trial officials; hospital employees and inhabitants were made aware of this in advance. The hospital occupants were also notified in advance of the procedures of the experiment as the ability to differentiate between a trial process and a real emergency was imperative for the safety of the building occupants.

The trial procedure began on the 11th floor. This section of the hospital was relatively isolated, consisting of offices and an infrequently used corridor. In this way, its use during the experiment limited the disruption to normal hospital activity. The designated corridor portion began at a room in which the preparation of the device would occur and ended at the emergency stairwell. This portion would serve to capture both the preparation of devices, as well as their performance in traversing along a horizontal plane. Figure 3-2 shows the plan of the Floor 11 geometry employed for the purpose of the trials.

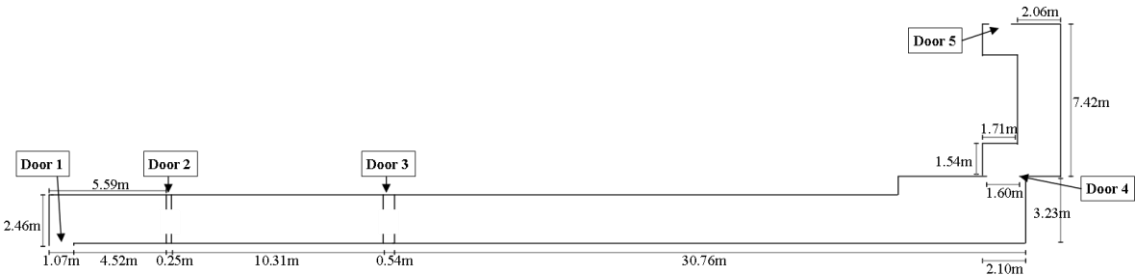


Figure 3-2: The layout of the allocated portion of Floor 11 in the Ghent University Hospital premises. All measurements are in metres.

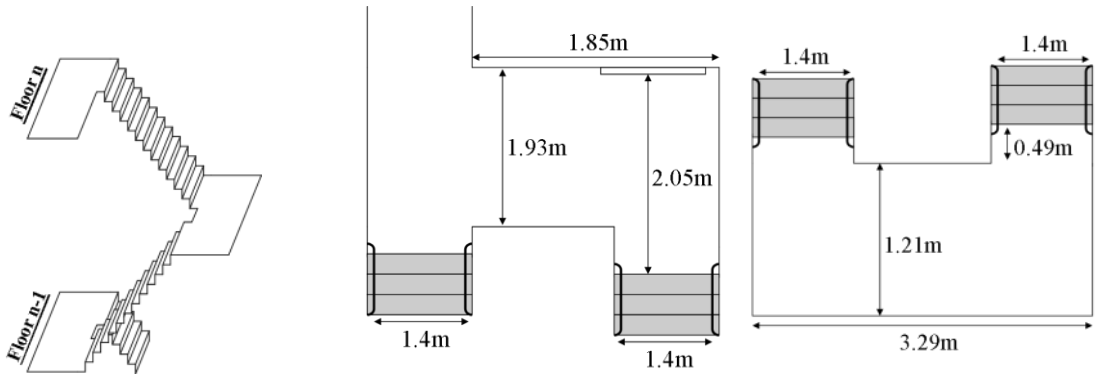
As indicated in Figure 3-2, there were five sets of doors within this corridor portion. The flow of traffic was from left to right, passing through the labelled doors in ascending order. Table 3-1 describes the nature of each door: the number of leaves it consisted of and the direction in which they were opened. This direction is from the perspective of the flow, i.e. as people travel along the corridor, a leaf opens either toward or away from them.

Table 3-1: The attributes of doors on the corridor path.

Door	No. of Leaves	Opening Direction	Door bolt	Leaf Opening Order
Door 1	1	Toward	-	Already open
Door 2	2	Toward	-	Left leaf; then right leaf
Door 3	2	Away	-	Right leaf; then left leaf
Door 4	2	Away	Left leaf bolted	Right leaf; then left leaf
Door 5	1	Away	-	Right leaf

The section of the emergency stairwell in operation during the trials began at the landing of the stairwell on Floor 11 and ended on the ground floor (Floor 0), which had a hallway that led towards the exit of the building. Each floor of the stairwell

consisted of a main landing, a flight of stairs to a sub-landing between floors and then another flight of stairs to the next floor's main landing. Figure 3-3 (i) shows the layout of these components that constituted one floor. This configuration is known as a dogleg staircase.



(i) **(ii)** **(iii)**

Figure 3-3: (i) The emergency stairwell configuration, (ii) Dimensions of the main landings, and (iii) Dimensions of the sub-landings.

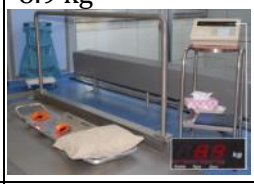
Each floor consisted of the same dimensions, i.e. every main landing was the same size and every sub-landing was the same size. The two flights of stairs between floor 3 and floor 2 consisted of 10 steps (risers), but every other flight of stairs consisted of 12 risers. Every riser measured 0.175m in height and 0.29m in depth (0.26m+0.03m nosing). The width of the staircases was 1.4 metres, as measured between the handrails on either side. Figure 3-3 (ii) and (iii) show the dimensions of the main landings and sub-landings, respectively. The path of the emergency staircase turns clockwise in descent.

3.1.1.1 Four Movement Devices

The trials investigated the use of four of the most common types of movement devices [213]: stretchers, stairway decent chairs, carry chairs and rescue sheets. One example of each of these varieties was used in the experiment. These devices were appropriate for the Ghent trials because they are regularly used in patient evacuation and were also part of previous regular University of Ghent staff training, therefore all of the participants were experienced in their operation. The use of well-practised devices minimized safety risks for the participants, while operating and within the devices. Table 3-2 compares the various attributes of

each device model used: its weight, material, dimensions, patient weight capacity and price at the time of the experiment in 2008.

Table 3-2: The attributes of each movement device.

	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
Brand	Fern Stretcher Scoop Model 65	Evac+Chair 300H AMB	Ferno model 42 (4204)	GSI Rescue 108088
Weight of all components	8.9 kg 	10.6 kg 	7.3 kg 	13.1 kg 
Material	Lightweight Alloy	Aluminium tubing	Aluminium	Fabric
Storage dimensions	Length: 120cm Width: 43cm	Height: 104 cm Width: 52cm Depth: 20cm	Height: 95 cm Width: 48cm Depth: 16cm	Length: 200cm Width: 75cm
Usage dimensions	Length: 166cm Width: 43cm	Height: 138 cm Width: 52cm Depth: 77cm	Height: 95 cm Width: 48cm Depth: 61cm	Length: 200cm Width: 75cm
Max. patient weight	159 kg	150 kg	159 kg	140 kg
Price at time of experiment	750 Euro (excl. VAT)	850 Euro (excl. VAT)	1075 Euro (excl. VAT)	124 Euro (excl. VAT)

The following sections depict and describe the techniques that the operators employed to use each device. The positions that an individual or a handling team should adopt to transport the device along a plane and down a stairwell are refered to as the Horizontal Handling Technique (HHT) and the Vertical Handling Technique (VHT), respectively.

3.1.1.1.1 Stretcher

As illustrated in Figure 3-4 (i), the stretcher used for the Ghent trials was a portable, lightweight metal frame that can be divided into two vertical parts. This allowed it to be constructed around a patient in a lying position; each side arcing under the patient and then clipping into place. The patient is further secured with straps, looping under and around the device. This type of stretcher is frequently used in emergency situations, to 'scoop' injured people up and quickly move them. In order to represent the transfer of a patient into a general stretcher, however, this 'scooping' faculty was not used in the trials; the stretcher was pre-constructed

in the position depicted in Figure 3-4 (i). In addition to the metal frame and three securing straps, a pillow was used to support the patient's head. Before the experiment, the frame, straps and one standard hospital pillow collectively weighed 8.9kg.

(i) **(ii)** **(iii)**

Figure 3-4: (i) The stretcher device, (ii) its Horizontal Handling Technique, and (iii) its Vertical Handling Technique.

Four people were required to carry the stretcher, one at each corner of the device. While travelling along a corridor or on a landing, each of the four team members holds a handle of the device in one hand, with their arm extended below the waist. This HHT is shown in Figure 3-4 (ii). When vertically transporting the stretcher device, the leading pair of the handling team lifted the two front corners of the device onto their shoulders. This VHT is shown in Figure 3-4 (iii).

3.1.1.1.2 Evacuation Chair

As illustrated in Figure 3-5 (i), the evacuation chair is an example of an evacuation device purpose built for the transportation of PRMs, horizontally and vertically. It is made from lightweight metal and is designed for the descent of straight stairwells at gradients between 28° and 39°. Because of its system of continuous belts, this device controls its stair decent, working in proportion to the PRM's weight. In this way, the chair itself supports the majority of the PRMs weight, not the operator. The evacuation chair model used included all necessary straps and fastenings and the entire device weighed 10.6kg prior to the Ghent trials.

(i) **(ii)** **(iii)**

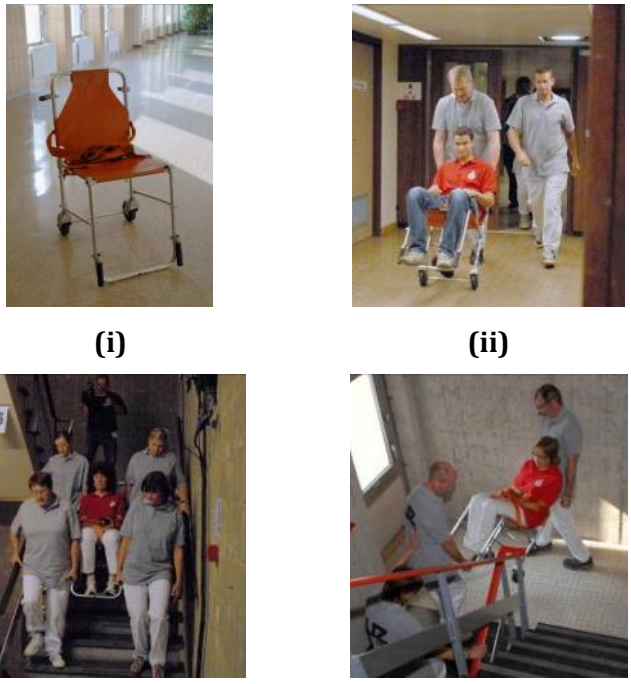
Figure 3-5: (i) The evacuation chair device, (ii) its Horizontal Handling Technique, and (iii) its Vertical Handling Technique.

The HHT for the evacuation chair is shown in Figure 3-5 (ii). The operator simply pushes the chair along, on four wheels as one would with a wheelchair. When vertically transporting the stretcher device, the rear wheels are folded into the device, allowing a smooth, skiing movement down stairs. The operator stands behind the chair navigating its descent and bearing a small amount of the weight burden by holding the handles. This VHT is shown in Figure 3-5 (iii).

3.1.1.1.3 Carry Chair

The carry chair is an example of an evacuation device specifically designed for the transportation of patients. As depicted in Figure 3-6 (i), this device consists of an aluminium frame, with handles positioned on the front and the rear in order to enable both horizontal and vertical movement. The PRM is secured in the fabric seat panel with attached safety straps. The whole device weighed 7.3kg. In order to manoeuvre the carry chair horizontally, the operator pushed the chair along on four wheels. The HHT for the carry chair is shown in Figure 3-6 (ii). In stair descent, the carry chair can be carried by two, three or four operators. The manual handling experts at Ghent advised that female teams would require more members than the male teams to physically carry the chair within stairwells. Therefore the female teams used four operators and the male teams used two. The Vertical Handling Technique for four operators is shown in Figure 3-6 (iii). Each of the four team members holds a handle of the device in one hand, with their arm extended below the waist. The VHT for two operators is shown in Figure 3-6 (iv). One team member is positioned behind the devices, holding the handles at the back of the

device: one in each hand. The other team member is positioned in front of the device, facing towards the PRM and holding the handles at the front of the device: one in each hand.



(i) **(ii)**

(iii) **(iv)**

Figure 3-6: (i) The carry chair device, (ii) its HHT, (iii) its Four-Operator VHT, and (iv) its Two-Operator VHT.

3.1.1.1.4 Rescue Sheet

As pictured in Figure 3-7 (i), the rescue sheet consists of a sheet with fastening straps attached, designed to be stored under a patient's mattress. The straps are pulled around the mattress, and the PRM, with the bedding and pillow included. The weight of all the components combined was 13.1kg.

When transporting a patient horizontally, two operators pull the rescue sheet and mattress behind them, holding on to the same forward facing strap with one hand each. This HHT for the rescue sheet is shown in Figure 3-7 (ii). When descending stairs, one operator is positioned at the rear of the device, facing the direction of travel and the other operator is positioned at the front of the mattress, in the opposite direction to travel. Holding one strap each (with one or two hands), they

push, pull and drag the mattress and PRM down the stairs. This VHT is shown in Figure 3-7 (iii).

(i) **(ii)** **(iii)**

Figure 3-7: (i) The rescue sheet device, (ii) its Horizontal Handling Technique, and (iii) its Vertical Handling Technique.

3.1.2 Trial Sequence

Employees and students from the University of Ghent served as device operators during the trials. These volunteers were extensively trained in the manual handling of patients. They were allocated to four handling teams: two teams consisted of four male participants and two teams of four female participants. Additionally, one male and one female volunteer were assigned the role of the patient. The "acting" patients were to remain inactive during the trial process in order to replicate mobility impairment and this role was referred to as the Person with Reduced Mobility (PRM.) It was considered necessary for both PRMs to weigh the same amount for the purpose of this trial: approximated 70 kilograms. To ensure this was the case, the lighter participant wore weights to match the other. Table 3-3 depicts the specifics and sequence of every trial conducted during the two day experiment. Each of the handling teams conducted eight trials: two with each device. There were two different procedures for the trials, labelled "Device" trials and "Group" trials (these are detailed in the next section pp. 94).

Table 3-3: Experimental trial sequence.

i) 17 September 2008: Device Trials

Time	Trial No.	Handling Team	Device
08.00	1	Male 1	Stretcher
08.30	2	Male 2	Stretcher
09.00	3	Female 1	Stretcher
09.30	4	Female 2	Stretcher
10.00	5	Male 1	Evac Chair
10.30	6	Male 2	Evac Chair
11.00	7	Female 1	Evac Chair
11.30	8	Female 2	Evac Chair

iii) 18 September 2008: Device Trials

Time	Trial No.	Handling Team	Device
08.00	17	Male 1	Carry Chair
08.30	18	Male 2	Carry Chair
09.00	19	Female 1	Carry Chair
09.30	20	Female 2	Carry Chair
10.00	21	Male 1	Rescue Sheet
10.30	22	Male 2	Rescue Sheet
11.00	23	Female 1	Rescue Sheet
11.30	24	Female 2	Rescue Sheet

ii) 17 September 2008: Group Trials

Time	Trial No.	Handling Team	Device
13.00	9	Male 2	Stretcher
13.30	10	Male 1	Stretcher
14.00	11	Female 1	Stretcher
14.30	12	Female 2	Stretcher
15.00	13	Male 1	Evac Chair
15.30	14	Male 2	Evac Chair
16.00	15	Female 1	Evac Chair
16.30	16	Female 2	Evac Chair

iv) 18 September 2008: Group Trials

Time	Trial No.	Handling Team	Device
13.00	25	Female 2	Carry Chair
13.30	26	Male 1	Carry Chair
14.00	27	Male 2	Carry Chair
14.30	28	Female 1	Carry Chair
15.00	29	Female 2	Rescue Sheet
15.30	30	Male 1	Rescue Sheet
16.00	31	Male 2	Rescue Sheet
16.30	32	Female 1	Rescue Sheet

A 30 minute time slot was allocated for each trial. Their sequence was devised to give each handling team as much rest between participation as possible, in order to minimise the effects of fatigue. It was intended, therefore, that each team was to participate in 4 trials per day, with a minimum of 1 hour and 45 minutes rest between each. However, due to unforeseen staffing complications, it was necessary for the sequence to be slightly altered. This meant that in one case (Trial no. 25), two members of the handling team, Female Group 2, had rested for a shorter time: 1 hour and 15 minutes.

3.1.3 Procedure

In each trial, the handling teams conducted a predetermined procedure, the phases of which are depicted, in storyboard diagrams, in Figure 3-8. Each trial commenced with a Preparation Phase, in which the PRM was secured into the device, followed by the Corridor Phase, where the PRM was transported through 60 metres of

corridor and then finally the Stairwell Phase, where the PRM was traversed in the descent of 11 flights of stairs.

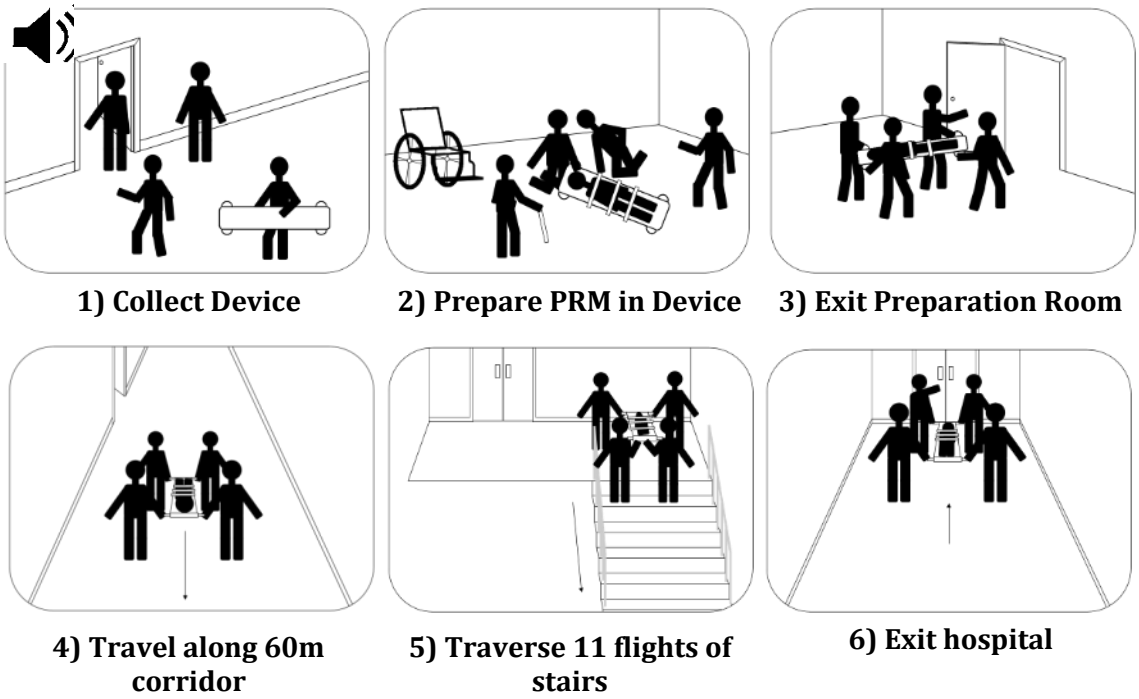


Figure 3-8: Storyboard of experimental procedure.

Each device required a minimum of two handlers for the preparation phase in order to use the appropriate lifting technique as outlined by the University of Ghent's Practical Guide for Emergency Teams [232] to safely transfer the PRM. However, due to the varying nature and physical demands of each device, different numbers of operators were required during the horizontal and vertical phases, and so the participants allocated to each team were as follows:

- The stretcher required four people for its HHT and VHT, therefore male and female teams both consisted of four participants.
- The evacuation chair required just one person for its HHT and VHT, therefore the male and female teams consisted of two participants.
- The carry chair required one person for its HHT. For the VHT, the manual handling experts at Ghent advised that female teams would require more members than the male teams to physically carry the chair within stairwells. Therefore, the female teams consisted of four participants and the male teams consisted of three participants.

- The rescue sheet required two people for its HHT and VHT, therefore both the male and female teams consisted of two participants.

3.1.3.1 Trial Commencement

Prior to the beginning of each trial, the required members of the handling team were situated behind a starting line in the corridor. This line was a few meters from the door to the preparation room and was marked on the floor in tape. Opposite the door to the preparation room, another area was marked out in tape. This was to indicate the starting location of the device. In order to signal the start of each trial, a trial assistant with a loud air horn was positioned at the end of the corridor on floor 11. When notified that everyone was in place for the trials, the assistant sounded the air horn in two short, sharp blasts. This warned that the trial was to begin in 15 seconds. After 15 seconds, the air horn was sounded again, to indicate the start of the trial. On this signal, the handling team crossed the starting-line, retrieved the device equipment from its set area and entered the preparation room.

3.1.3.1.1 Preparation Phase

The PRM was positioned in a wheelchair in the preparation room. The location of the wheelchair in the room was marked on the ground in tape in order to achieve consistency between trials. Once in the preparation room, the handling teams transferred the PRM from the wheelchair into the movement device. Again, the positioning of the device for this preparation phase was pre-marked in tape on the ground. Once secured into the particular device, the handling teams employed the device to transport the PRM out of the preparation room and into the corridor.

3.1.3.1.2 Corridor Phase

Each handling team then transported the PRM in the movement device along the corridor portion of floor 11 towards the stairwell. This journey had areas that required travel in a straight line as well as areas in which the devices had to navigate a turn. There were four sets of doors on this path, all of which were closed prior to the commencement of each trial.

- The first set had two leaves that required the handling team to pull each leaf towards them;

- The second set had two leaves that required the handling team to push each leaf away from them;
- The third set had two leaves, the left of which was locked with a bolt on the opposite side to which it was approached, and it required the handling team to push both leaves away from them;
- The fourth door had just one leaf that required a push from the handling team to open away from them.

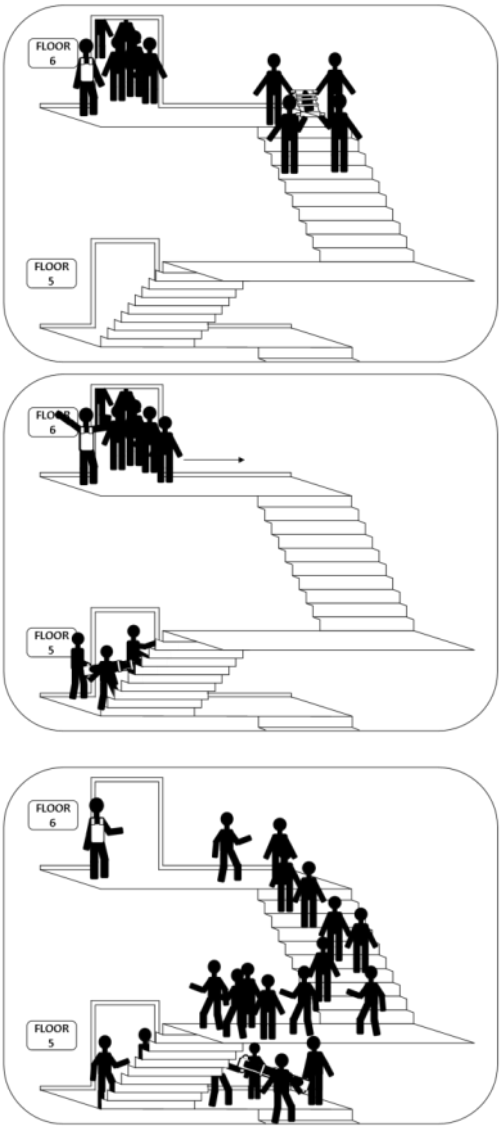
3.1.3.1.3 Stairwell Phase: Device Trials

Once the handling team had passed through the fourth door of the corridor section, they emerged at the emergency stairwell. Some devices required the handling team to transition from their Horizontal Movement Technique to their Vertical Movement Technique (see 3.1.2.) The PRM was then transported vertically down the emergency stairs. The handling team negotiated the main landing, the middle landing and two flights of stairs for each floor. In each trial, a total of 11 floors were traversed and the handling team emerged from the emergency stairwell on the ground floor at a main emergency exit. When outside of the building, the team continued towards another taped line marked on the ground. Once the PRM and the whole team had crossed this line, it marked the end of each trial.

3.1.3.1.4 Stairwell Phase: Group Trials

The second procedure involved the same process as the Device Trials by the handling teams, but additionally a group of 24 volunteers from Ghent University Hospital were injected into the emergency stairwell. The group of volunteers were all young, fit and agile people. They queued on the 6th floor and waited to be told to enter the stairwell, progress down the stairs and exit the building. Figure 3-9 depicts the procedure for injecting the group into the stairwell, behind the device and handling team.

Floor 6 was a suitable position for the injection of people into the stairwell as its halfway point allowed a good comparison between the speed of each movement device before and after the introduction of the group. Additionally, it meant that there was adequate time within the stairwell for interaction, e.g. overtaking, between the handling team with the device, and the group passing.



i) 24 volunteers queued on Floor 6, awaiting instruction. The trial assistant observes the progress of the device.

ii) The trial assistant notes the point at which every member of the handling team is on Floor 5, and verbally prompts the group to enter the stairwell.

iii) The 24 group members progress down the stairwell, overtaking where they deem possible, and exit the building.

Figure 3-9: The procedure employed to position the passing pedestrian group behind the device team.

For the group trials, the trial was complete once the PRM, the handling team and every member of the group had all crossed the finish-line. The very last member of the group wore a distinctive yellow jacket and was instructed to maintain close proximity to the rear of the group.

3.2 Data Capture

The process of each trial was captured with a number of quantitative and qualitative techniques to ensure comprehensive recording of the experiment. This provided a backup of recoverable data, should any capturing method fail. A video team was employed to visually and aurally record the trial processes. In addition, a

team of assistants also documented key times using stopwatches. Assistants operated handheld cameras and a photographer took pictures of the preparation and process of the experiment. Additionally, questionnaires were distributed at the end of every trial in order to document the experience of each member of the handling team, as well as the PRM and the 24 pedestrian volunteers.

3.2.1 Video

Digital video was used as the principal way to record each trial. The video team secured 13 cameras within the emergency stairwell; one camera placed in the same position on each floor, one on the ground floor and an additional camera on the landing between floor 4 and floor 3. This extra camera was positioned as it was thought [213] that extra supporting footage may be advantageous in this area to observe any overtaking in the group trials. A member of the video team also operated a roaming camera during each trial. This closely followed the handling team, recording the device preparation and their progress through the corridor and stairwell phases of their egress. The operator of this roaming camera carefully ensured that the filming was conducted at an appropriate distance and from behind the handling team, so as not to interfere with the progress of the trial. A control room was established within the building premises with live feeds from each camera. This enabled the camera team to check that the experiment was being adequately recorded and, importantly, to monitor the safety of the participants during each trial. The 14 cameras were running constantly during each trial, documenting the entirety of the devices' journey. Additionally, two assistants operated handheld cameras at various points, providing a back-up of the events as well as a supplementary perspective.

3.2.2 Stopwatches

An assistant was positioned at each floor of the evacuation staircase: in the hallway of the landing to avoid any obstruction of the experiment process. Each operated a stopwatch and was prompted to begin their record upon hearing the air horn. The assistants recorded two key times as the device and the handling team progressed through each floor: the time at which the first member of the handling team had both feet on the landing and the time at which the last member of the handling team had both feet on the next set of stairs. For the group trials, the assistants also

noted the times at which the first and last group members had reached the landing. These times were recorded by hand during the trials.

3.2.3 Photographs

A photographer was present to record various aspects of the experiment. The equipment used was photographed to document, for example, the exact screen reading of a device being weighed. Various trial processes were also photographed, e.g. the carrying techniques employed by the handling teams. Pictures also recorded the live experiment method: the layout of the building, the areas used for the setup of the experiment and the working of the experiment assistants.

3.2.4 Questionnaires

On completion of each trial, the participants were immediately set aside to complete a questionnaire. Different questionnaires were designed for the PRM, the Handling Team and the members of the group passing, (see Appendix F). The questions were devised to gauge the experience of the participants during the trial and to gain their subjective views of the performance of each device. Topics of particular concern were:

- The safety of those within and operating the device.
- The ease in which the device could be prepared and operated.
- The physical demands experienced during the trials.
- Personal estimates of how much further each could sustain this physical effort.

3.3 Video Analysis

Collectively, over the two day experiment, the 16 cameras provided over 1.5 terabytes of video footage. This footage was collated for analysis using Adobe Premiere Pro C3. Using this software, the video analyst synchronised the footage from the various sources using the air horn prompt to align them on a timeline. It was then possible to place markers on the video timeline: observing an event on screen and marking the frame in which the event happened. Given that the footage was captured at 25 frames per second, this timeline could be analysed to a relatively high degree of accuracy. The analyst devised a set of codes in order to

efficiently label the markers placed in the video footage. These codes are presented in Appendix D. A program designed by the analysis team then extracted the times of every marker, alongside the code that was assigned to the marker. The data from each trial was then collated and examined in a spreadsheet.

Careful definition, assumption and interpretation were required during the analysis process. It was essential to outline criteria to determine which members of the handling teams should be tracked in order to extract data from the video footage. It was also important to establish the exact points of interest in order for them to be precisely identified and marked by the analyst. For the observation of the majority of the footage, the analyst was consistent in noting the First Foot and Last Foot observation points, as defined in this section. For more complicated or qualitative observations, the analyst derived other schemes of marking the timeline of events. These are explained in subsequent sections. To enable numerical analysis, it was also necessary to make assumptions regarding the distance travelled by the teams, as this can have a large impact on the subsequent data [153].

3.3.1 Active Team Members

When tracking the devices' progress during the trials, it was necessary to differentiate between the phases in which members of the handling team were actively employed in the transportation of the PRM and the phases in which they were inactive (i.e. simply moving alongside the device without contributing to its progress). For example, when transporting the carry chair horizontally, only one member of the handling team was active; but when transporting it vertically, all of the members of the handling team were active. However, when they weren't occupied in moving the device, other members of the team contributed to the progress, for example by opening doors ahead of the device in the corridor portion.

The Active Device Team (ADT) was considered to be a single unit formed of the PRM in the device and the active members of the Handling Team (i.e. those physically touching the device). This definition ensured that each device could be tracked as one travelling unit, inclusive of the people actively transporting it at any

given time. Additionally, varying roles of the active team members during each experiment phase were noted as part of the video analysis. As detailed in Table 3-4, three support levels were established to describe the influence of each role at each phase: “Essential”, “Major support” and “Minor support”.

Table 3-4: Identification of handling team roles, per experiment phase.

	Preparation Phase	Corridor Phase	Stairwell Phase
Essential Role: Members who were physically required to carry out experiment phase.	Lifting and preparation of PRM.	Physically transporting PRM through corridor.	Physically transporting PRM down stairs.
Major Support Role: Members who contributed major actions that significantly contributed to the teams’ efficiency.	Preparing the device only.	Unlocking and opening doors in advance of device.	Supporting device movement and occasionally swapping into essential role.
Minor Support Role: Members who contributed minor actions but not significantly contributed to the teams’ efficiency.	Placing straps and pillows.	Walking alongside device.	Providing safety support ahead of device.

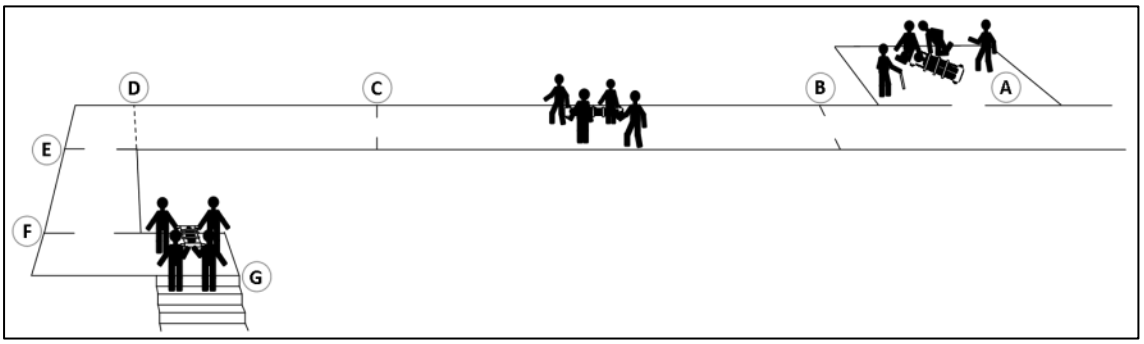
The footage showed that, for every device and gender, there were a constant number of team members in each role; these results are outlined in Table 3-5. These data are necessary for subsequent comparative analyses, as they enable the assessment of device performance based on the number of people required to operate the device per task.

Table 3-5: The number of operators and their roles for each device

			Stretcher	Evac Chair	Carry Chair M	Carry Chair **F**	Rescue Sheet
Experiment Phase	Preparation	Essential	2	2	2	2	2
		Major	1	0	1	1	0
		Minor	1	0	0	1	0
	Corridor	Essential	4	1	1	1	2
		Major	0	1	1	1	0
		Minor	0	0	1	2	0
	Stairwell	Essential	4	1	2	4	2
		Major	0	0	1	0	0
		Minor	0	1	0	0	0
Total number of operators			4	2	3	4	2

3.3.2 Observation Criteria

In determining the phase-by-phase progress of the device teams, their entire journey was divided into sections, each bound by lines as depicted in Figure 3-10: Video observation points. The corridor portion was divided into seven sections: the preparation room and six corridor sections; these portions were bounded by the door thresholds. The start of the corner was identified by a line (see D in Figure 3-10), which was used to determine the start of the turning manoeuvre. The times at which the devices reached and crossed all of these lines were recorded.



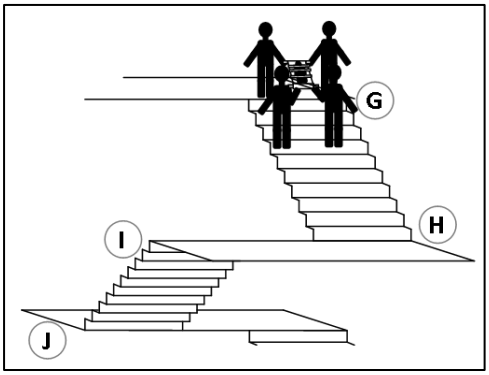
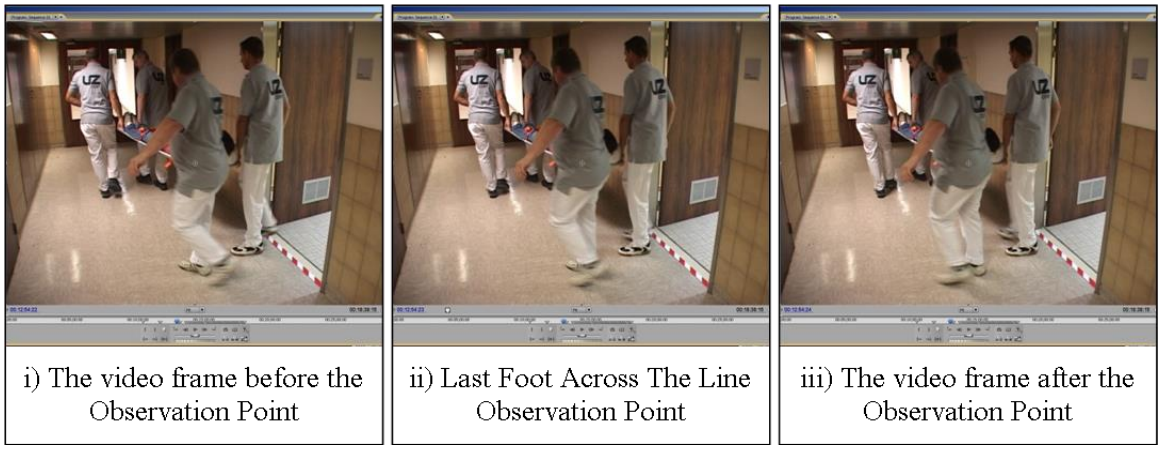


Figure Reference	Video Observation Point
A	Preparation Room and Door 1
B	Door 2
C	Door 3
D	Assumed corner divide
E	Door 4
F	Door 5
G	"Floor to Stair" threshold
H	"Stair to Landing" threshold
I	"Landing to Stair" threshold
J	"Stair to Floor" threshold

Figure 3-10: Video observation points

When tracking the teams through these observation points, the interrogation of the video footage was subject to interpretation and so it was essential to outline criteria to classify events consistently for each trial video. Typically, the required observations pertained to the crossing of the threshold of a door or the edge of a stair riser. In these cases, the first and last parts of the active team members were the focus of analysis. Figure 3-11 shows an example of the classification of "Last Foot" observation point; the point at which the rear most part of the last active team member's foot had fully crossed the line of interest. This was measured, again in Adobe Premiere Pro, as the first frame in which every part of the ADT had

crossed the line (where the last active team member's foot was fully across the line and into the subsequent section). Figure 3-11 illustrates this point, where a team is transporting the stretcher through a set of doors. The line of interest is the threshold of the door, as marked by striped tape. It shows three consecutive frames: the second of which (ii) is the pertinent data point recorded by the analyst according to this definition, i.e. it is the first frame that every part of the last foot of the Active Team Member's has crossed the line of interest.



i) The video frame before the Observation Point	ii) Last Foot Across The Line Observation Point	iii) The video frame after the Observation Point

Figure 3-11 (i), (ii) and (iii): Three consecutive frames from Trial 1 - Male Team 1 leaving the Preparation Room with the Stretcher.

In the majority of observation definitions, it was assumed that the line marks a vertical area. The analyst considered the space above the line as marked by the line also. Therefore, when a foot was positioned over the line, as shown in Figure 3-11 (i), it had not yet crossed the line according to these definitions. This method was applied not only to the active device team, but also when tracking individual members of the group passing on the stairs. The members of the group were considered as individual units in the same way that the team was deemed as one travelling unit. The First Foot and Last Foot principals outlined here were applied in most cases. Although these definitions were those most frequently observed, other points in the video footage were also detected.

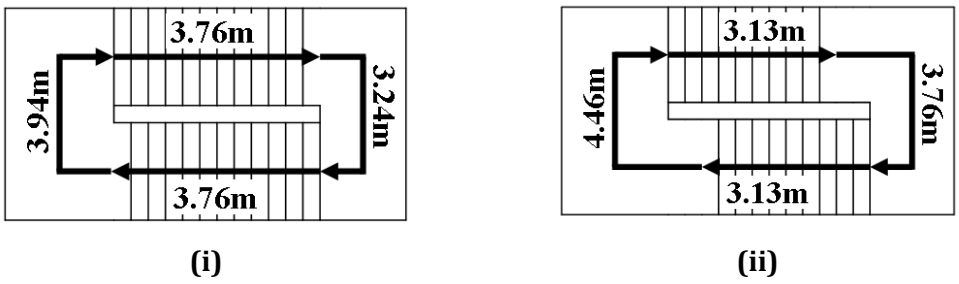
In addition to the calculation of travel speeds for the devices, qualitative observations were also made in the video analysis. Observations were made to find the times at which the operators lifted the PRM in preparation, their transition

through doorways, the level of overtaking in the group trials, and the times at which the teams had stopped to rest in the stairwell. These observation points had their own specific criteria, and are described alongside the respective results in Chapter 4. More than 2,500 video observations were noted during the video analysis. A full matrix was developed with the possible observation definitions, and a set of codes devised to efficiently label the markers placed in the video footage. Appendix D lists these codes along with their descriptors. A program designed by the analysis team then extracted the times of every marker, alongside the code that was assigned, allowing the complete data set from each trial to be collated and examined in a spreadsheet.

3.3.3 Path Measurements

To enable the numerical analysis of the extracted data, it was necessary to make assumptions regarding the distance travelled by the teams. The shape of assumed travel path can significantly influence any subsequent speed calculations [153]; therefore, it is important that the paths reflect the route taken. During the trials, teams typically travelled along the central path of the corridor. In the same way while descending the stairs, most teams took a central path on the stairs, with the most common deviation being a slight inclination toward the inner handrail for support. Here, therefore, it is assumed that the teams traversed the central line path through the corridors, stairs and landings, and that the distance traversed in stair descent is calculated as the Pythagorean diagonal.

The dimensions of the evacuation route were measured to indicate the available space that could be physically occupied during the experiment. For example, the stair widths were taken between the handrails and the landing widths excluded the depths of radiators. Between floor 3 and floor 2, the diagonal stair flight distance was 3.13 metres, but every other flight was 3.76 metres. Figure 3-12 (i) depicts the central path measurement of an entire floor of the emergency staircase (totalling 14.7m) and the measurement of the exceptional flights between floors 3 and 2 (totalling 14.48m).



(i) (ii)

Figure 3-12: Central path measurements of (i) a typical floor of the emergency staircase and (ii) between floors 3 and 2.

In the same way, the central path measurements were taken for the corridor area of the experiment. This was divided into five sections as depicted in Figure 3-13 in order to differentiate between the different shaped portions of the corridor. The data obtained by analysing these sections separately, as well as in one portion, could provide insight into the use of the devices around corners and other more complicated routes.

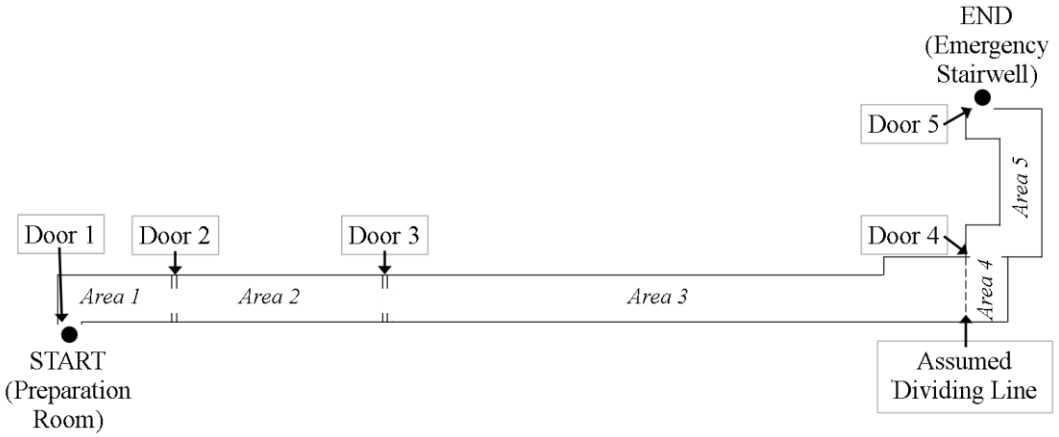


Figure 3-13: Sections in corridor for central path measurements and subsequent analyses.

The doors provided natural geometric boundaries for most sections of corridor, providing a clear reference point for video observation markers. An additional boundary was derived to divide area 3 and area 4. This was in an ideal position to separate the recorded travel times into the devices' movement in a straight line (area 3) and the devices' movement while anticipating and turning a corner (area 4). Appendix E depicts the geometric calculation of each corridor and stair central path. Table 3-6 presents the full summary of these central path measurements

used for the subsequent data analysis, per section of the route, and the sum of these portions.

Table 3-6: The central path distances measured per area of the trial route.

CORRIDOR PORTION	Area 1	6.535 m
	Area 2	10.850 m
	Area 3	28.660 m
	Area 4	3.050 m
	Area 5	10.995 m
	TOTAL (Corridor Portion):	60.090 m
STAIRWELL PORTION	Floor 11 – Floor 10	14.700 m
	Floor 10 – Floor 9	14.700 m
	Floor 9 – Floor 8	14.700 m
	Floor 8 – Floor 7	14.700 m
	Floor 7 – Floor 6	14.700 m
	Floor 6 – Floor 5	14.700 m
	Floor 5 – Floor 4	14.700 m
	Floor 4 – Floor 3	14.700 m
	Floor 3 – Floor 2	14.480 m
	Floor 2 – Floor 1	14.700 m
	Floor 1 – Floor 0	*10.940 m
	TOTAL (Stairwell Portion):	157.720 m
TOTAL EXPERIMENT DISTANCE:		217.790 m

* It is noted that, because the route on the ground floor led directly to the exit, the central path distance for this did not include a subsequent landing. Therefore, the distance between Floor 1 and Floor 0 was measured as 10.94 metres.

By dividing the route in this way, each ADT could be tracked in their progress through each area of the experiment route. Therefore analysts could compare the times recorded for the entire distance travelled (218 metres) as well as separately considering the devices' speeds during their horizontal travel (60 metres) and their vertical travel (158 metres.) Additionally, it allowed many useful comparisons between the smaller subsections of the route. For example, the differing speeds recorded per floor meant that fatigue could be investigated.

This chapter has delineated the experiment methodology, the means of data capture and the process of video analysis during the Ghent trials. The next chapter outlines the results of the experiment based on these methodologies.

4 EXPERIMENTAL RESULTS

The video analysis of the Ghent trial footage recorded the evacuation progress of each team. According to the methodology outlined in Chapter 3, the documented times were analysed to establish the evacuation performance of the devices and were used alongside the central path measurements to determine the speeds of each handling team as they evacuated each PRM. Over 2500 data points were established from the trial footage. The resulting data, as presented here, include preparation time, horizontal speed, door transition time, vertical speed and overtaking potential. For each phase of the trial route, comparisons are made between the performance of male and female handling teams and the four devices. Additionally, results are presented from questionnaire data, as each participant completed a survey (see Appendix F) at the end of each trial to describe their physical experience of the trial and their perception of safety factors.

These findings are then aggregated for use in the subsequent sections of analysis: in chapter 5 a performance evaluation methodology is presented, along with results from numerical simulations of the data; and in chapters 6 and 7 the data are used in the explicit (physical) representation of devices within evacuation software.

The “last foot” technique as outlined in the previous chapter (3.3.2) is used for the majority of speed calculations in this chapter. Where a different technique has been used to define the observations from the video, or when more qualitative descriptions are used, these are described in this chapter, alongside their respective results. The set of raw data, on which these video analysis results are based, are tabulated along with their video observation references in Appendix G.

4.1 Preparation Times

The preparation phase of the experiment is depicted in Figure 4-1. At the beginning of each trial, the handling team entered the Preparation Room; where

the PRM was situated in a wheelchair. The team then proceeded to prepare and, where necessary, construct the device in order to safely transport a person. The PRM was then lifted from the wheelchair using established manual handling techniques directed by the manual handling experts at the University of Ghent [213] and secured into the device. Once ready, the team adopted their HHT and used the device to transport the PRM out of the Preparation Room and into the corridor for the horizontal phase.

For consistency, each team followed this procedure. However it is noted that the preparation times for the rescue sheet may not be representative of the times required to prepare a patient in hospital or a care facility. If the rescue sheet is incorporated underneath a mattress, patients will already be in the bed, and thus the wheelchair-to-bed preparation time would not apply. However, there would still be a preparation delay as the PRM would need to be secured to the device and the device lowered to the floor. It is also noted that there are other rescue sheet type designs commercially available such as the Albacmat Rescue Mat [97] and the Evacupod [233] that are not incorporated into the bed as and therefore may require the transfer of a PRM from a wheelchair to a device.

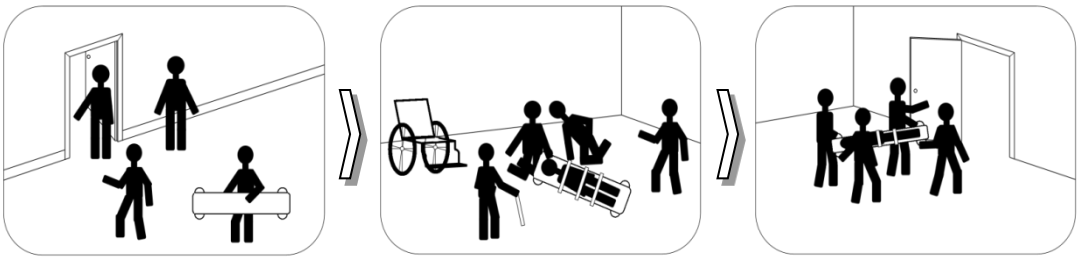


Figure 4-1: Preparation phase storyboard.

When observing this phase of each trial, two key durations were recorded: the total time taken to retrieve the PRM from the Preparation Room (Patient Retrieval Time) and the time taken to fully secure the PRM into the device (Patient Preparation Time.) The purpose of evaluating this phase in two independent measurements is their potential applications in evacuation modelling. Some models (for example, coarse node models such as Evacnet 74 and Wayout [188]), could represent this process as a delay time within a room, therefore requiring a

general retrieval delay parameter. Others (for example, agent based models such as Exodus [234] and Pathfinder [184]) could represent this process as a group delay, without incorporating the entering or leaving of a room, therefore requiring a specific preparation delay parameter.

4.1.1.1 Patient Retrieval Time

In order to record the time taken to retrieve the PRM from the Preparation Room, the analyst measured between the point at which the first person in the ADT entered the Preparation Room and the point at which the first person in the ADT left the Preparation Room. As illustrated in Figure 4-2 (and similar to the "Last Foot" video observation definition described in Chapter 3) this "First Foot" video observation was recorded as the first frame that any portion of the Active Team Member's foot has crossed the line of interest.

Figure 4-2: i), ii) and iii) Three consecutive frames from Trial 1 - Male Team 1 leaving the Preparation Room with the Stretcher.

Each of the handling teams performed this manoeuvre twice: once for the Device Trials involving just the transportation of the device and once for the Group Trials that later introduced a group into the stairwell. Table 4-1 shows the number of seconds each handling team took to retrieve the PRM. The average (mean) retrieval times indicate that the evacuation chair is the quickest device to retrieve patients. The stretcher is the slowest, taking more than twice as long as the evacuation chair. Male teams are faster than female teams, but it is notable that for both genders the retrieval times for devices where the patient was secured in a sitting position (the evacuation chair and carry chair) are considerably faster than

the time taken with devices where the patient was secured in a lying position (the stretcher and the rescue sheet).

Table 4-1: Patient retrieval time (seconds)

	Device			
Team	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
Male 1	75.6	39.7	40.7	60.4
Male 1	75.4	28.0	40.9	55.0
Male 2	80.4	42.2	38.0	67.6
Male 2	69.6	38.0	46.2	60.9
Female 1	79.0	50.2	58.1	96.7
Female 1	68.7	40.7	48.6	82.1
Female 2	126.4	37.6	57.1	79.6
Female 2	103.7	46.2	59.5	100.7
Male Average	75.3 ± 3.8	37.0 ± 5.4	41.5 ± 3.0	61.0 ± 4.5
Female Average	94.5 ± 22.4	43.7 ± 4.9	55.8 ± 4.3	89.8 ± 9.1
Overall Average	84.9 ± 18.7	40.3 ± 6.1	48.6 ± 8.1	75.4 ± 16.1

Generally, the retrieval times deviate further from the mean for female teams than for male teams, particularly for the lying position devices. As depicted in Figure 4-3, on average, the difference between male and female performance is smallest for the evacuation chair (18%), followed by the stretcher (25%), the carry chair (35%) and the rescue sheet, which has the greatest gender performance difference (47%).

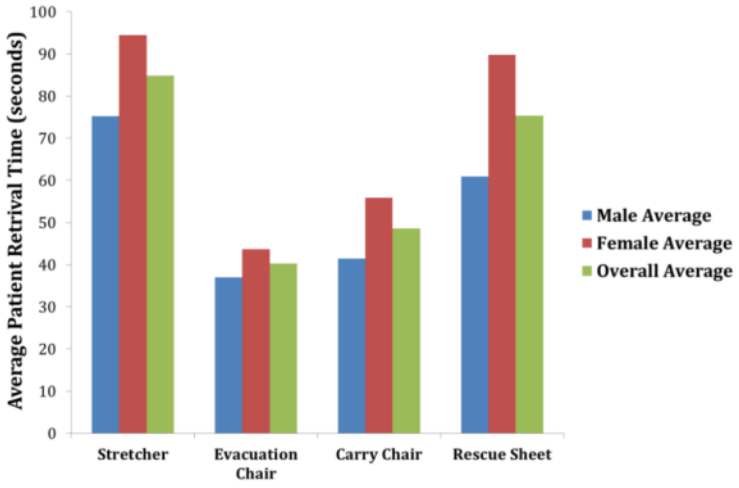


Figure 4-3: Average patient retrieval time.

Each handling team repeated the preparation process for each device, and the data indicate that teams are significantly faster at retrieving patients on their second attempt (Wilcoxon signed-rank test, $T = 34$, $p < .05$). Table 4-2 presents the percentage difference between these attempts; teams are on average 4.85%

quicker the second time that they complete the patient retrieval process. This suggests that there may be a positive effect of practise when repeating this process within the same team.

Table 4-2: The percentage faster for patient retrieval time on second attempt

	Device			
Team	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
Male 1	0 %	30 %	0 %	9 %
Male 2	13 %	10 %	-22 %	10 %
Female 1	13 %	19 %	16 %	15 %
Female 2	18 %	-23 %	-4 %	-27 %
Male Average	7 %	20 %	-11 %	9 %
Female Average	16 %	-2 %	6 %	-6 %
Overall Average	11 %	9 %	-2 %	2 %

While these retrieval data reflect the process of entering and leaving the preparation room, the patient preparation time is independently defined in the next section. This reflects the time taken to physically secure the patient within a device (and is therefore a sub-process of patient retrieval).

4.1.1.2 Patient Preparation Time

In order to record the time taken to prepare the PRM within each device, the analyst took the difference between the times that the first person in the Handling Team made contact with the PRM and the time when the PRM was secured into the device and ready to be transported by the ADT in the HHT:

- The first point of note was when a member of the handling team had first made contact with the PRM. As illustrated in Figure 4-4 (i), this is defined as "*the time at which a member of the handling team first makes physical contact with the PRM*".
- The second point of note was when ADT is ready to begin the horizontal movement with the device. As illustrated in Figure 4-4 (ii), this is defined as *"the time at which the preparation is complete, as determined by the first forward evacuation movement by the team."*

(i) **(ii)**

Figure 4-4: Video stills (i) Trial 3: First point of physical contact with the PRM, and (ii) Trial 1: First horizontal move to evacuate.

Table 4-3 presents the number of seconds each handling team took to prepare the PRM.

Table 4-3: Patient preparation time (seconds)

	Device			
Team	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
Male 1	66.9	31.2	32.6	51.4
Male 1	66.6	23.6	34.5	46.4
Male 2	73.9	32.4	31.6	59.7
Male 2	63.1	30.4	39.6	53.0
Female 1	72.6	41.7	50.2	83.9
Female 1	61.0	32.6	41.1	74.1
Female 2	119.8	29.8	50.4	67.0
Female 2	97.6	39.7	52.2	86.2
Male Average	67.6 ± 3.9	29.4 ± 3.4	34.6 ± 3.1	52.6 ± 4.8
Female Average	87.7 ± 22.8	35.9 ± 4.9	48.5 ± 4.3	77.8 ± 7.7
Overall Average	77.7 ± 19.2	32.7 ± 5.3	41.5 ± 7.9	65.2 ± 14.1

Consistent with the patient retrieval results, the patient preparation data indicate that the evacuation chair is the quickest device in which to prepare patients. As illustrated in Figure 4-5, the stretcher is again the slowest, taking more than twice as long as the evacuation chair. Male teams are again faster than female teams, and for both genders the preparation times for devices where the patient was secured in a sitting position (the evacuation chair and carry chair) are considerably faster than the time taken with devices where the patient was secured in a lying position

(the stretcher and the rescue sheet). Consistently, the preparation times deviate further from the mean for female teams than for male teams, particularly for the lying position devices. On average, the difference between male and female performance is smallest for the evacuation chair (22%), followed by the stretcher (30%), the carry chair (40%) and the rescue sheet, which has the greatest gender performance difference (48%).

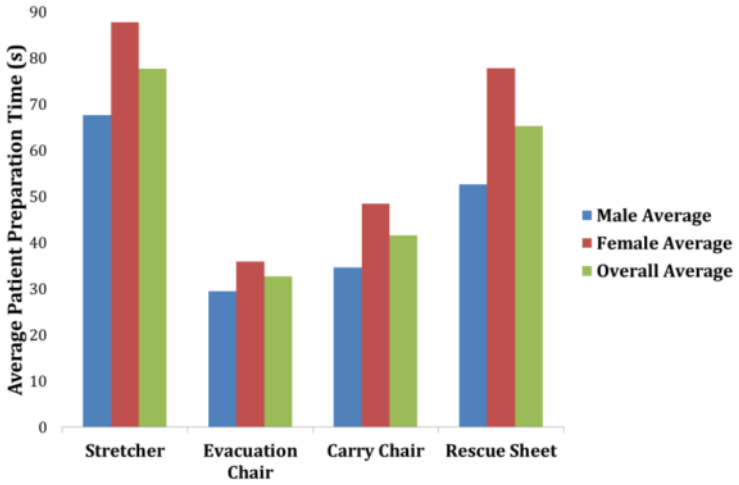


Figure 4-5: Average patient preparation time.

Table 4-4 presents the percentage difference between each team's first and second preparation attempts; teams are on average 3.54% quicker the second time that they prepare a PRM.

Table 4-4: The percentage faster for patient preparation time on second attempt

	Device			
Team	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
Male 1	0 %	24 %	-6 %	10 %
Male 2	15 %	6 %	-25 %	11 %
Female 1	16 %	22 %	18 %	12 %
Female 2	19 %	-33 %	-3 %	-29 %
Male Average	8 %	15 %	-15 %	10 %
Female Average	17 %	-6 %	7 %	-8 %
Overall Average	12 %	5 %	-4 %	1 %

Although each participant was expertly trained in the preparation and operation of movement devices, this improvement may indicate the effect of recently repeating

an action, or the effect of repeating an action with the same group of people. Unlike the retrieval times, these data do not indicate that teams are significantly faster at preparing patients on their second attempt (Wilcoxon signed-rank test, $T = 40$, $p < .05$). This could be indicative that the improvement in time on the second attempt is attributed to non-preparation activities (e.g. pre-assembly of the device, or faster exit from the room), or that the participants in this sample are too comprehensively trained to determine the effect of repeating the activity. More data are required to test the influences of training and repetition on evacuation activities such as these preparation processes.

4.2 Horizontal Travel Speeds

The handling teams travelled horizontally with each device for 60 metres, from the exit of the preparation room to the entrance of the emergency stairwell. As described in the previous chapter, the "Last Foot" observation method was used to measure the time taken for the whole corridor portion. The speed for each team calculated over the 60m journey are presented in Table 4-5, including the average (mean) horizontal travel speeds for both male and female handling teams and the overall average speeds (inclusive of both genders).

Table 4-5: Horizontal travel speed over 60m corridor (metres/second)

	Device			
Team	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
Male 1	0.99	1.51	1.44	1.08
Male 1	1.09	1.52	1.44	1.23
Male 2	1.09	1.53	1.75	1.14
Male 2	1.23	1.65	1.56	1.20
Female 1	1.00	1.37	1.45	0.92
Female 1	1.09	1.44	1.41	0.97
Female 2	0.91	1.39	1.51	0.66
Female 2	0.97	1.34	1.46	0.52
Male Average	1.09 ± 0.08	1.55 ± 0.06	1.54 ± 0.13	1.16 ± 0.06
Female Average	0.99 ± 0.06	1.39 ± 0.03	1.46 ± 0.04	0.72 ± 0.18
Overall Average	1.04 ± 0.09	1.46 ± 0.09	1.50 ± 0.10	0.89 ± 0.24

These results indicate that in horizontal transportation the devices with wheels (i.e. the evacuation chair and carry chair) are the fastest, with average speeds of 1.5 m/s, slightly better than the average free walking speed typically quoted in pedestrian analysis [235] of 1.4 m/s. As shown in Figure 4-6, the rescue sheet is the slowest device with an overall average speed of 0.9 m/s.

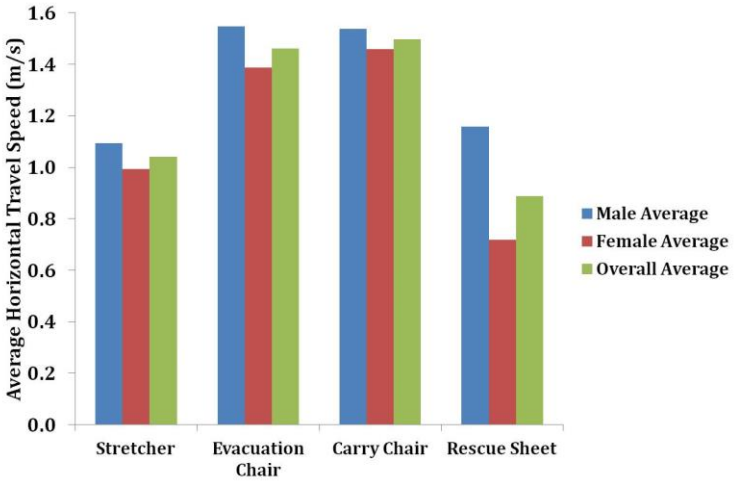


Figure 4-6: Average horizontal travel speed

For each device, male teams are faster than female teams when travelling along the corridor, with the carry chair having the smallest difference between male and female performance (5.2%), followed by the stretcher (9.4%), the evacuation chair (10.4%), and the rescue sheet having the greatest difference (37.9%). Furthermore, the carry chair is the only device where there was no significant effect of gender, $t(6)=1.36$, $p<.05$. For each of the other devices, there was a significant effect for gender, with males achieving higher speeds in horizontal transportation: the stretcher, $t(6)=2.01$, $p<.05$; the evacuation chair, $t(6)=4.87$, $p<.05$; and the rescue sheet, $t(6)=4.10$, $p<.05$.

The analysis of the trial footage also considered the five separate corridor areas, as depicted in the previous chapter (Figure 3-13). The full set of horizontal times measured for each team is tabulated in Appendix H and Table 4-6 summarises the average (mean) horizontal speeds per corridor section, incorporating all of the male and female data.

Table 4-6: Average horizontal speed per corridor section (metres/second)

	Device			
Area	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
1	0.74 ± 0.07	1.29 ± 0.17	1.57 ± 0.12	0.52 ± 0.17
2	1.30 ± 0.04	1.51 ± 0.13	1.58 ± 0.09	1.31 ± 0.37
3	1.22 ± 0.08	1.47 ± 0.13	1.39 ± 0.14	1.07 ± 0.29
4	0.87 ± 0.20	1.33 ± 0.40	1.36 ± 0.16	0.32 ± 0.22
5	0.81 ± 0.14	1.55 ± 0.21	1.78 ± 0.14	1.05 ± 0.24

Within area 4, each device had to turn on the approach to door 4. Taking the average speeds for each team (Table 4-6) it is found that the devices with wheels are 9% slower on this turn than their average corridor speed. However, the stretcher is on average 16% slower while the rescue sheet 64% slower. It is expected that the nature of the floor covering will have an impact on horizontal travel speeds, in particular for the rescue sheet. The corridor in the hospital was covered with hard vinyl flooring which is expected to be a good surface for horizontal movement. The time taken to traverse each corridor was measured for each threshold as the last part of each team to cross the line. Therefore, the speeds include the time delay incurred by opening the various doors during the experiment (see later for details).

4.3 Doorway Manoeuvrability: Right Angle Corners

As depicted in Figure 3-13, the teams began their evacuation in the preparation room and then turned 90 degrees into the corridor at area 1. This turn was evaluated separately to the corridor areas, by assessing the travel path through the line of the doorway (106 cm usable width) and an assumed line of the same length perpendicular to the doorway. Figure 4-7 shows these observation lines. The “First Foot” observation technique, as outlined in this chapter, was used for the first observation point, where the line of interest was the doorway threshold and the “Last Foot” observation technique, as outlined in the previous chapter was used for the second observation point, where the line of interest was the assumed perpendicular line.

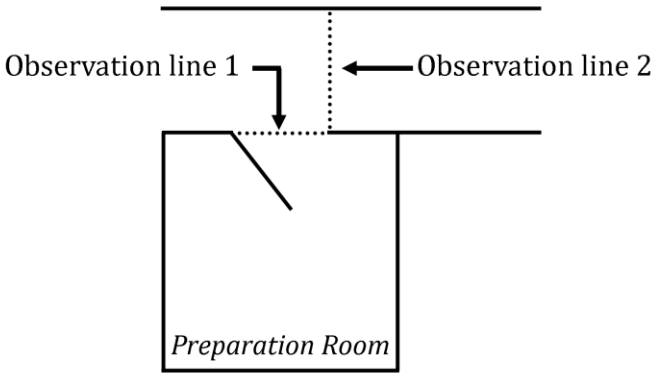


Figure 4-7: Position of corner observation lines.

The distances travelled during this turn were therefore the central line path of this square (106 cm), plus the length of the device, tabulated per device as "Max Length", or "Depth" in Table 3-2. The resulting speeds presented in Table 4-7 indicate that it is the devices with wheels (the carry chair and the evacuation chair) that achieve the greatest turning speeds. As before, males are quicker than females in manoeuvring the devices around corners and in most cases the horizontal speed is greater than the speed in turning through a right angle corner.

Table 4-7: Right-angle turning speed

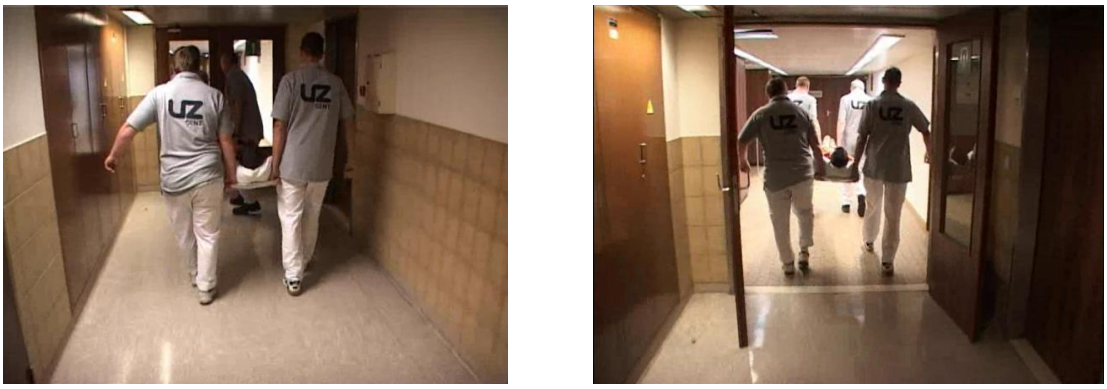
	Device							
Team	Stretcher		Evacuation Chair		Carry Chair		Rescue Sheet	
Male/Female	M	F	M	F	M	F	M	F
Corner Turning (Seconds)	2.73	2.81	1.31	1.61	1.17	1.24	2.87	3.57
Distance Travelled (m)	3.07	3.07	1.83	1.83	1.67	1.67	3.06	3.06
Corner Turning Speed (m/s)	1.12	1.09	1.40	1.14	1.43	1.35	1.07	0.86

For the devices with wheels, both genders are quicker in horizontal travel than around a 90° bend. For the stretcher, both genders average horizontal speeds are slower than turning speeds and for the rescue sheet, male horizontal speeds are quicker than turning speeds while for females, turning speeds are greater than horizontal speeds. Furthermore, the carry chair was quicker than the evacuation chair in going around the corner for both males and females, perhaps indicating that it is easier to manoeuvre using the four-wheeled frame of the carry chair. The

rescue sheet had the poorest performance for turning suggesting that this manoeuvre is more laborious when dragging a large mattress around a corner.

4.4 Door Transition Times

As previously depicted in Figure 3-13, the corridor portion was separated by five doors that were all closed prior to the commencement of each trial. Door 1 was opened at the beginning of each trial to retrieve the patient, but the remaining four doors were opened by the teams while they were manoeuvring the device. For each door, the roaming video footage recorded the time at which the first member of the handling team touched the door (i.e. made contact with the door handle to open it towards or away from them) as well as the time at which the last part of the last handling team member's foot crossed the doorway. These two video observation points are depicted in example trial footage in Figure 4-8.



(i) **(ii)**

Figure 4-8: Video stills (i) Trial 1: First team member touches door 2, and (ii) Trial 1: Last foot observation of door 2 threshold.

As outlined in chapter 3, only one person was required to push the evacuation chair and carry chair along the corridor portion. This meant that other handling team members walked alongside these chairs, and were available to open doors ahead of them. Therefore, the video analysis shows the time taken to traverse closed doors while using the stretcher and the rescue sheet, but not for the evacuation chair and carry chair, as the person pushing each chair did not have to negotiate the doors whilst operating the device. However, additional trials were conducted at the University of Greenwich, where three males and three females

repeatedly moved the evacuation chair device through doors with the same attributes as door 2 and door 3 of the Ghent trials. In each trial, an individual male or female pushed the evacuation chair towards the door, turned around in order to open the door and push the chair into the next corridor section. These trials were recorded by video and analysed in accordance with the methodology outlined in this section. The matrix of times recorded from these supplementary trials is presented in Appendix D. Thus in Table 4-8 the door transition times derived from the Ghent trials are presented for the stretcher and the rescue sheet, and the transition times derived from the University of Greenwich trials are presented for the evacuation chair. The opening direction indicates the movement of the door leaf as it is approached by the handling team; whether it opens towards the operators, or away from them.

Table 4-8: Average door transition time (seconds), for males (M) and females (F)

Door	No. of leaves	Opening direction	Door bolt	Leaf opening Order	Stretcher		Rescue Sheet		Evacuation Chair	
					M	F	M	F	M	F
2	2	Toward	N	Left, right	6.7 ±0.6	6.9 ±0.5	8.2 ±2.2	11.6 ±6.1	5.1 ±0.8	5.9 ±1.0
3	2	Away	N	Right, left	4.9 ±0.4	4.5 ±0.6	6.1 ±2.8	7.3 ±1.5	4.2 ±0.7	6.1 ±1.5
4	2	Away	Y	Right, left	12.1 ±3.4	15.5 ±1.8	10.5 ±0.5	20.3 ±5.7	-	-
5	1	Away	N	Right leaf	6.0 ±0.5	7.1 ±0.8	6.0 ±1.2	10.9 ±1.8	-	-

The results indicate that female teams take longer than male teams to manoeuvre closed doors while using movement devices. When doors are bolted shut, the male teams take on average twice as long to negotiate the door while the female teams take on average 3.5 times as long. A cross comparison across three devices is only possible for doors 2 and 3. Here it is found that it is easier for the handlers to negotiate doors that open away from the handlers. The evacuation chair has the fastest average door transition time for both “toward” and “away” doors (5.5 s and 4.5 s respectively), and the rescue sheet is the slowest with average traversal times of 9.9 s and 6.7 s respectively.

4.5 Vertical (Stair) Speeds

In each trial, the handling team used a device to assist a PRM in the descent of 11 flights of stairs. The Device Trial footage was used to determine the devices' speed within stairwell, unobstructed by any pedestrians during the entire evacuation route. Previously defined "Last Foot" video observations were used to observe the progress of the teams' decent. The thresholds of the stair case at the top and at the bottom of each flight of stairs were observed as the lines of interest, as depicted in Figure 4-9. The difference between these consecutive points gave the number of seconds it took each team to traverse each floor. It was additionally noted the points at which the teams stopped and the number of seconds rest taken (the amount of time when the device was not moving).

(i) **(ii)**

Figure 4-9: Video stills (i) Trial 1: all team members have crossed the landing-to-stair threshold, and (ii) Trial 1: all team members have crossed the stair-to-landing threshold.

The average (mean) travel speeds on stairs were determined from top to bottom of the whole stairwell portion (see Table 4-9) and also on a floor by floor basis, as presented in the next section. The travel speed measured for the whole stairwell portion was determined from: the time the trailing leg of the last person in the handling team crossed the threshold between the landing and the stair at the top floor, to the time for the trailing leg of the last person in the handling team to cross the threshold between stair and landing on the ground floor.

Table 4-9: Average speed over the whole stairwell portion (metres/second)

	Device			
Team	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
Male 1	0.66	0.88	0.40	0.85
Male 2	0.59	0.78	0.61	0.78
Female 1	0.48	0.79	0.74	0.55
Female 2	0.40	0.85	0.58	0.50
Male Average	0.63	0.83	0.50	0.82
Female Average	0.44	0.82	0.66	0.52
Overall Average	0.53 ± 0.10	0.83 ± 0.04	0.58 ± 0.12	0.67 ± 0.15

The average stair speeds indicate that the evacuation chair is the fastest device with an overall average descent speed of 0.83 m/s, being 57% faster than the slowest device, the stretcher at 0.53 m/s. Gender had a strong influence on the average speed, with the female speeds being generally considerably slower than the male speeds for most devices, with the exception of the evacuation chair and the carry chair. The evacuation chair is the only device for which male and female speeds are alike (1.2% difference). Furthermore, the standard deviation across all teams using the evacuation chair is merely 0.4m/s. The results for the carry chair suggest that the female descent speed is greater than the male descent speed. However, it is noted that this was achieved with a four person handling team for the females and a two person handling team for the males. It is noted that the male team had three members, but only two actually carried the chair at any one time. When one of the male operators needed a rest, the third person would take their place. The female stretcher team was 30% slower than the male team and the female rescue sheet team was 37% slower than the male team. These results suggest that the evacuation chair was the least physically demanding as it produced the greatest average speed and there was no gender difference in performance. Furthermore, the female descent speed using the evacuation chair is greater than the Fruin average stair descent speed for 30 year females (0.755 m/s) [235], [16] while all other devices were considerably slower.

4.5.1 Stair speed per floor

In addition to the stair descent speed over the whole portion, the average descent speed per floor was determined (tabulated in Appendix J). These speeds, from the Device Trials and thus unobstructed by other stair users, form a comparative basis, as the teams traversed sections of identical terrain: landing, stair, landing and stair. The ground floor had a different layout to the others, so for comparability the ten floors from 11 to 1 were considered. The average (mean) of the two male teams and the two female teams are depicted in Figure 4-10, as well as the overall average stair speed per floor.

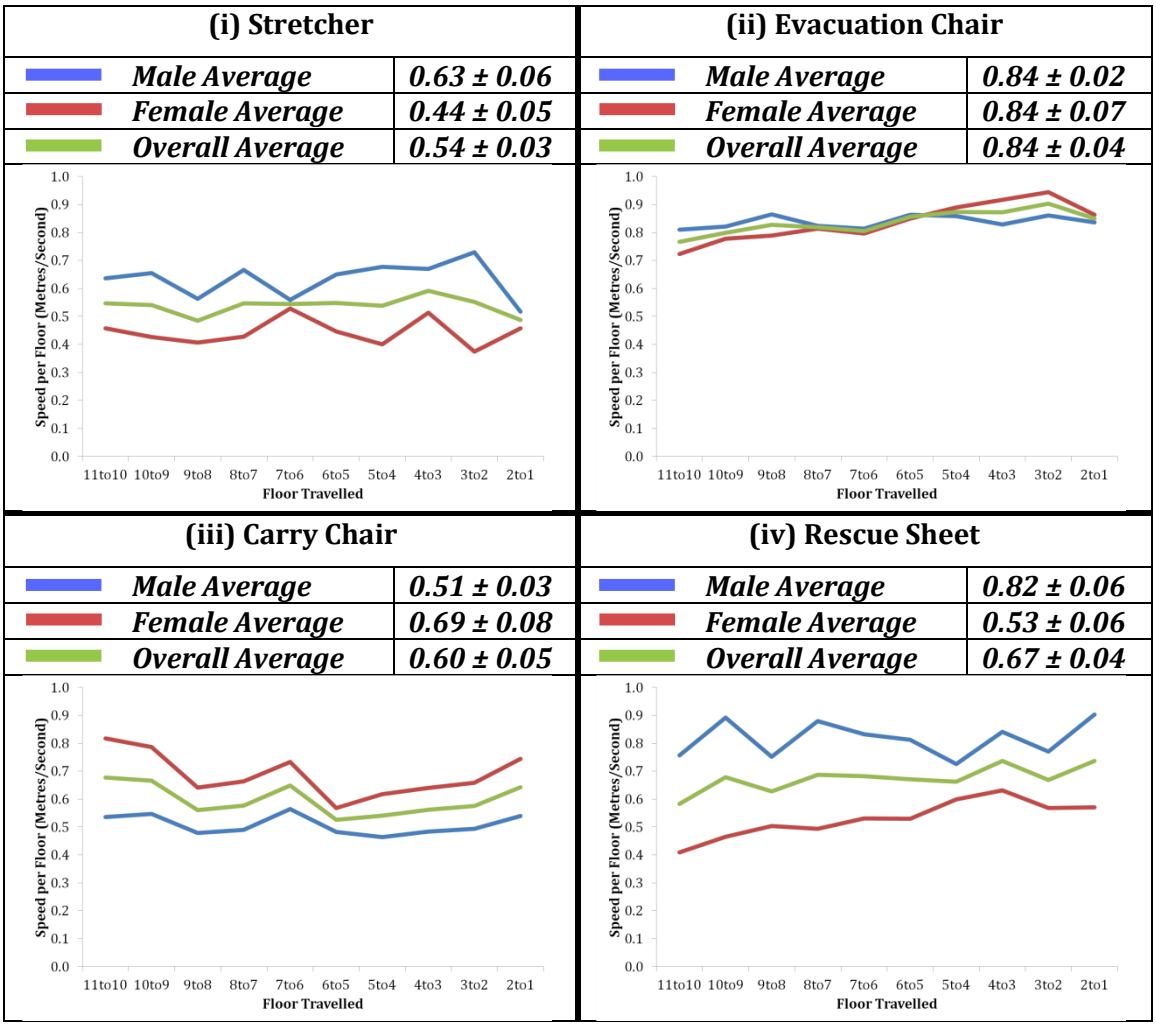


Figure 4-10: Male, female and overall average speed per floor for each device.

These curves again show the gender independence of the evacuation chair, as well as low variance in speeds between floors. The most uniform performance was achieved by the stretcher. The overall average speed per floor indicates that, per

floor, the evacuation chair is the fastest device (averaging 0.84 m/s) followed by the rescue sheet (averaging 0.67 m/s), the carry chair (averaging 0.60 m/s) and finally the stretcher (averaging 0.54 m/s.)

An objective of analysing the data per floor is to investigate the effect of fatigue when descending stairs with movement devices. If handler fatigue reduces the speed of the device team, there will be a decreasing trend in speed as the distance travelled increases. As presented in Table 4-10, the trend lines of the male and female average curves depicted in Figure 4-10 are characterised by a slight linear slope. These are negative for the carry chair (suggesting that in general speeds slightly decreased per floor as the teams progressed down the stairs) and positive for all other devices (suggesting, that in general speeds slightly increased per floor as teams progressed down the stairs). However, the correlation statistic R^2 indicates that there is no significant relationship between the number of floors the devices have travelled and the speed per floor in all cases except the female evacuation chair teams and the female rescue sheet teams. In both of these cases, a significant positive relationship was found, indicating that, as the teams progressed down the stairs, their speeds increased. Furthermore, for female teams using the evacuation chair the number of floors travelled significantly predicted the speed per floor, $\beta=.02$, $t(8)=5.68$, $p<.05$. For female teams using the rescue sheet the number of floors travelled significantly predicted the speed per floor, $\beta=.02$, $t(8)=5.05$, $p<.05$. In all other cases floors travelled is not a predictor of floor speed. This is consistent with Choi *et al.*'s recent study on stair descent speeds, which found that over 50% of people increased their stair descent speed in the second half of a 50-storey descent [236].

This clearly indicates that there is no significant negative relationship found between the floors travelled and the speed attained over this sized stairway. This does not mean, however, that fatigue would not be an important factor for a greater distance of stair descent, or for those who are not expertly trained. More data are required to investigate the fatigue dynamics repeatedly evacuating patients.

Table 4-10: Least squares trends between number of floors travelled (x) and speed per floor (y)

Device	Average Curve	Trendline	Coefficient of determination (R^2)
Stretcher	Male	$y = 0.629 + 0.001x$	No x,y relationship; R^2 = .001, F(1,8)= 0.01, p < 0.05.
	Female	$y = 0.444 + 0.000x$	No x,y relationship; R^2 = .000, F(1,8)= 0.00, p < 0.05.
Evacuation Chair	Male	$y = 0.822 + 0.003x$	No x,y relationship; R^2 = .167, F(1,8)= 1.60, p < 0.05.
	Female	$y = 0.725 + 0.020x$	Significant x,y relationship; R^2 = .801, F(1,8)= 32.25, p < 0.05.
Carry Chair	Male	$y = 0.524 - 0.003x$	No x,y relationship; R^2 = .063, F(1,8)= 0.54, p < 0.05.
	Female	$y = 0.749 - 0.011x$	No x,y relationship; R^2 = .185, F(1,8)= 1.82, p < 0.05.
Rescue Sheet	Male	$y = 0.802 + 0.003x$	No x,y relationship; R^2 = .016, F(1,8)= 0.13, p < 0.05.
	Female	$y = 0.426 + 0.019x$	Significant x,y relationship; R^2 = .761, F(1,8)= 25.47, p < 0.05.

Moreover, the questionnaires completed by each member of the handling team indicated that 60% felt they needed to take one or more rest breaks during stair descent. Therefore the next section investigates the team stoppages during stair descent.

4.6 Device Stoppages on Stairs

Stoppages were defined in the video analysis as a time where the device was stationary (for more than 2 s) in order for the team to; adjust the device, or change handling positions, or change handlers or rest. The footage showed that devices tended to pause at the top step of every flight of stairs, to change handling technique (e.g. in the case of the stretcher) or to tilt the device (in the case of the evacuation chair) but these pauses were not recorded as part of the stopping analysis as they were generally shorter than 2 s, occurred at every floor and were already accounted for in the floor speed of the device. Presented in Table 4-11 are the number of stops recorded during the teams' stairwell descent and the total stoppage time.

Table 4-11: Number of stops recorded and total stoppage duration per trial.

	Device			
	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
Team	Number of stops [Stopping Duration (seconds)]			
Male 1	2 [19 s]	0 [0 s]	7 [59 s]	1 [8 s]
Male 2	2 [22 s]	0 [0 s]	2 [13 s]	0 [0 s]
Female 1	4 [45 s]	0 [0 s]	3 [22 s]	2 [7 s]
Female 2	5 [82 s]	0 [0 s]	3 [42 s]	1 [3 s]
Average Stopping Duration	M: 10 s F: 14 s	M: 0 s F: 0 s	M: 8 s F: 11 s	M: 8 s F: 3 s

Appendix K tabulates each stop's duration and position within the stairwell. All stops occurred when the handling teams were partly on a flight of stairs and partly on a landing. When carrying the carry chair and the stretcher, teams primarily stopped to swap position (thereby resting an arm that was carrying the weight) and to wipe their hands or the handles of the device. The rescue sheet operators stopped to readjust the strapping of the device (and once because they had accidentally dropped the device and PRM). The female handling teams did generally stop more than the male teams, possibly indicating higher levels of muscular fatigue. It is noted that the rescue sheet did not stop for very long in any trial however, and the evacuation chair was the only device that did not stop at any time during the descent.

The device with the most frequent stops was the carry chair. For the male assist teams, the PRM and device was carried by only two people, while for the female assist team the weight of the PRM and chair was shared between four people. This explains why the total number of stops for the male teams (9) exceeded that of the female teams (6). It is also noted that Male 1 team stopped a total of 7 times compared to only 2 times for the Male 2 team. While both teams stopped to swap position or to swap device handlers, inspection of the video reveals that at each of their 7 stops, the Male 1 team wiped their hands or the handles of the carry chair, whereas the Male 2 team did not need to wipe their hands nor the handles. While Male 1 team swapped staff during the decent more often than Male 2 team, the driver for the stop may have been related to the loss of grip experienced by the handlers caused by higher levels of perspiration or by fitness levels. If correct, this

also suggests that the design of the device handles could be improved to a more ergonomic design providing both better grip and moisture absorbency. This accords with findings by Lavender et al. [23], where extended handles on movement devices were found to improve carrying technique. The full record of actions noted within these stoppages is tabulated in Appendix L.

The position in the stairwell that the stops occurred are depicted within the average stair speed graphs in Figure 4-11, showing that the slowest speeds generally associate with the positions in which either one or both teams stopped.

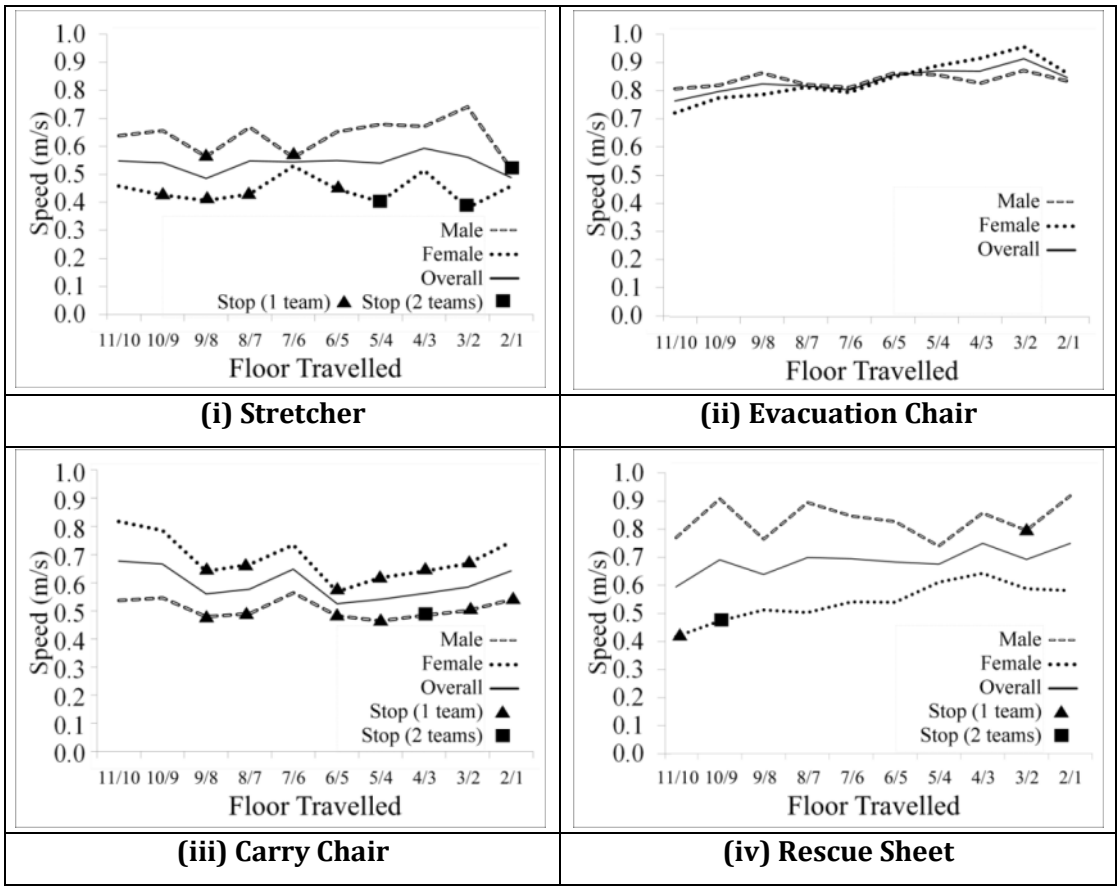


Figure 4-11: The position of stoppages and average speeds per floor.

Considering the position of stoppages in a regression analysis of each trial's floor-by-floor speed, by introducing a binary variable associated with a stop (not accounting for the duration of the stop), it is found that the position of stoppages significantly predicted speed per floor for the stretcher and the carry chair, but not for the rescue sheet (see Table 4-12). This is consistent with Figure 4-11, where

the fluctuations in speed do not coincide as frequently with the stoppages noted for the rescue sheet as they do for the stretcher and the carry chair.

Table 4-12: Stoppage position as a predictor for stair descent speed per floor

Device	Team	Stoppage t-statistic (tested against significance p<.05)	Predictor variable
Stretcher: For each team, stoppage position predicts speed per floor.	Male 1	β=-.22, t(7)=17.56,	Y
	Male 2	β=-.02, t(7)=7.68,	Y
	Female 1	β=-.01, t(7)=9.10,	Y
	Female 2	β=-.01, t(7)=9.74,	Y
Carry Chair: For each team, stoppage position predicts speed per floor.	Male 1	β=-.01, t(7)=6.59,	Y
	Male 2	β=-.01, t(7)=5.48,	Y
	Female 1	β=-.04, t(7)=12.72,	Y
	Female 2	β=-.02, t(7)=10.77,	Y
Rescue Sheet: Only for male team 1, stoppage position predicts speed per floor.	Male 1	β=-.03, t(7)=2.52,	Y
	Male 2	No stoppages	N
	Female 1	β=-.01, t(7)=1.00,	N
	Female 2	β=-.01, t(7)=0.58,	N

While the previous section found that fatigue was not a determining factor for descending ten floors, the effect of stoppages established in this section perhaps indicates that the handling teams stopped due to fatigue, but somewhat recuperated when once they had swapped positions/rested.

4.7 Overtaking Potential

The ability for other evacuees to use the stair when the PRM is being assisted down the stairs is an important consideration. The stairs in the building were quite wide, being 1.4m from handrail to handrail and were therefore sufficiently wide to allow two people to comfortably descend side by side. Thus, when the device only occupies one stair lane, other stair users could evacuate alongside the device and overtake the handling team. When two lanes were occupied by the device and handlers, no one else could overtake the device on the stairs as the stairs were completely blocked. In some cases, the device and handlers occupied more than a lane but less than two lanes. In this case, some of the other evacuees could pass the device and handlers, but not all. In the post-trial questionnaire participants were asked; “How easy was it to overtake the Handling Team with the PRM?” and

responded with a rating from 1 to 5, where 1 was "very difficult" and 5 was "very easy". The average responses from 353 questionnaires are presented as the overtaking rating in Table 4-13. However, there are several difficulties with the responses. First is the translation into Flemish. The literal translation may not have conveyed the correct meaning. Furthermore, the participants may have misunderstood the meaning of the question. For example in the case of the evacuation chair, the device was moving very fast and from the video footage it is clear that many of the participants had difficulty in catching the chair. The relatively low ranking of the evacuation chair could indicate that they *did not* overtake instead of the *difficulty* experienced in overtaking. In addition, when the handlers of the stretcher stopped on the landing/stair interface, occupants were able to pass the stationary device, hence the high score for the device. Thus, in addition to the questionnaire results, the number of stair lanes the device/handlers occupied is noted in Table 4-13 as this provides an indication of overtaking potential.

Table 4-13: Overtaking potential per device.

	Device							
Team	Stretcher		Evacuation Chair		Carry Chair		Rescue Sheet	
Male/Female	M	F	M	F	M	F	M	F
No. stair lanes occupied	2	2	1	1	1	2	1.5	1.5
Overtaking rating (1-5)	3.4	2.7	3.5	3.2	3.9	1.9	3.6	2.9

The video footage clearly demonstrated that people would overtake when there was a physical opportunity to do so. As the evacuation chair and the carry chair (male handlers) only occupied one lane, the other evacuees could easily overtake these devices. The rescue sheet occupied more than one lane, and group members took the opportunity to overtake in the instances when there was sufficient space. For the stretcher and the carry chair with female handling team, it was impossible to overtake while concurrently descending the stairs; the group waited for the device to stop before passing.

4.8 Safety Factors

Another consideration in evaluating movement devices is the safety of the staff and patients involved. One of the Ghent trials indicated that there are potential safety issues with the rescue sheet: a trial was halted by the experiment manager as it was deemed potentially dangerous to the PRM. Following each trial, the PRM and every member of the handling team were asked about the devices' safety. These questionnaire data are presented in Table 4-14, where the participants were surveyed about how safe they felt in each experiment phase (preparation, horizontal travel and vertical travel.) Each responded from 1 to 5, where 1 indicated that they felt "very unsafe" and 5 that they felt "very safe".

Table 4-14: Perceived safety of PRM and operators

	Operators feeling of safety per phase			PRM feeling of safety per phase		
Device	Preparation (M/F)	Horizontal (M/F)	Vertical (M/F)	Preparation	Horizontal	Vertical
Stretcher	4.1 / 4.1	4.3 / 4.1	3.7 / 3.0	5.0	4.6	4.5
Evacuation Chair	4.4 / 4.3	4.9 / 4.9	4.8 / 4.3	5.0	5.0	4.8
Carry Chair	4.1 / 4.3	4.3 / 4.4	2.7 / 3.5	4.9	4.9	4.1
Rescue Sheet	4.0 / 3.9	4.0 / 3.8	3.5 / 2.4	4.8	4.9	5.0

The results indicate that the PRM generally felt safe in each experiment phase, but that operators generally felt less safe when traversing the stairs. Table 4-15 presents the average safety rating across all experiment phases from the operators questionnaires. As the simulated PRM is an experienced member of the hospital handling team, their opinion as an actual PRM is not considered valid as they are not actually a PRM and they are familiar with the operation of the devices and they are also familiar with the capabilities of their colleagues in the handling teams. Thus, their opinion is not considered to be a valid representation of how an actual PRM may feel, in particular one who is unfamiliar with the devices and the handlers. Their results are presented here for completeness.

Table 4-15: Average safety rating

Device	Male Operators	Female Operators
Stretcher	4.0	3.7
Evacuation Chair	4.7	4.5
Carry Chair	3.7	4.0
Rescue Sheet	3.8	3.4

This indicates that operators feel the most safe when using the evacuation chair. In general, female handling teams felt less safe during the experiment than the male teams, with the exception of the Carry Chair trials (where there were more operators in the female teams than there were in the male teams). Also, the least safe device, in the opinion of the handlers was the rescue sheet for the female operators with the carry chair and the rescue sheet being about equal for the male operators.

In addition, it is notable that the only trial in which the trials were halted was a rescue sheet trail. The organisers observing the progress of the rescue sheet on the stairway portion of this trial regarded the handling position as being potentially dangerous to the PRM. It appeared that the PRM had shifted within the device and her neck was no longer supported by the mattress within the straps. For this reason, this trial was stopped by the organisers on safety grounds. This indicated an issue with the strapping of the PRM, where it either loosened over time or was not fully secure following the initial preparation procedure. The former would suggest a need to review the PRM position during evacuation, and the latter an issue with the operators' preparation technique.

Using the findings presented in this chapter, subsequent chapters of this work will address the modelling requirements proposed in section 2.4.2, introducing methods of performance comparison, along with algorithms derived to represent the use of movement devices within evacuation modelling software buildingEXODUS [26]. Chapter 8 discusses the key findings from the experimental work undertaken, and addresses the research questions posed in Chapter 1.

5 PERFORMANCE EVALUATION

The Ghent experiment evaluated the use of movement devices by trained staff within a hospital setting. The measurements taken reflect the key performance factors of the movement device: how quickly they can be prepared and operated in each phase of their evacuation, the effect of gender (i.e. physical ability) on these speeds, the number of handlers required, and their perceived safety. These data are instructive in assessing the key differences between the use of these devices for hospital evacuation, and these factors may be considered separately to inform appropriate use in a healthcare context. However it may be useful for engineering calculations to collate these results in a more practical way. In an attempt to provide a means of combining the performance factors in a transparent, flexible and meaningful manner a simple metric is presented based on the weighted sum of each performance factor. The metric offers a simple approach to gauge the overall performance advantage of one device over another, allowing user-based priorities and user-specific performance factors to be considered.

In addition, a numerical simulation is devised to demonstrate the applicability of this data within existing evacuation models. Agent-based evacuation software can represent the movement of PRM by imposing reductions in the speed of the agents involved [15], and therefore may numerically approximate the performance of the devices by combining various factors. To demonstrate this, the data are incorporated within the buildingEXODUS software [234] to evaluate the impact of using each device for the evacuation of a hypothetical hospital ward using available day and night shift staff. The results of this simulation provide valuable insights into the performance of the devices as well as the ability to test the potential effect of unknown factors, like handler fatigue. However, as this simulation does not include a geometric representation of movement devices, i.e. they are represented by human-sized agents, this software demonstration also highlights the limitations of numerical simulation. Implicitly representing a device by using experimental data in this way does not physically represent the space it occupies, nor the associated behaviour of other occupants. The evacuation times

derived from this type of numerical simulation is therefore indicative of a situation where geometric boundaries are not an issue (i.e. there is plenty of space for a device to manoeuvre) and where other evacuees are not present. Consequently, this type of simulation does not adequately represent the real evacuation dynamics of transporting PRM. Work is thus presented in subsequent chapters in order to develop explicit models that better simulate these devices for evacuating patients from hospitals.

5.1 Device performance metric

The previous chapter compared the performance of each movement device on particular tasks, for example: the time taken to prepare the device, the speeds it achieved in horizontal and vertical travel, and its overtaking potential. When selecting the most appropriate device to use in a particular situation, these performance factors may be considered, along with other constraints (e.g. cost, space) that organisations may also take into account. Therefore, it is difficult to determine which device may be best to use based on the individual performance factors taken in isolation. The overall performance of a device will be a function of some or all of these factors and some factors may be of greater significance to potential users or in particular applications than other factors. For example, an evacuation situation involving one PRM located on the upper floor of a building with lots of potential device handlers will have different considerations to a situation involving many PRM located on the upper floor of a building with few device handlers available. There is no single solution to the wide range of evacuation scenarios that may require the use of movement devices. Even in hospitals, a one-size-fits-all-approach may not fulfil the requirements of specialist wards, unusual building structures, highly variable staffing levels and staff training levels.

In an attempt to provide a way of combining the factors in a transparent, flexible and meaningful manner, a simple metric is devised based on the weighted sum of each factor (see equation 1). The factor weights (W_f) can be selected based on the requirements of the user and the demands of the intended application. The

allocation of these weights is constrained so that their sum, when divided by the number of factors, is equal to 1.0. For each factor (f), the devices are allocated a normalised performance rating (NPR_f), which is the performance rating derived from the Ghent experiments normalised by the poorest performance score for that factor. So the poorest performing device will have an NPR_f of 1.0 while the other devices will have an NPR_f greater than 1.0. The overall performance score (OPS) for the device is then given by the sum of each normalised performance rating multiplied by the user-defined factor weighting as shown in Equation 5-1. The device with the best combination of performance factors for the identified application will have the largest OPS (i.e. the one with the highest sum norm rating).

Equation 5-1

$$OPS = \sum_{f_1}^{f_n} NPR_f \,.\, W_f$$

$$where \sum_{f_1}^{f_n} \frac{W_f}{n} = 1.0$$

The performance rating for each factor can be based on the male performance, the female performance or the average performance. Here, the ratings are calculated separately for the performance of male handling teams (Table 5-1) and female handling teams (Table 5-2). When the average performance is considered, an additional factor describing gender independence may be introduced (as tabulated in Appendix M), that yields similar results.

For this initial comparison, ten performance factors were considered:

f_1: Preparation times (Table 4-3).

f_2: Number of essential operators for the preparation phase (Table 3-5).

f_3: Straight horizontal speeds (Speeds across Area 3: Appendix H)

f_4: Right angle turning speeds (Table 4-7)

f_5: Number of essential operators for the horizontal phase (Table 3-5).

f_6: Door transition times (Table 4-8)

f_7: Overall stair descent speed (Table 4-9)

f_8: Number of essential operators for the vertical phase (Table 3-5).

f_9: Number of lanes occupied in a two-lane staircase (Table 4-13)

f_{10}: Operator safety rating (average from Table 4-14)

These factors are representative of the key aspects of the Ghent experiment, however any other quantifiable performance factor from this thesis, or other bodies of data, could potentially be included in this simple comparative structure.

Table 5-1: Rated factors in device performance for male teams

	f	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
	Prep Time (s)	68	29	35	53
$\boldsymbol{NPR_1}$	Norm Prep Time	1	2.3	1.9	1.3
	No. Prep Operators	2	2	2	2
$\boldsymbol{NPR_2}$	Norm Prep Ops	1	1	1	1
	Straight H. Speed (m/s)	1.24	1.54	1.44	1.38
$\boldsymbol{NPR_3}$	Norm S.H. Speed	1	1.2	1.2	1.1
	Corner H. Speed (m/s)	1.12	1.4	1.43	1.07
$\boldsymbol{NPR_4}$	Norm C.H. Speed	1	1.3	1.3	1
	No. H. Operators	4	1	1	2
$\boldsymbol{NPR_5}$	Norm H Ops	1	4	4	2
	Door Transition (s)	6	4.5	4.5 *	7
$\boldsymbol{NPR_6}$	Norm Door Trans	1.2	1.6	1.6	1
	V. Speed (m/s)	0.63	0.83	0.5	0.82
$\boldsymbol{NPR_7}$	Norm V. Speed	1.3	1.7	1	1.6
	No. V. Operators	4	1	3	2
$\boldsymbol{NPR_8}$	Norm V. Ops	1	4	1.3	2
	No. lanes occupied	2	1	1	1.5
$\boldsymbol{NPR_9}$	Norm lanes	1	2	2	1.3
	Op Safety Rating	4	4.7	3.7	3.8
$\boldsymbol{NPR_{10}}$	Norm OS Rating	1.1	1.3	1	1
	Sum Norm Rating	10.6	20.4	16.3	13.3

** NOTE: DUE TO LACK OF DATA, THE DOOR TRANSITION TIME FOR THE CARRY CHAIR IS BASED ON DOOR TRANSITION TIME FOR THE EVACUATION CHAIR. THE HORIZONTAL PERFORMANCE AND DOOR TRANSITION TECHNIQUE OF THESE TWO CHAIR DEVICES WERE SIMILAR.*

Under the assumption that all the performance factors carry equal weight, the evacuation chair has the highest performance score: 25% better than the carry chair, 53% better than the rescue sheet and 92% better than the stretcher for male teams and, similarly, 30% better than the carry chair, 67% better than the rescue sheet and, 83% better than the stretcher for female teams.

Table 5-2: Rated factors in device performance for female teams

	f	Stretcher	Evacuation Chair	Carry Chair	Rescue Sheet
	Prep Time (s)	88	36	49	78
$\boldsymbol{NPR_1}$	Norm Prep Time	1	2.4	1.8	1.1
	No. Prep Operators	2	2	2	2
$\boldsymbol{NPR_2}$	Norm Prep Ops	1	1	1	1
	Straight H. Speed (m/s)	1.19	1.42	1.33	0.87
$\boldsymbol{NPR_3}$	Norm S.H. Speed	1.4	1.6	1.5	1
	Corner H. Speed (m/s)	1.09	1.14	1.35	0.86
$\boldsymbol{NPR_4}$	Norm C.H. Speed	1.3	1.3	1.6	1
	No. H. Operators	4	1	1	2
$\boldsymbol{NPR_5}$	Norm H Ops	1	4	4	2
	Door Transition (s)	5.5	6	6 *	9.5
$\boldsymbol{NPR_6}$	Norm Door Trans	1.7	1.6	1.6	1
	V. Speed (m/s)	0.44	0.82	0.66	0.52
$\boldsymbol{NPR_7}$	Norm V. Speed	1	1.9	1.5	1.2
	No. V. Operators +	4	1	4	2
$\boldsymbol{NPR_8}$	Norm V. Ops	1	4	1	2
	No. lanes occupied	2	1	2	1.5
$\boldsymbol{NPR_9}$	Norm lanes	1	2	1	1.3
	Op Safety Rating	3.7	4.5	4	3.4
$\boldsymbol{NPR_{10}}$	Norm OS Rating	1.1	1.3	1.2	1
	Sum Norm Rating	11.5	21.1	16.2	12.6

** NOTE: DUE TO LACK OF DATA, THE DOOR TRANSITION TIME FOR THE CARRY CHAIR IS BASED ON DOOR TRANSITION TIME FOR THE EVACUATION CHAIR. THE HORIZONTAL PERFORMANCE AND DOOR TRANSITION TECHNIQUE OF THESE TWO CHAIR DEVICES WERE SIMILAR.*

Table 5-1 and Table 5-2 represent the base case, where each factor is weighted equally: $Wf_1, Wf_2, \ldots., Wf_{10} = 1.0$. They therefore assume that each performance factor is equally important. However, more realistic performance assessment criteria depend significantly on the environment in which the use of devices is being considered. For example, consider a situation where vertical performance, horizontal performance and preparation time are considered to be of paramount importance: for instance where the PRM is located on the upper floor of a high rise building which has long corridors that need to be traversed, but staffing is not an issue. As such, the weight for the vertical performance (Wf_7) can be increased from its default value (1.0) to 1.5, the weight for the preparation time (Wf_1) can be decreased from its default value (1.0) to 0.9 and the weight for the horizontal performance (Wf_3) can be decreased from its default value (1.0) to 0.6 and the weights for all the other NPR ignored ($Wf_2, Wf_4, Wf_5, Wf_{6,} Wf_8, Wf_9, Wf_{10} = 0.0$)

In this case, the OPS for the stretcher, evacuation chair, carry chair and rescue sheet become:

- For male teams, 3.5, 5.3, 3.9, and 4.2 respectively.

The evacuation chair scores 55% better than the stretcher, 36% better than the carry chair and 26% better than the rescue sheet.

- For female teams, 3.2, 6.0, 4.8, and 3.4 respectively.

The evacuation chair scores 84% better than the stretcher, 25% better than the carry chair and 76% better than the rescue sheet.

Therefore while the evacuation chair still offers the best performance, the advantage over some of the other devices is diminished while over other devices it is increased.

In another example, staffing may be the predominant issue, for instance a situation when there are a number of PRM and only a small number of staff prepared to be handlers. In this case, the weight for the staffing performance factors Wf_2, Wf_5, and Wf_8 may be increased from their default value (1.0) to 1.8 while all other parameters equally share the rest of the weighting allocation by decreasing from their default value (1.0) to 0.66, i.e. ($Wf_1, Wf_3, Wf_4, Wf_6, Wf_7, Wf_9, Wf_{10} = 0.66$). In this case the OPS for the stretcher, evacuation chair, carry chair and rescue sheet become:

- For male teams, 10.4, 23.7, 17.9, and 14.5 respectively.

The evacuation chair scores 128% better than the stretcher, 32% better than the carry chair and 64% better than the rescue sheet.

- For female teams, 11.0, 24.2, 17.5, and 14.0 respectively.

The evacuation chair scores 120% better than the stretcher, 38% better than the carry chair and 73% better than the rescue sheet.

Thus the evacuation chair still offers the best performance and returns an improved performance advantage over the other devices, with a significant improvement in performance over the stretcher compared to the case where all the factors are of equal weight.

This metric offers a simple approach to gauge the overall performance advantage of one device over another, allowing user-based priorities and user specific performance factors not already included to be incorporated in the assessment. Logistical considerations can be included, such as the cost of the devices, their storage and maintenance requirements, and associated training requirements. In this analysis it is assumed that the medical requirements of the PRM have already been used to filter out inappropriate devices. For example, if the PRM cannot be physically moved from a wheelchair to the assist device then none of the devices considered here would be appropriate for use, regardless of the score. Furthermore, if the PRM has a condition which means that they cannot lie down this would rule out the stretcher and the rescue sheet, or if they could not sit up, this would rule out the evacuation chair and the carry chair.

It is important to emphasise that all the data used in this comparison reflect the performance factors of highly trained staff. Therefore, the results presented cannot be generalised to inexperienced or untrained individuals. Furthermore, the level of training required to become proficient with each device is unclear and is likely to vary between devices. For some devices, such as the evacuation chair, while easy to use, the transition from landing to stair is unintuitive and so requires a level of training/demonstration to provide the handler with the confidence to take a PRM down a flight of stairs. In addition, the level of recurrent training required for each device is uncertain and is likely to vary from device to device. For example an evacuation chair was recorded as having a slow stair descent speed in the WTC 9/11 evacuation (account WTC1/069/0002 [111]), to evacuate a PRM. It was reported that most of the handlers had seen an instructional video on how to use the device some time prior to the event, but most had forgotten the details. it is suggested that better training would have made this process significantly quicker and easier.

To expand the device comparison, other factors that could be incorporated include the effect of physical effort on the handlers, for example the evacuation of the ergonomics of manual carried and track type devices as evaluated by Lavender *et*

al. [23]. The evacuation performance on the horizontal and vertical could also be considered regarding the individual progress per operator by including a parameter that measures metres travelled per operator per second. To further aid these comparison methods, hospital scenarios can be simulated numerically utilising the performance data for each device, as the next section explores.

5.2 Numerical Simulation of Hospital Ward Evacuation

To further evaluate the performance of the evacuation devices, the data presented in this thesis have been utilised in a modelling application. Here the data are applied to a demonstration evacuation analysis concerning the hypothetical evacuation of a ward on the 11th floor of a hospital. To maximise applicability, the geometric scenario was chosen to be similar to those in which the data were collected. The data are then incorporated within the buildingEXODUS software [234] to numerically simulate the impact of using each device for the evacuation of the hospital ward using available day and night shift staff.

5.2.1 Geometry and Scenario Description

The geometry used in the analysis is based on the Ghent University Hospital Dermatology/Pain Clinic ward (see Figure 5-1). The stair dimensions are identical to that used in the trial, described in the previous section. The ward contains 16 rooms, 12 two-patient rooms and four one-patient rooms. For this analysis it is assumed that the ward to be evacuated is fully occupied with 28 patients and that all patients have reduced mobility, and require assistance to evacuate. It is assumed that only members of ward staff are available to assist in the evacuation. In accordance with Ghent Hospital rotas, during a day shift there are seven staff members while during a night shift there are four staff members. In addition, it is assumed that the available staff members are all male or all female. As there are insufficient staff available to evacuate all the patients in one trip, on assisting a patient to evacuate, handlers are required to return to the ward (via the stairs) and assist the next patient. Thus the staff members are required to make multiple

trips. As part of the scenario description, each of the four movement devices is used in turn to evacuate the entire ward.

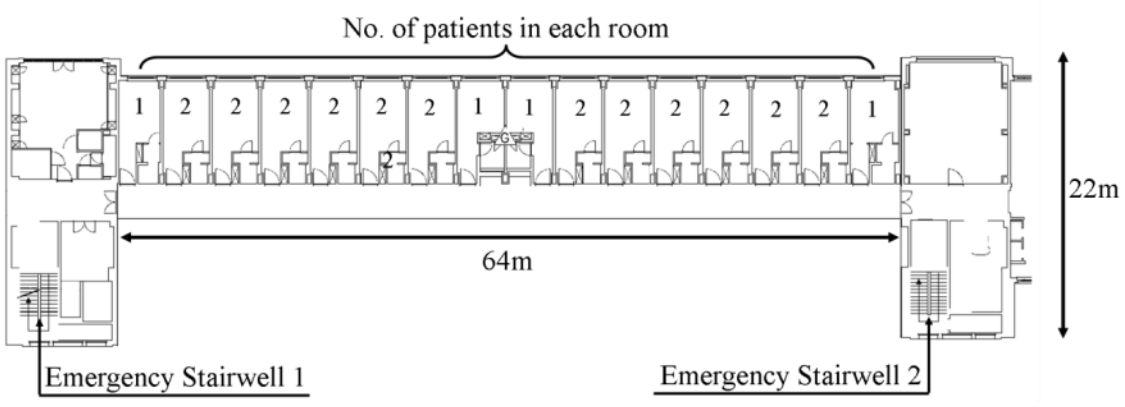


Figure 5-1: Key dimensions of hospital ward used in evacuation simulations

The emergency stairwells are assumed to be identical to the stairwells in the Ghent experiment (Figure 3-3), where each of the 11 floors is in a dog-leg configuration with two flights of stairs and two landings. Each flight of stairs consists of 12 risers which each measure 0.175m in height and 0.29m in depth. The effective width of the staircases is 1.4 metres, representing the space between handrails on either side. As per Figure 5-1, the paths of both staircases turn clockwise in descent.

A range of scenarios are considered to explore evacuation outcomes based on: the device used, the gender of the staff members and the number of staff available (representing day and night shift staff numbers). As such, there are 16 separate scenarios to consider, as presented in Table 5-3. In addition, a range of scenarios are simulated exploring the potential impact of operator fatigue as staff repeatedly collected patients during the simulation process. The eight fatigue scenarios are applied to the slowest scenarios for each device, in order to represent the greatest possible effect of fatigue factors. Therefore only the case with the female assist teams on night shift are extended in this way to model hypothetical fatigue coefficients.

As the impact of fatigue is currently poorly understood, in these simulations it is assumed that the impact of fatigue is felt on each trip following the first. Within

these simulations, fatigue is represented by a reduction in the descent/ascent speed by a fixed amount. Here fatigue effects of 5% and 10% are considered. Thus, for the first descent/ascent, the team travels at their normal stair speed and at the start of their second decent/ascent, the descent/ascent stair speed is reduced by 5% (or 10%). At the start of the third descent/ascent it is further reduced by an additional 5% (or 10%) and so on.

Table 5-3: Scenarios for Numerical Simulation

Scenario no.	Device	Staff Rota	No. Teams	Members in Team	Team Gender	Fatigue Percent
1	Stretcher	Day	1	4	Male	0
2	Evacuation Chair	Day	6	1	Male	0
3	Carry Chair	Day	2	3	Male	0
4	Rescue Sheet	Day	3	2	Male	0
5	Stretcher	Night	1	4	Male	0
6	Evacuation Chair	Night	3	1	Male	0
7	Carry Chair	Night	1	3	Male	0
8	Rescue Sheet	Night	2	2	Male	0
9	Stretcher	Day	1	4	Female	0
10	Evacuation Chair	Day	6	1	Female	0
11	Carry Chair	Day	1	4	Female	0
12	Rescue Sheet	Day	3	2	Female	0
13	Stretcher	Night	1	4	Female	0
14	Evacuation Chair	Night	3	1	Female	0
15	Carry Chair	Night	1	4	Female	0
16	Rescue Sheet	Night	2	2	Female	0
17	Stretcher	Night	1	4	Female	5
18	Evacuation Chair	Night	3	1	Female	5
19	Carry Chair	Night	1	4	Female	5
20	Rescue Sheet	Night	2	2	Female	5
21	Stretcher	Night	1	4	Female	10
22	Evacuation Chair	Night	3	1	Female	10
23	Carry Chair	Night	1	4	Female	10
24	Rescue Sheet	Night	2	2	Female	10

As described in chapter 3, different numbers of assist staff are required to operate each device, therefore multiple evacuation teams were represented in the simulations. For example, as the evacuation chair only requires a single member of staff for evacuation but two for preparation, it is assumed that there are six teams on the day shift and three teams on the night shift, with one staff member in each

shift required to stay on the ward for preparation. In contrast, as the stretcher requires four people for both preparation and evacuation, it is assumed that there is only one team on the day shift and one team on the night shift. Staff not utilised for assist teams are assumed to be with the patients, and helping to prepare patients for their evacuation.

5.2.2 Model Setup

Existing buildingEXODUS v5.1 [16] functionality was used to simulate the process of staff members repeatedly collecting patients. As described in section 2.2.2, this agent-based model can implicitly represent device speeds, therefore the movement times of the staff-patient teams representing the device were implemented. This was achieved using the extant itinerary and group functionality within the model. Using itineraries it is possible to assign tasks to agents that must be completed prior to self-evacuating. Using the group functionality, agents can be assigned to groups which can assemble and disband during evacuation. When assigned to a group, members travel at the speed of the slowest group member. In this way, it is possible to represent the assist team and the PRM and specify their travel at a predetermined speed.

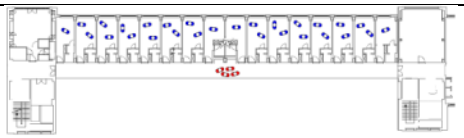
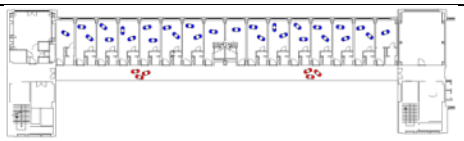
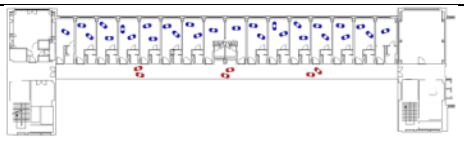
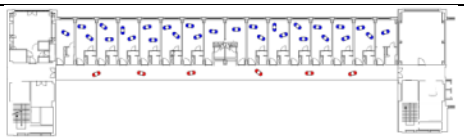
For these scenarios, itineraries are defined as a set of *tasks* that must be completed in order. Each agent in the model is situated on a node (i.e. a discretised portion of the geometry); therefore the *tasks* of the handling teams are described by allocating target nodes at the desired itinerary locations. For example, in order to collect a patient, the *task* identifies the node where the patient is situated, and sends the handling team toward that node. Additionally, all agents are allocated *genes*: identification numbers that indicate who can join groups with whom. Some agents are additionally defined as *leaders*, which enables the priority of their itineraries over others. The itinerary functions used in this simulation are tabulated in Table 5-4.

Table 5-4: Itinerary tasks employed for the numerical simulation of a hospital ward evacuation

Task Functionality in buildingEXODUS v5.1 [16]	Application within Hospital Simulation
Task: Form Group Allows occupant groups to be formed at a pre-defined location and then move off as a group (i.e. moving along the same route and with speeds adapted to reflect slower moving group members). Group members are defined by the user attributing a *Gene* number to each member. Each group is also assigned a *Leader.*	This task represents the individual agents joining together in order to form a group of handling team members. The leader's itinerary is then specified to the evacuation of patients.
Task: Coordinated Delay Allows a group of people to experience a simultaneous delay at a pre-defined location. The delay experienced by the group of individuals does not commence until the defined number of individuals within the group have all arrived. Once the specified number of occupants have arrived (as defined by the *Size* attribute), a delay will then be randomly calculated between the minimum and maximum delay times defined by the user.	This task represents the preparation delay, where all of the handling team members arrive at the patient, and delay for a specified duration. The minimum and maximum specified as the preparation times from the Ghent data.
Task: Collect Person Allows a person classified as a *Leader* to collect an individual at a pre-defined location and then move off as a group. Once the specified number of occupants have arrived (as defined by the *Size* attribute), the collected occupants itinerary will be updated by adopting the leaders itinerary tasks as they are specified the same *gene*. In this manner, the collected individual (and the full group) will follow the actions of the group's leader.	Once the preparation is complete, this task means the group of handling team members can collect the patient (i.e. join them to their group) which means they all then move together towards the exit.

For the purposes of these itineraries, the patients were numbered from left to right: Patient 1, Patient 2, …, Patient 28. A pre-determined collection list was used to determine the order in which patients would be collected, based on collecting the nearest patient each time. In this way, the first patient an agent collects is their nearest patient, using the nearest staircase. The agent then ascends the same staircase and collects the next nearest patient on the floor. These lists are itemised in Table 5-5, where each bracketed set specifies the order in which patients numbered 1-28 are collected by each team. Also depicted are the starting positions of the handling teams as the simulation commences.

Table 5-5: Patient collection lists and agent positioning for numerical simulation

Collection List A (for one team of three or four handlers): Team 1: [15, 28, 27, 26, 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 14, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]	
Collection List B (for 2 teams of two or three handlers): Team 1: [8, 1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 11, 13, 14] Team 2: [22, 28, 27, 26, 25, 24, 23, 21, 20, 19, 18, 17, 16, 15]	
Collection List C (for three teams of one or two handlers): Team 1: [8, 1, 2, 3, 4, 5, 6, 7, 9, 10] Team 2: [15, 27, 25, 23, 20, 18, 16, 13, 11] Team 3: [22, 28, 26, 24, 21, 19, 17, 14, 12]	
Collection List D (for six teams of one handler): Team 1: [2, 1, 5, 9, 13] Team 2: [6, 3, 7, 10, 14] Team 3: [12, 4, 8, 11] Team 4: [16, 25, 22, 18] Team 5: [20, 27, 23, 19, 15] Team 6: [26, 28, 24, 21, 17]	

In these simulations, the preparation times, horizontal speeds and vertical (stair descent) speeds derived from the Ghent trials were applied for each device for male and female handling teams. When the assist team reached a patient room, a time equivalent to the preparation time for the device would elapse before the group started to move. The evacuation chairs required one handler each for movement, but two handlers for preparation, therefore one member of staff remained on the ward at all times during the simulations to be present for the preparation of patients. Similarly, where there was one member of staff leftover after the teams were allocated (e.g. for the mattress there were three teams of two handlers, so one of the seven day staff were not in a team), they were assumed to remain on the ward to aid preparation. In both of these cases, having only one staff member on the ward meant that they waited for teams to return in order to fully prepare the next patient, as this requires a minimum of two people. However, when there were two or more staff members not allocated to teams (e.g. for the stretcher, there was one team of four, so three of the seven day staff were not in a team), they had enough people to entirely prepare the next patient, so the returning team retrieved the patients without a preparation delay. The group

would move with the appropriate horizontal speed for the device until they reached the stairs at which point they would adopt the appropriate stair descent speed; with or without fatigue effects as appropriate for the scenario. When travelling without a device, each agent representing a member of the handling team was modelled by default characteristics for a 25 year old male/female with horizontal speed varying from 1.33 to 1.44 m/s, stair descent speed varying from 0.76 to 1.01 m/s and stair ascent speed varying from 0.64 to 0.67 m/s [16]. When travelling with a device, the Ghent data from chapter 4 informed the speeds travelled, as presented in Table 5-6.

Table 5-6: Model parameters

Scenario no.	Collection List	Preparation Range		Walk Speed (m/s)	Stair Speed (m/s)
		Min (Secs)	Max (Secs)		
1	A	63	74	1.1	0.6
2	D	24	32	1.6	0.8
3	B	32	40	1.5	0.5
4	C	46	60	1.2	0.8
5	A	63	74	1.1	0.6
6	C	24	32	1.6	0.8
7	A	32	40	1.5	0.5
8	B	46	60	1.2	0.8
9	A	61	120	1	0.4
10	D	30	42	1.4	0.8
11	A	41	52	1.5	0.7
12	C	67	86	0.7	0.5
13	A	61	120	1	0.4
14	C	30	42	1.4	0.8
15	A	41	52	1.5	0.7
16	B	67	86	0.7	0.5
17	A	61	120	1 (-5%*)	0.4 (-5%*)
18	C	30	42	1.4 (-5%*)	0.8 (-5%*)
19	A	41	52	1.5 (-5%*)	0.7 (-5%*)
20	B	67	86	0.7 (-5%*)	0.5 (-5%*)
21	A	61	120	1 (-10%*)	0.4 (-10%*)
22	C	30	42	1.4 (-10%*)	0.8 (-10%*)
23	A	41	52	1.5 (-10%*)	0.7 (-10%*)
24	B	67	86	0.7 (-10%*)	0.5 (-10%*)

***FATIGUE FACTORS APPLIED TO THE TEAM SPEEDS AFTER EACH PATIENT WAS COLLECTED AND EVACUATED.**

As depicted in Figure 5-2, the 28 patients are distributed in each room (either two to a room or one to a room) and six staff in three teams of two are shown about to enter the rooms. Each team must collect and prepare the patient, move them along the corridor and descend 11 floors to the exit on the ground floor, and then ascend the staircase to collect another patient until the ward is empty.

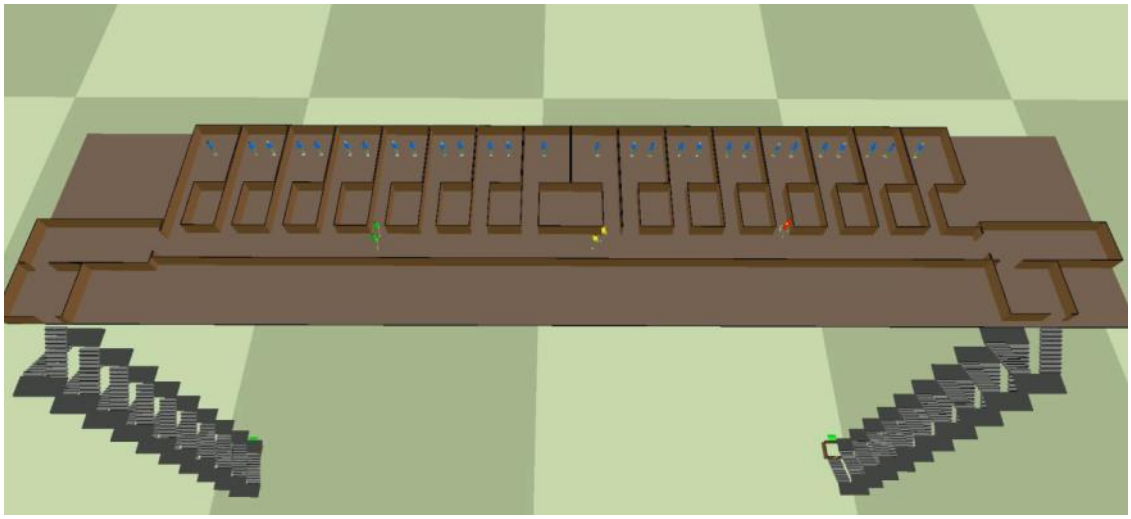


Figure 5-2: buildingEXODUS VR screenshot of the Ghent Hospital Simulation

5.2.3 Simulation Results

Each of the 24 scenarios was repeated 3 times producing a total of 72 simulations. Presented in Table 5-7 are the average times taken by the male and female teams, for both day and night scenarios for each device. The times represent the time to empty the entire ward assuming no fatigue.

Table 5-7: Simulated ward evacuation times for Male and Female handling teams without the effects of fatigue

	Male Teams		Female Teams	
Device	Day (Hours)	Night (Hours)	Day (Hours)	Night (Hours)
Stretcher	3.3	3.8	3.9	4.7
Evacuation Chair	0.5	0.9	0.6	1.1
Carry Chair	1.6	3.1	3.2	3.5
Rescue Sheet	1.1	1.6	1.5	2.1

The results indicate that the time required to evacuate the entire ward using only the available ward staff is excessive for devices requiring more than one staff member to operate them. However, even using the fastest device which only

requires a single handler (the evacuation chair), it would take at least 0.5 hours (29 minutes) to evacuate the ward using only the male day staff and 0.9 hours (55 minutes) using only the male night staff. Even using the evacuation chair, the time required to evacuate the ward using only the available night staff (male or female) may be excessive. In comparison, the next fastest device, which requires two handlers, requires approximately twice as long as the evacuation chair – a minimum of 1.1 hours to evacuate the ward using day shift male handlers. The slowest devices are the ones that require three or four staff (carry chair and stretcher). If the slowest device is used (i.e. stretcher) the evacuation times increase for both day and night staff, up to 3.8 hours (228 minutes) for male teams and 4.7 hours (283 minutes) for female teams. It is unlikely that an evacuation using these devices would be viable in an emergency fire situation.

With the exception of the evacuation chair, the gender of the handling teams appears to have a significant impact on the time required to evacuate the ward, with all female teams being slower than all male teams. The largest gender difference occurs for the carry chair, which is as much as 100% slower for the all-female day team compared to the all-male day team. This is because the male team only required three handlers while the female team required four handlers. Consequently, in the scenarios presented, there are two handling teams using the male day shift staff compared to only one team using the female day shift staff.

Table 5-8: Evacuation times with fatigue factors applied to female staff teams on night shifts. (Hours)

	No Fatigue	5% Fatigue (comparison)	10% Fatigue (comparison)
Stretcher	4.7	8.1 (1.7x)	17.9 (3.8x)
Evacuation Chair	1.1	1.3 (1.2x)	1.5 (1.5x)
Carry Chair	3.5	5.9 (1.7x)	12.9 (3.7x)
Rescue Sheet	2.1	2.7 (1.3x)	3.8 (1.8x)

Taking the worst case scenario (All-female Team; Night Staff), and applying the pre-set fatigue factors to the performance of the handling teams results in the increased evacuation times shown in Table 5-8. As can be seen, using a fatigue factor of 5% increases the egress times by a minimum of 20% for the fastest device, using only one handler, to a maximum of 70% for the slowest devices using

three of four handlers. The larger increase is a result of these devices requiring more trips to empty the ward, as they require more handlers, and hence the fatigue factor continues to degrade the travel speeds on each additional trip. Furthermore, if a fatigue factor of 10% is employed the evacuation times for the fastest device increase by over 50% and for the slowest device by 280%. Thus, an important finding from this work is that if all 28 patients are immobile, the ward cannot be evacuated within a reasonable period of time with just the available staff members assuming a 5% fatigue factor is applied to repeat journeys.

Taking the fastest device, the evacuation chair, and the slowest device, the stretcher, and assuming a fatigue factor of 5%, the time required to evacuate each non-ambulant patient is shown in Figure 5-3. This indicates that the imposed fatigue factor greatly impacts the stretcher performance, particularly as there is only one team making repeated trips to evacuate the entire ward.

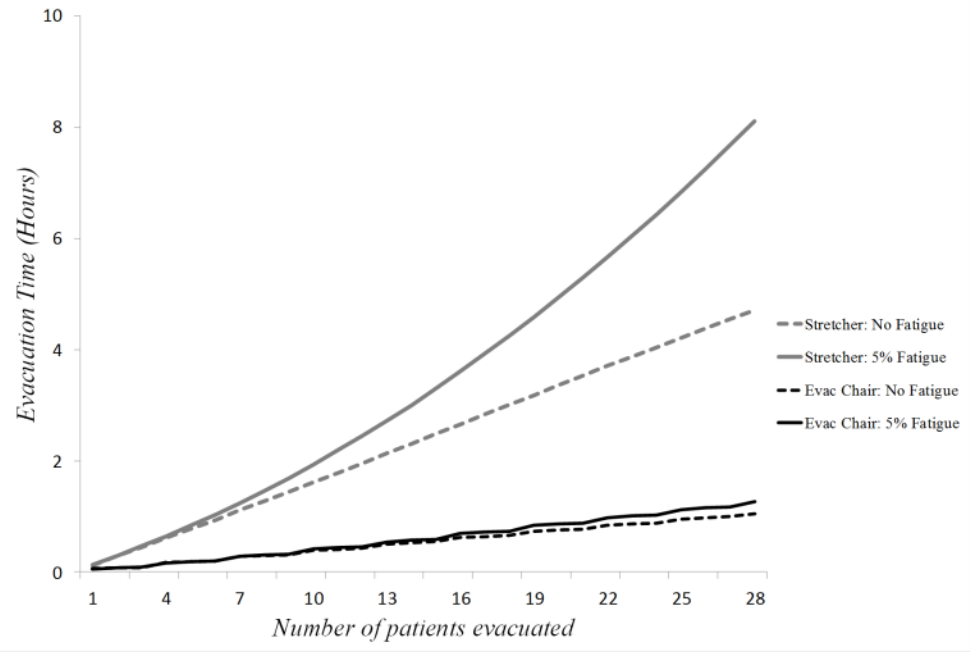


Figure 5-3: Average time taken to evacuate patients using the stretcher and evacuation chair devices, with 0% and 5% fatigue factors.

5.2.4 Discussion

This numerical simulation offers a device performance comparison and limited exploration into the potential effects of fatigue. As discussed in section 2.3.2, it is expected that there must be a physical fatigue experienced by hospital staff repeatedly collecting patients, especially over the large distances considered here. However, the modelling of this is problematic due to the lack of applicable data. Recently, Choi *et al.* [236] found that males and females individually ascending a 50 storey staircase all reduced their ascending speed over the final half of their journey by an average of 60%. Therefore, it is reasonable to presume that, as in this test case, staff repeatedly ascending and descending an 11 storey staircase would experience some cumulative effect of fatigue and a resulting decrease in speed. This is likely further amplified by carrying PRM. However, more work is required in this area so that the effect of staff fatigue can be better understood and incorporated into hospital evacuation planning.

Simulating the use of devices in repeated collection of PRM using this type of numerical simulation has limitations because of the simplifying assumptions required and the restrictive functionality of the current model. Outlined here are the key issues identified with this implicit approach.

- The ward to be evacuated was assumed to be fully occupied with 28 patients and that all patients had reduced mobility requiring assistance to evacuate. An improved model should include a range of mobility impairments, including ambulant evacuees moving alongside the staff and devices.
- During a day shift there are seven staff members while during a night shift there are four staff members. Only members of ward staff are available to assist in the evacuation. This does not account for external assistance from other staff members (e.g. porters), from emergency services (e.g. fire fighters), nor hospital visitors (e.g. relatives of non-ambulant patients).
- It is assumed that the available staff members are all of a single gender i.e. all male or all female. A variety of teams may be tested in an improved

model, although it may be prudent to assume the slowest (female) speeds for evacuation analysis.

- Only one type of device is used in each scenario. Procedures that include a combination of different devices within a single evacuation scenario could be tested in an explicit model.
- There are pre-determined collection lists for patients. A dynamic decision making model would be more representative of the evacuation choices in a real ward.

Importantly, these numerical simulations did not include a physical representation of the device, only the speed of movement of the handler(s)/PRM. Analysis of the Ghent video data revealed that the physical presence of the movement device in the evacuation route can have a profound impact on the evacuation of other people using the evacuation route at the same time. For example, it was found that others could not overtake handling teams with devices that occupy two stair lanes, unless the device had stopped. The nature of the interaction was dependent on the size and shape of the device and the location of the device e.g. on stairs or on landings. Thus, the physicality of the movement device cannot be ignored in the simulations. Therefore, if simulating the use of the device with other stair users, it is essential to not only represent the movement speed of handler(s)/PRM, but also the physical presence of the device. Furthermore, for some devices, it may not be possible to manoeuvre the device around some corners due to the relative size of the device and the confining corridors. In this way it is essential to take into consideration the size of the device into an explicit model.

These factors are taken into account in the development of a theoretical model to explicitly represent the devices used to transport PRM in hospital evacuation, as outlined in the next chapter. Chapter 8 discusses the key findings from this performance evaluation and addresses the research questions posed in Chapter 1.

6 THEORETICAL MODEL

As identified in the previous chapter and in the literature review, a key requirement in simulating hospital evacuation is the explicit representation of the devices used to transport PRM. Presently, established evacuation models represent the movement of evacuating agents, using statistical techniques to emulate human decision-making [14, 237]. This method of simulation can highlight emergent conditions within evacuation situations, and aid in the planning for evacuations. While performance data for the use of movement devices can be employed to implicitly represent their use in evacuation models, as explored in section 5.2, this method does not explicitly represent the spatial implications of a moving object. Even in the case of small objects, e.g. wheelchairs, modelling them as individual agents with some decreased speed, or as grouped shapes of agents does not accurately model the larger, typically quadrilateral, shapes of moving objects [15, 200, 231]. Additionally, for simulating people with full mobility, current approximations for walking speeds, densities and flows that are based on data for groups of individual occupants may not be appropriately applied to hospital environments where moving objects are included alongside evacuating individuals. Therefore, the reduction in speed of one agent, or a group of agents does not adequately represent a rigid object that is operated by agents and moving within an evacuation flow. It requires a geometrical representation that reflects its movement and the space it occupies, as well as the human factors associated with its use.

While the inclusion of movement devices within simulation tools is a crucial development towards representing the evacuation of PRM within hospital settings, there is wider scope for this application. Outside of hospital environments, there is currently an emphasis on ensuring safe egress for those with disabilities and therefore associated data are being collated [22, 82, 213]. In the field of evacuation dynamics, there has been an effort to quantify the evacuation performance of disabled people and a variety of commonly used mobility aids [17, 22, 219]. As such, the capacity for evacuation models to simulate assisted means of escape in

buildings has been recognised as an important area for development [25, 238]. Such functionality could also advance the ability to represent other human-manoeuvred objects, such as prams, trolleys and luggage in evacuation scenarios. It may also be applied to larger transport structures, such as systems of cars and buses, emergency fire and medical vehicles, and moving barriers in crowds, such as police horses. While this thesis focuses on the development of simulation tools for movement devices in hospitals, its widely applicable functionality is developed in general and versatile terms in order to represent these other factors. As such, this chapter describes functionality that can be generalised as "objects", and those specific to movement devices as "devices" throughout this chapter.

This chapter presents a synoptic outline of the object model that represents human operated objects within evacuation software buildingEXODUS (bEX) [16]. The work undertaken address the specific modelling objectives outlined in the literature review (2.4.2): MR1 – MR7. Initially, an overview of the theoretical model is described, to outline the parameters established from the performance factors identified by the Ghent trials (presented in Chapter 4), including an outline of their applications and interactions within the model. The implementation structure is then delineated, and each sub-model is described in turn.

The first sub-model (Route Assessment) is a pre-simulation analysis of the hospital geometry, employed in advance of the computational simulation. After it has assessed a building structure for object manoeuvrability, it prescribes the routes available to objects, enabling them to navigate during evacuation simulations on the existing fine node mesh as an individual agent does; albeit occupying numerous nodes at once. It is therefore designed to align with, and to directly interact with, the established pedestrian and evacuation dynamics in bEX.

During the simulation, the movement and the space occupied by objects are explicitly modelled within the established nodal system. The next sub-model (Object Specification) outlines the system under which an object is specified, including: its dimensions, shape analysis, travel direction, handler positioning, and performance data. Then the horizontal and vertical movement algorithms are

detailed, including travel through doorways, and the periodic stopping of objects on stairwells, as documented in the Ghent trials. The interactions between the agents and the objects are also modelled in this section.

It is important that the objects can interact with the other sub-models within bEX. Therefore, in addition to the new models, the full range of existing capability is required, including the group and leadership behaviours, the wayfinding and signage features, the interaction and conflict resolution with other occupants, and the potential for pairing with the fire simulation software SMARTFIRE [239]. Therefore, the methodologies presented here are designed to preserve these established interactions by integrating with the existing bEX functionality where possible.

6.1 Model Overview

The purpose of this section is to provide a broad overview of the theoretical model. The Ghent experiment investigated the use of movement devices for hospital evacuation, yielding parameters used in this model. The following model specifications were devised as a result of the observed evacuation process during the trials. Furthermore, the previous numerical simulation (section 5.2) highlighted simulation issues that are addressed in the development of this model, including the explicit representation of movement devices, and the capacity to simulate different devices concurrently. By incorporating these devices, or generically, human operated objects, into the established agent based model bEX, the impact of a varying mobility requirements within a hospital population can be explored.

6.1.1 Object Model Parameters

Table 6-1 outlines the required Object Model (OM) parameters as categorised by delays (d), speeds (s), numbers (n), and measurements (m). Each device represented requires definition of all of these parameters. The evacuation process and associated data are specified to align with the initial Ghent experiment, for which there are separate distributions for all-male and all-female teams. However, in a dynamic simulation scenario, it will be possible for teams to have a mix of male

and female operators. Because there are limited data on the impact this may have on the object speeds, any inference from the Ghent data would be speculative. Therefore, for the purpose of this model, it is assumed that any team of object operators that includes one or more female operators, will employ the female team variables.

Table 6-1: Object Model parameters

	Parameter (units)	Description (Data reference)
d_p	Preparation Time (seconds)	Range of average preparation times (4.1.1.2)
d_{d1}	Door Transition Time 1: Doors open towards the device on approach (seconds)	Average time recorded to open left, then right door leaves. (4.4)*
d_{d2}	Door Transition Time 2: Doors open away from the device on approach (seconds)	Average time recorded to open right, then left door leaves. (4.4)*
d_s	Stoppage duration (seconds)	Average stopping duration on stairs (4.6)
d_r	Device Retrieval Time (seconds)	Nominated delay for readying device for evacuation**
s_h	Horizontal Speed (metres/second)	Distribution of average horizontal speeds (4.2)
s_v	Interpolated Vertical Speed (metres/second)	Average interpolated speed when stoppages are removed (6.7.2)***
s_c	"Carry Empty Device up stairs" Speed (metres/second)	Nominated Speed for Ascending Stairs while carrying device.
n_s	Stopping frequency (no.)	Average no. of stops. per 10 flights of stairs (4.6)
n_p	Number of agents for preparation (no.)	The number of people in "essential" preparation role (3.3.1)
n_h	Number of agents for horizontal travel (no.)	The number of people in "essential" horizontal travel role (3.3.1)
n_v	Number of agents for vertical travel (no.)	The number of people in "essential" vertical travel role (3.3.1)
n_l	Stair lanes occupied (no.)	The number of lanes occupied on the stairs (3.3.1)
m_s	Distance between stoppages (metres)	Average distance between device stoppages on stairs (6.7.3)
m_l	Device length (metres)	The length of a device: parallel to its direction of movement (3.1.1.1)
m_w	Device width (metres)	The width of the device: perpendicular to its direction of movement (3.1.1.1)

***AS PER SECTION 4.4, EVACUATION CHAIR DATA ARE USED FOR THE CARRY CHAIR**

**** THIS IS DEPENDENT ON THE STORAGE OF DEVICES. FOR EXAMPLE, EVACUATION CHAIRS ARE OFTEN MOUNTED ON WALLS, THEREFORE IT WOULD TAKE AN AMOUNT OF TIME TO READY THEM, WHEREAS, HOSPITAL BEDS ARE ALREADY READY TO BE USED. THERE ARE FEW DATA FOR THESE RETRIEVAL TIMES, SO NOMINATED DELAYS ARE USED IN THE INTERIM.**

***** THIS PARAMETER IS ONLY APPLICABLE WITH STOPPING MODEL, AS DISCUSSED IN SECTION 6.7.1.**

The objects are specified in terms of their length ($\boldsymbol{m_l}$), width ($\boldsymbol{m_w}$) and a direction of travel. Typically, in the case of movement devices, the length is the largest dimension, however to generalise for objects with different uses, the length is defined as the dimension of the rectangular object that is parallel to the direction of travel. In the same way, the width is defined as the dimension of the rectangular object that is perpendicular to the direction of travel.

6.1.2 Model Description

To represent in a computer simulation of a hospital various objects such as wheelchairs, movement devices, and wheeled beds, it is necessary to assess whether or not it is feasible for objects of varying dimensions to move within the confines of the building structure. For example, a large bed on wheels with equipment attached may only be able to travel along certain routes within a hospital, avoiding narrower paths. Furthermore, there are areas within hospitals that are not designed for bed access, including: waiting rooms, pharmacies, chapels, laboratories, storage and disposal areas, staff offices, outpatient consultation rooms, public catering facilities, and supply elevators.

In this model building structures are assessed, before simulation commences, to determine the areas in which objects are able to travel. Hospital building plans are decomposed to establish whether objects will fit within their boundaries. Viable routes are therefore pre-determined and are effectively delineated in bEX as a set of itineraries [240]. The derivation of these routes is described in the next section. Once a geometry has been assessed for viable routes, the live simulation process explicitly represents the objects' movement in evacuations as outlined in the following sections:

- Object Specification (section 6.3)

Here, the object is specified using the parameters presented in the previous section. Experimental data are associated with the object to indicate the speed at which it travels, associated preparation times, and the size and space it occupies.

- Agent-Object Interaction (section 6.4)

Modelled here are the behaviours of the agents that operate the objects: their preparation of the device, the impact of their genders on the speed of the object,

and the manual handling positions adopted when operating the object. Using existing bEX behavioural functions and developing new patient collection functionality, the interaction between evacuating objects and the agents that operate them, as well as the agents that are evacuating alongside them, is modelled as a set of itineraries. The agents are thus allocated tasks in order to represent their interaction with the objects.

- Horizontal Travel (section 6.5) and Door Transition (section 6.6)

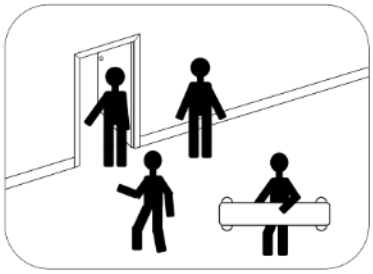
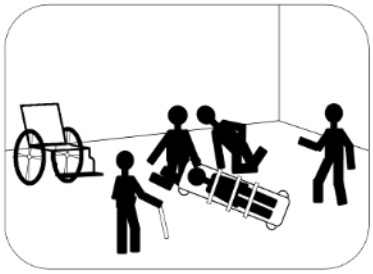
These algorithms are constructed to enable devices to move within a fine-node system, to navigate alongside other agents on a flat surface, and to manoeuvre corners and doorways during the simulation.

- Vertical Travel (section 6.7)

This algorithm is constructed to enable devices to descend stairs within bEX, utilising its existing representation of stairs (as "transit nodes") and landings to represent evacuation down stairs. A stopping model is also developed to represent device operators periodically stopping their descent within the stairwell, and to allow other evacuees to overtake if necessary. The interaction between horizontal and vertical algorithms are presented in section 6.8.

These sub-models are outlined in detail in the subsequent sections, and component testing is documented for each model in the following chapter. Table 6-2 describes the Object Model as a whole, separated into pre-simulation and simulation stages, including the associated movement algorithms, agent itineraries, and model parameters as defined in Table 6-1.

Table 6-2: Model Description

Pre-simulation Stage: Viable Route Selection	
The building geometry is assessed to determine whether the device of length $\boldsymbol{m_l}$ metres and width $\boldsymbol{m_w}$ metres will fit along evacuation routes.	
Simulation Stage 1: Preparation	
bEX Agent Movement Algorithms Agent Itineraries: • *Delay* • *Target Node* • *Pick up object* • *Coordinated Delay*	 

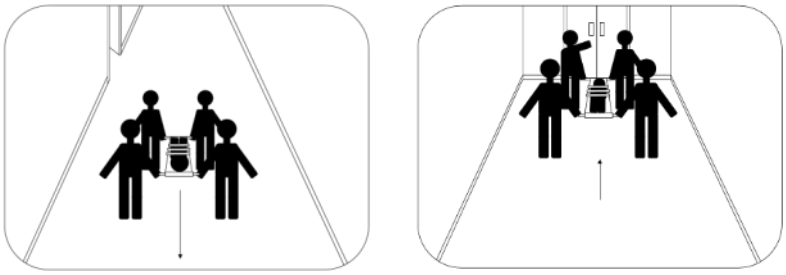
The device is retrieved (with a delay of d_r seconds) and carried to PRM (at speed s_c m/s). A group is formed until n_p agents are at the device, and preparation commences (with a delay of d_p seconds).

Simulation Stage 2: Horizontal Movement

Horizontal Movement Algorithm

Agent Itineraries:

- *Target Node*
- *Form Group*
- *Leave Group*



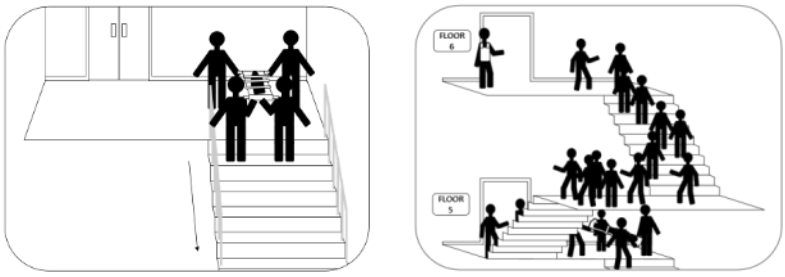
If $n_p \neq n_h$, members leave/join the group until n_h agents are at the device. The device is transported horizontally (at speed n_hm/s). If a door (of type 1 or 2) is encountered, the speed of the device is reduced (to speed d_{d1}/d_{d2}m/s) until the whole device has traversed the doorway.

Simulation Stage 3: Vertical Movement

Vertical Movement Algorithm

Agent Itineraries:

- *Target Node*
- *Form Group*
- *Drop off object*
- *Coordinated Delay*



If $n_h \neq n_v$, members leave/join the group until n_v agents are at the device. The device is transported vertically (at speed n_v m/s) and occupies n_l lanes. During its descent, the device will stop periodically (n_s times per ten flights of stairs, with a delay of $d_s$seconds). These stops will be at a maximum of m_s metres apart, but may also occur more frequently, based on the population density preceding the device.

6.2 Route Assessment

In fine node models, building floor-plans are decomposed geometrically to enable the representation of people movement [14]. In bEX, structural designs such as CAD drawings, are discretised into nodes that represent the position of individuals within the geometry, and therefore the space that they occupy. To simulate pedestrian movement, individual agents travel from node to node by their connecting arcs. In this way, the number of nodes predetermines the physical capacity of a structure. During simulation scenarios, agents determine and alter their travel paths based on a multitude of factors, for example their structural and exit knowledge, signage information, group/queuing behaviours, and individual tasks specified as a successive itinerary [16].

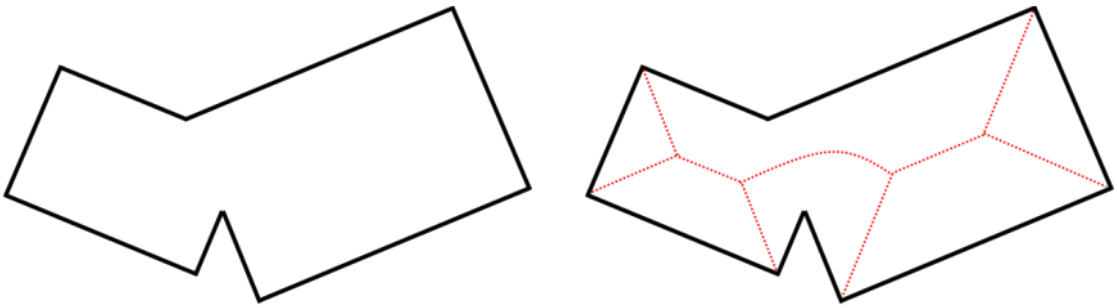
However, objects that are larger than an agent will necessarily span two or more nodes in the geometry. It is required then, that an object occupies the number of connected nodes that equate to the space it occupies. This poses a problem because the nodes themselves are not necessarily connected by arcs with regular angles or constant measurements; the distance between them is variable. Furthermore, because the objects are operated by and may be occupied by, agents, it is important that they function autonomously, comparable to the behavioural models of individual agents. Therefore, it is required that objects interact with the nodal system during the process of a simulation: it is not sufficient to represent the objects external to this system, for example by using a continuous mesh overlaying the nodes. This would omit, or require a significant restructuring of, established sub-models within bEX; for example, the agent response to signage [241], the agent response to tenability conditions in smoke [242], and the conflict resolution between agents [243].

During simulations in bEX, time-steps of $1/6^{th}$ of a second are used in which the model recalibrates. Therefore various methods were considered in which an object, in a similar way to an individual agent, could update its position and external awareness at each time-step. However, it was found that spatial assessment conducted at every time-step of a simulation was both computationally expensive, and open to discretisation errors. Hence, it is proposed that the spatial assessment of the geometry is conducted before simulation. In this way, possible routes for devices can be determined in advance of simulation, as a once-off treatment. Following this, many different scenarios can be simulated efficiently based on the findings of the original spatial assessment. This pre-processing saves simulation time.

In bEX, a map of the available space can be constructed or the software can upload an existing technical drawing (e.g. a CAD drawing). To geometrically analyse the space available on this map before developing evacuation scenarios, it can be decomposed into a Generalized Voronoi Diagram (GVD) as per the following definition [244]:

- Let a set of geometric objects, be denoted $s_1, s_2, \ldots s_n$. For each site s_i, define a distance function $d_i(x) = dist(s_i, x)$. The Voronoi region of s_i is the set $V_i = \{x \mid d_i(x) \leq d_j \; \forall \; j \neq i\}$. The collection of regions $V_1, V_2, \ldots V_n$ is called the GVD.

Therefore, on a map, the GVD is the set of points that are exactly the furthest distance away from two or more indices on the map (i.e. all of the points in the map whose distance to a boundary is not greater than their distance to any other boundary [245]). It is typically used to divide regions into cells, but in this case can be used to structure routes.



(a) **(b)**

Figure 6-1: Shape decomposition using a General Voronoi Diagram to determine the Medial Axis

Considering the map as a shape within which routes will be determined, the points on the Medial Axis (MA) of a map are a subset of those in the GVD [246]: they are the set of Voronoi points that are interior to the shape. Figure 6-1 (b) shows an example of the shape presented in Figure 6-1 (a) decomposed in this way.

Automatically approximating the MA is useful for planning routes, and the motion of rigid objects [244, 247, 248]. For assessing viable routes for movement devices, a Proximity Field Generator (PFG) developed by SMARTFIRE [239] is used. This PFG evaluates a 2D geometry by imposing onto it a regular mesh of m*m squares. The shortest Euclidean distance from each point on the mesh to its nearest geometric boundary can then be determined, and the set of the local saddle points can plot internal routes. Figure 6-2 shows an example hospital section, with two rooms on a corridor joined to a stairwell. For each point on the mesh, the PFG has

determined its shortest distance to a boundary, and assigned a contour map accordingly. Sequentially, the locus of points equidistant from the contours of the shape in the map approximates a Medial Axis, as depicted by the additional black lines in Figure 6-2(b).

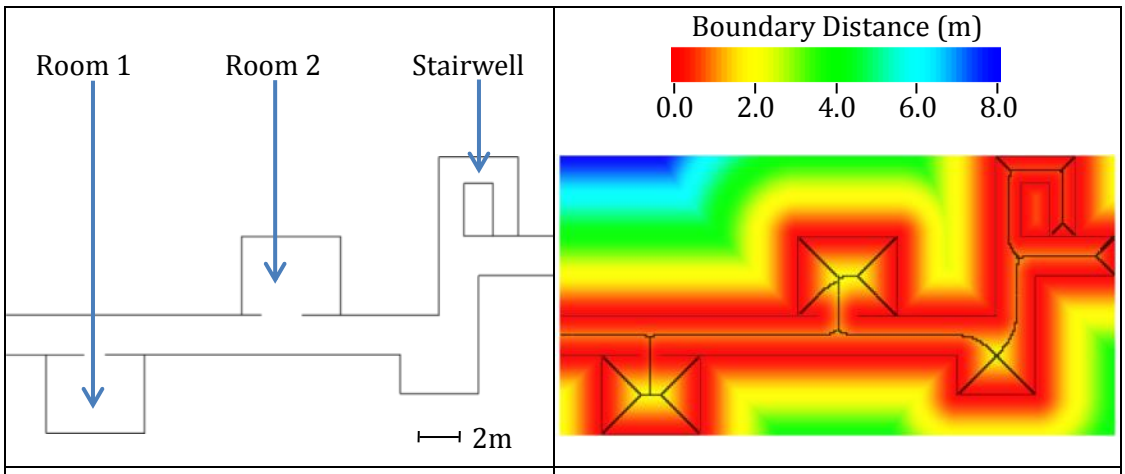
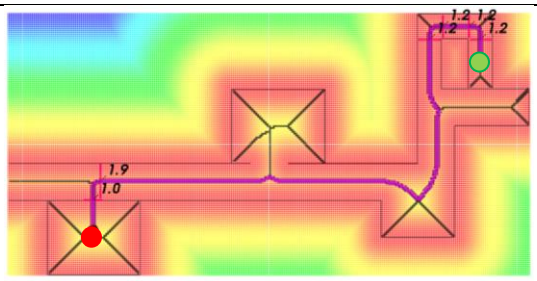


Figure 6-2: (a) An example corridor geometry and (b) its approximate Medial Axis.

The distance associated with each point on this discretised MA represents the greatest distance to two or more boundaries, which can be visualised as the radius of an empty circle. This decomposition therefore yields useful spatial information [249, 250]. Usefully, for convex shapes the GVD is identical to the MA, but for non-convex geometries, i.e. evacuation routes that lead to an open exit, the MA is a subset of the GVD [251]. This means the MA can be interrogated internally; considered as the locus of centres of maximal circles [247] and along with its Radius Function (RF) can describe the space within a shape.

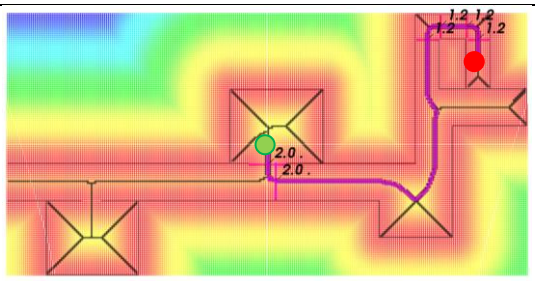
The MA and the RF together constitute the Medial Axis Transform (MAT) [243], which can estimate the geometric conditions in possible routes within structures. There are a number of techniques to find the MAT on a 2D plane, for example analytical results are possible for simple objects [242] and iterative methods are used for complex shapes (e.g. newton iteration [244]). For the assessment of hospital geometries, and given the likelihood of s simple (i.e. non-curved) building structure, iterative techniques may approximate the MAT to an appropriate degree of accuracy.

As the set of points constituting the MA is approximated by the PFG, this enables routes to be defined along the paths of the MA, by defining start and end-points within the geometry. Taking the corridor geometry presented in Figure 6-2, Figure 6-3 depicts two possible routes of the MA as approximated with a mesh. The route is not intended to prescribe the *path* that an object would take, but instead assess the geometric conditions along the route prescribed.



Route: Start: End:

(a) Room 1 to the Stairwell



Route: Start: End:

(b) The Stairwell to Room 2

Figure 6-3: Central paths along the Medial Axis to describe routes (a) and (b).

The routes highlighted in Figure 6-3 depict the path of the MA as approximated with a mesh. Therefore there is a discretisation error Ɛ between the approximation and the true MA that is proportional to the size of the mesh cells m. The largest error for a point on this axis is:

Equation 6-1

$$\varepsilon = \frac{m}{\sqrt{2}}$$

In these examples, the mesh construct is of 0.1 metre squares, therefore the error at each side is: $\varepsilon \leq 0.071$ metres. However, the method used for proximity calculations means that the approximate distance will always be less than or equal to the true distance, i.e. points will always be considered too close to a boundary instead of too far away. Therefore, devices may be rejected for a route because their edges are within 7 cm of a boundary, and will not be accepted for a route if they are too large. In this context, where it is being assessed whether a moving objects will fit within geometric spaces, a 7 cm error may be considered a negligible effect. Indeed, when considering objects that may be transporting

people, a nominated space between them and potential boundaries may be a necessary assumption because of the agents attached. The mesh size could be reduced to improve this approximation, or adaptive meshing included for curves in the geometry [253].

The initial check conducted when assessing a route on the MAT, is whether the smallest dimension of the object is larger than the smallest width on the MA. In this case, the device will not be able to use the route; i.e. the route, and associated exit(s), is not made available to the object in question. Once this check is conducted, the paths themselves are scrutinised to assess whether any 90° corners are present on the route.

6.2.1 90° Corner Detection

To investigate which objects can feasibly fit within the possible paths, also implemented into the PFG is the automatic detection of right-angled turns within this geometry. These corners are the likely configurations in which an object may potentially become stuck on its evacuation route and therefore assessing the dimensions of each corner can determine whether the device will fit along that route. Using the MAT, the program can detect when a route has taken a 90° turn by tracking the change in angle from point to point. The key dimensions to define these corners are the corridor widths before and after the turn. With these values, it can be determined geometrically whether rectangular objects can manoeuvre around the corner [254]. Displayed in Figure 6-3, the dimensions of these detected 90° turns are marked numerically and with magenta lines; both maps display right angled turns in the stairwell and on entering or exiting a room.

By defining various start and end points for possible routes a central path can be approximated as a sequence of points P_i (where $i = 1,2,3 \dots n$). Each P_i has an x co-ordinate x_i and y co-ordinate y_i. There is also an associated distance, which approximates the respective radius function of the MA: r_i. The r_i values at entrance to and exit from a right-angled turn approximate the dimension of that

turn. Figure 6-4 depicts this calculation by plotting the MAT output from the PFG, for two example routes sections.

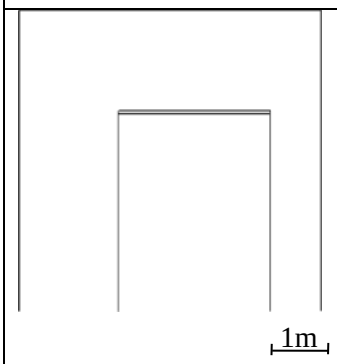
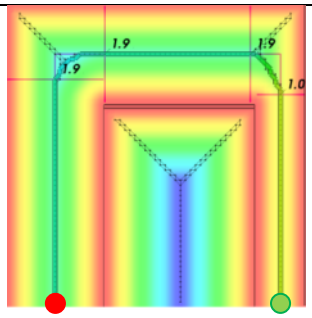
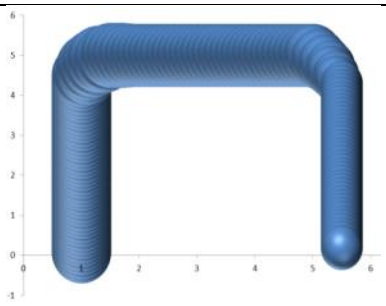
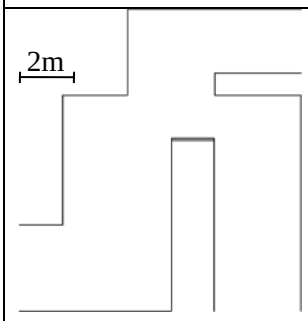
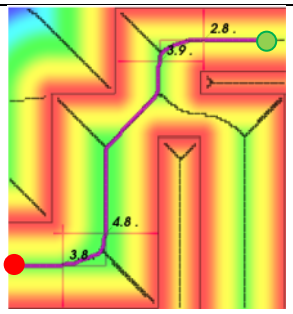
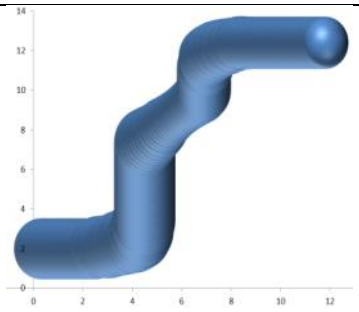
Sample geometry section	Medial Axis route and right-angle identification	Medial Axis Transform output graph: (x_i, y_i) and r_i
		
		

Figure 6-4: Medial Axis Transform for right-angle identification

From the variables describing the sequential circles, as plotted in Figure 6-4, the geometric space that bounds the route can be assessed to see which objects can manoeuvre through that geometric space. It is assumed the route will be checked for rectangular objects of width w and length l, where $w \leq l$. It is initially determined whether the smallest radius on the route is less than half the width of the object in question, as this infers that the object will not be able to pass at that point, i.e. if $min[r_i] < 0.5w$, the route is not viable. Similarly, if $min[r_i] > 0.5w$, then the route is always viable. Once it is established that an object meets these initial conditions, the identified 90° corners are assessed to identify whether an object can turn within them.

6.2.2 Objects turning around corners

Once a path is established, it can be determined mathematically [254] whether different shaped devices can fit around the 90° corners. Again, it is assumed the

route will be checked for rectangular objects of width w and length l, where $w \leq l$. Two corridor dimensions define a 90° turn: a and b where $a \leq b$, as depicted in Figure 6-5.

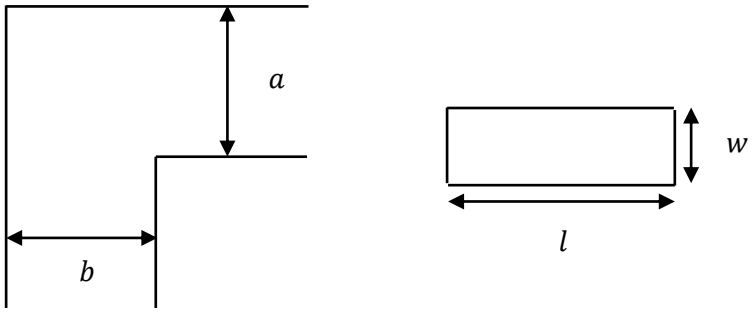


Figure 6-5: Corner assessment parameters

Give the corridor dimensions and the width of the device, the maximum length (maxL) can be established [254]:

Equation 6-2

$$maxL = \sqrt{\left((1+\frac{1}{x^2})(a+xb-w\sqrt{x^2+1}\,)^2\right)}$$

Where x is a real root of equation (2) in the interval $\left(0, \sqrt[3]{\frac{a}{b}}\right)$

Equation 6-3

$$(bx^3-a)^2 - w^2(x^2-1)^2(x^2+1) = 0$$

For example, taking the first route from the corridor in the Ghent experiment there are three 90° corners from the starting point to the ending point: Corner A (a=1.0m, b=1.9m); Corner B (a=1.25m, b=1.3m); and Corner C (a=1.25m, b=1.3m). If the object in question was 1.0m wide, to fit around Corner A, Equation 6-3 is solved for a= 1.0, b = 1.9 and w = 1.0 to find max length 1.83m.

Comparing the corner dimensions as approximated by the PFG to the actual dimensions, Table 6-3 calculates the corner viability for the Ghent horizontal route. In these calculations, it is assumed that width and length are determined from the aerial perspective of each device from the dimensions of the movement devices in the Ghent experiment (Table 3-2); i.e. the width and the length for the stretcher and the sheet, and the width and depth for the two chairs.

Table 6-3: Comparing route viability with real corner dimensions and approximated corner dimensions

Approximated Corner Dimensions	Stretcher $w = 0.43$m $l = 2.01$m	Evacuation Chair $w = 0.52$m $l = 0.77$m	Carry Chair $w = 0.48$m $l = 0.61$m	Rescue Sheet $w = 0.75$m $l = 2.00$m
Corner A: $a = 1.0$ m $b = 1.9$ m	$maxL = 3.15$ $l < maxL$ ∴ Viable	$maxL = 2.96$ $l < maxL$ ∴ Viable	$maxL = 3.04$ $l < maxL$ ∴ Viable	$maxL = 2.46$ $l < maxL$ ∴ Viable
Corners B and C: $a = 1.2$ m $b = 1.2$ m	$maxL = 2.53$ $l < maxL$ ∴ Viable	$maxL = 2.35$ $l < maxL$ ∴ Viable	$maxL = 2.43$ $l < maxL$ ∴ Viable	$maxL = 1.89$ $l > maxL$ ∴ Not Viable
Real Corner Dimensions	Stretcher w = 0.43m l = 2.01m	Evacuation Chair w = 0.52m l = 0.77m	Carry Chair w = 0.48m l = 0.61m	Rescue Sheet w = 0.75m l = 2.00m
Corner A: a = 1.0 m b = 2.0 m	maxL = 3.26 l < $maxL$ ∴ Viable	maxL = 3.08 l < $maxL$ ∴ Viable	maxL = 3.16 l < $maxL$ ∴ Viable	maxL = 2.58 l < $maxL$ ∴ Viable
Corners B and C: a = 1.25 m b = 1.3 m	maxL = 2.75 l < $maxL$ ∴ Viable	maxL = 2.57 l < $maxL$ ∴ Viable	maxL = 2.65 l < $maxL$ ∴ Viable	maxL = 2.11 l < $maxL$ ∴ Viable

As highlighted in Table 2-1, the smallest right angled turn is not deemed viable for the rescue sheet under these assumptions, whereas the Ghent trials indicated that the rescue sheet was able to traverse these narrow corners. This illuminates an issue with the assumption of device shape in this case; the rescue sheet presents a flexible shape as it is a soft mattress. Therefore, in transport, the effective length of the rescue sheet is shorter than the length measured on the flat, when it is being transported by two handlers. This variability in the dimensions of flexible objects is therefore established as a tolerance factor in these calculations. Several tolerances can be applied to represent variable length to counteract this; this calculation indicates a minimum tolerance of 0.11m is required for the rescue sheet, however more data are required to establish whether this applies to corner dimensions not tested as part of the experimental work in this thesis.

This automated MAT functionality is tested in section 7.1 for various configurations of 90° turns, including combinations of corners, as tabulated in section 7.1. Realistic hospital dimensions that accord with UK codes [2] are used in 12 component test cases.

6.3 Object Specification

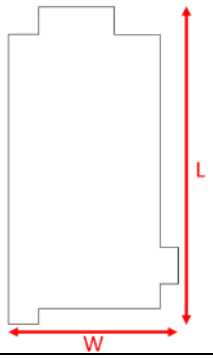
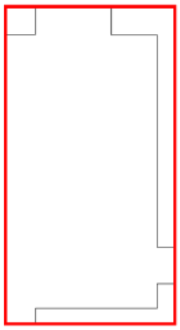
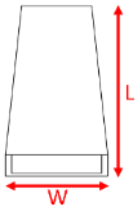
As per the route assessment technique in section 6.2, each rectangular shape is specified in terms of its effective length ($\boldsymbol{m_l}$), width ($\boldsymbol{m_w}$) and a direction of travel. All measurements are considered to represent the birds-eye shape and area that the object occupies when in use. This input is typically generalised in bEX as four points defined as coordinates: $P_o(x_0, y_0)$, $P_1(x_1, y_1)$, $P_2(x_2, y_2)$, and $P_3(x_3, y_3)$. The stretcher, evacuation chair, carry chair and rescue sheet devices are presented as objects specified within bEX, however users can create other objects given the provision of their measurements.

It is therefore technically permissible for non-rectangular quadrilaterals and other polygons to be defined using four coordinates in the bEX. However, it is noted that irregular shapes may not be appropriate for the pre-simulation route assessment described in section 6.2, as this model is based on strictly rectangular geometric calculations. In general, the use of rectangular objects is considered appropriate for modelling within a hospital environment as the vast majority of transportable objects within hospitals can be approximated by a rectangular birds-eye shape [81], including wheelchairs, beds, stair movement devices, equipment trolleys, hoists, commodes and drip stands. In exceptional cases, an object may be considered to have a non-rectangular birds-eye shape. For example if a patient is to be moved from intensive care, equipment such as portable ventilators, suction equipment, and defibrillators may be attached to the front, back or sides of the wheeled bed. In this case, the bed shape will be highly irregular. There are a number of ways in which to represent a complex shape such as this, and it is the user's responsibility to consider the modelling implications of their methodology. The two key considerations are the measurements used for the route assessment, as outlined in the previous chapter, and the shape used for simulation. While the measurement input for route assessment must take the form of a rectangle, the simulation shape can be any polygon. When the user inputs an object the decision of shape must be taken in the evacuation context, particularly with a view to the expected behaviour of other evacuating agents and handlers. Table 6-4 outlines an example of the shape analysis for an intensive care bed with equipment attached, and for a supermarket shopping trolley to demonstrate the adaptability of the

Object Model to non-hospital settings. For the route assessment, rectangular measurements must be considered and suitable tolerance applied to flexible objects, and in each case in Table 6-4 the smallest best-fit rectangle is suggested. However, this does not explicitly assess the intricacies of each shape, therefore it should be considered that the best-fit rectangle only provides an initial test. Should the best-fit rectangle meet the route assessment criteria, it can clearly be said that the shape is viable. If it does not, more investigation is required to fully assess its viability, for instance: hand calculations may sufficiently asses non-rectangular quadrilateral shapes, but for more complex (or changeable) shapes, further data may be required.

Conversely, any polygon object is permitted during simulation, once it is considered geometrically feasible for the routes it will travel along. In the simulation context, the shape dictates the space occupied on the $0.5m$ x $0.5m$ nodal system. It determines the nodes that other agents are unable to occupy and therefore its position can be influenced by the nodes occupied by surrounding agents. In the case of an intensive care bed with equipment attached depicted in Table 6-4, it may be reasonably assumed that other agents would not evacuate in between the pieces of equipment attached to the bed, or indeed directly alongside the bed, because of the perceived fragility of the medical equipment. Therefore, its evacuating shape can be approximated by the smallest best-fit rectangle, encompassing the bed and equipment as a whole. Conversely, agents evacuating in a shop may be assumed to walk directly alongside a moving or stationary trolley, therefore in this case its explicit trapezoidal shape may be more appropriate. More data are required to assess the space required for each type of object, and these types of assumptions must be made in the specific evacuation context until more is known in this area. Indeed, a useful application of the hospital simulation tool is to compare the performances of devices of different sizes and shapes, and therefore it will be possible to investigate the impact of different evacuee behaviours around larger objects when more data are available.

Table 6-4: An analysis of the shapes of intensive care beds with attached medical equipment and shop-type trolleys for route assessment and simulation.

	Route assessment measurement *(restricted to rectangles)*	**In-simulation shape** *(any polygon permitted)*
Intesive Care Bed	 For known spatial additions to rectangular shapes, the rectangular measurement can be expanded to encompass the new larger shape.	 It may be assumed that other agents would not occupy the areas alongside the object when equipment is attached. So the intricate shape is not explicitly simulated, but instead encompassed by a larger shape.
Shop trolley	 For non-rectangular shapes, the longest dimensions for length and width can be used.	 Here, it may be assumed that other agents may occupy the areas directly alongside the object, therefore the trolley is not encompassed by a larger shape.

To enable the extra consideration of these irregular objects, a check is conducted to establish whether the input is rectangular, i.e. if both pairs of opposite vectors are parallel and of the same length, then:

Equation 6-4

$$x_0 - x_1 = x_3 - x_2 \; ; \; y_0 - y_1 = y_3 - y_2 \; ; \; x_1 - x_2 = x_0 - x_3, \; ; \; y_1 - y_2 = y_0 - y_3.$$

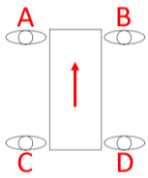
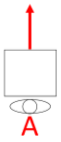
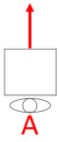
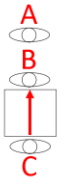
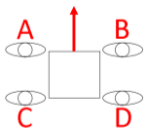
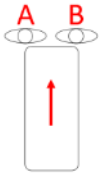
Therefore, if the user has defined a non-rectangular shape, bEX prompts the user to ensure geometric assessment has been achieved by some other means, for example with hand calculations, or by using the smallest best-fit rectangle around the points in the route assessment.

To align with the route assessment methodology described in Chapter 6, each movement device to be represented within bEX is considered to be rectangular. This accords with the approximate shape of currently manufactured movement devices [21, 93], including those investigated in the Ghent experiment [25] and depicted in hospital fire guidance [2]. The geometric specification of each device is presented in Table 6-5 and this model of object specification is tested in component tests 13 and 14 in section 7.2.

6.4 Agent-Device Interactions

Once a device is specified, its interaction with agents is modelled. The initial task in associating agents to devices is to consider the points at which they carry the devices. Some devices may have different points depending on their phase of movements. For example the carry chair only requires one person to wheel it along the horizontal, but requires three or four people in the vertical phase; and the rescue sheet requires two people at the front of the device on the horizontal but one person at each end in the vertical phase.

Table 6-5: Coordinates for dimensions and attachment positions for device objects in horizontal and vertical handling positions.

<table>
<tr><th colspan="2">Stretcher: Horizontal/ Vertical</th><th colspan="2">Evacuation Chair: Horizontal/ Vertical</th></tr>
<tr><td> 
</td><td>DIMENSIONS
$P_o(0.00,0.00)$
$P_1(0.00,1.66)$
$P_2(0.43,1.66)$
$P_3(0.43,0.00)$
ATTACHMENT
$A(0.00,1.66)$
$B(0.43,1.66)$
$C(0.00,0.00)$
$D(0.43,0.00)$</td><td> 
</td><td>DIMENSIONS
$P_o(0.00,0.00)$
$P_1(0.00,0.77)$
$P_2(0.52,0.77)$
$P_3(0.52,0.00)$
ATTACHMENT
$A(0.26,0.00)$</td></tr>
<tr><th colspan="2">Carry Chair (M/F): Horizontal</th><th colspan="2">Carry Chair (M): Vertical</th></tr>
<tr><td> 
</td><td>DIMENSIONS
$P_o(0.00,0.00)$
$P_1(0.00,0.61)$
$P_2(0.48,0.61)$
$P_3(0.48,0.00)$
ATTACHMENT
$A(0.24,0.00)$</td><td> 
</td><td>DIMENSIONS
$P_o(0.00,0.00)$
$P_1(0.00,0.61)$
$P_2(0.48,0.61)$
$P_3(0.48,0.00)$
ATTACHMENT
$A(B)$*
$B(0.24,0.61)$
$C(0.24,0.00)$</td></tr>
<tr><th colspan="2">Carry Chair (F): Vertical</th><th colspan="2">Rescue Sheet: Horizontal</th></tr>
<tr><td> 
</td><td>DIMENSIONS
$P_o(0.00,0.00)$
$P_1(0.00,0.61)$
$P_2(0.48,0.61)$
$P_3(0.48,0.00)$
ATTACHMENT
$A(0.00,0.61)$
$B(0.48,0.61)$
$C(0.00,0.00)$
$D(0.48,0.00)$</td><td> 
</td><td>DIMENSIONS
$P_o(0.00,0.00)$
$P_1(0.00,2.00)$
$P_2(0.75,2.00)$
$P_3(0.75,0.00)$
ATTACHMENT
$A(0.00,2.00)$
$B(0.75,2.00)$</td></tr>
<tr><th colspan="2">Rescue Sheet: Vertical</th><td colspan="2" rowspan="2">* THE THIRD HANDLER FOR THE CARRY CHAIR SWAPS INTO POSITION B AT REST PERIODS, SO A THIRD ATTACHMENT POINT IS NOT REQUIRED.</td></tr>
<tr><td> 
</td><td>DIMENSIONS
$P_o(0.00,0.00)$
$P_1(0.00,2.00)$
$P_2(0.75,2.00)$
$P_3(0.75,0.00)$
ATTACHMENT
$A(0.28,0.00)$
$B(0.28,2.00)$</td></tr>
</table>

In the same way as in device specification, Cartesian coordinates designate the target points at which the handlers approach the devices, in order to form the fully

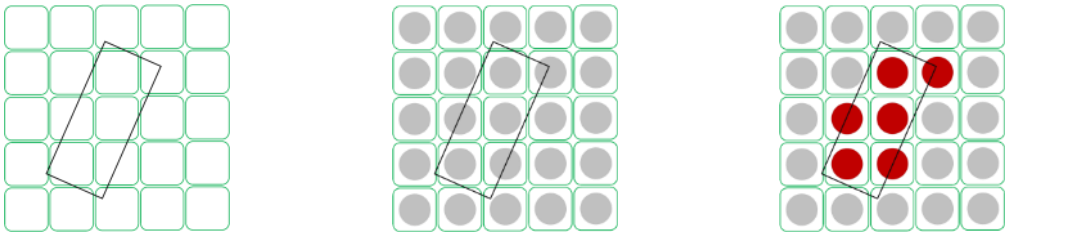
attached position as tabulated in Table 6-5. In general, a minimum of one attachment point must be specified: $\boldsymbol{A}(\boldsymbol{x_A}, \boldsymbol{y_A})$, however further attachment points can also be specified: $\boldsymbol{B}(\boldsymbol{x_B}, \boldsymbol{y_B}), \boldsymbol{C}(\boldsymbol{x_C}, \boldsymbol{y_C})$ etc. Objects may have different attachment arrangements depending on whether they are in horizontal or vertical transit. For the movement devices considered in this thesis,
Table 6-5 depicts these specifications, however the model can be generalised to other cases. In each case, the footprint of the device is represented as depicted, once all handlers are present at their attachment points.

These attachment points represent the target position of the handlers in each evacuation stage, so they provide the target locations for handlers' collection itineraries. Attributes are assigned to the devices as per the parameters presented in Table 6-1. The preparation time is the delay time incurred when the agents move and secure a patient into a device, but can be set to zero in cases where the patient is deemed "ready to go". For example, if a person is already positioned in a wheelchair, the preparation time before they are ready to be evacuated is zero. Other attributes may not be required, for example on a ground floor evacuation, the vertical parameters are not necessary. The minimum required input to specify a device is the all-female, i.e. slowest, speed for horizontal travel.

In bEX, agents typically move along a potential map towards a point in the geometry; for example, an exit. Their speeds and behaviours, e.g. conflict resolution, group dynamics, wayfinding, have been modelled over years of research [16]. In this specification, these original agent movement algorithms are used for agents when they are not operating a device, and for agents who are evacuating at the same time as an object. As such, those operating devices can have the full range of individual attributes assignable by the model; for example, they can travel at individual speeds when moving independently. Agents who are part of a handling team are allocated a pre-determined itinerary of tasks.

Each object in the model is specified as per the methodology described in the previous section, and is positioned on a node. It is specified that, at any time, only an agent or a device can be present on a node. Each node in bEX has a unique

identifier, and thus when an object is positioned in the geometry, it necessarily spans at least one node. The nodes it occupies depend on it position. As demonstrated in Figure 6-6, where a device is placed within a $0.5m$ x $0.5m$ nodal grid, a radial function of 0.2m detects whether the device is on each node.



(i) A device imposed on a nodal grid

(ii) The radial function from the centre of each node;

(iii) The nodes in which the device boundary intersects with the radial function.

Figure 6-6: A demonstration of nodal occupation criteria

As such, the space occupied by the device is represented by the nodes in which it occupies. This provides a means for agents and devices to be specified alongside each other, as other agents will occupy the available nodes as required on their egress paths. The 0.2-metre radial function was derived as a result of iterative testing, where it was established as the value in which the areas prescribed by device dimensions were best represented. For scenarios in which it is assumed that agents will closely occupy the space around a device, this variable can be reduced; and for scenarios where it is assumed that agents will give a device a wide berth, this variable can be increased.

When an object is generated in the model, it is assigned a location and as such occupies the surrounding nodes as determined under the radial function. The unique identifiers of these nodes therefore provide a location target for the handling teams. To represent the tasks undertaken, including the repeated collection of patients, agents are specified itineraries: a set of locations and time-dependant tasks with which to represent their behaviour. Handlers are allocated the task *pick up device* with a corresponding node location and a following task *drop off device* with another corresponding node. This enables handlers to target a device, pick it up and drop it off at another location (for horizontal evacuation), or

at an exit (for complete evacuation). Once the minimum number of handlers required for preparation ($\boldsymbol{n_p}$) has reached the device's location, the specified preparation time ($\boldsymbol{d_p}$) commences. As soon as the preparation time has elapsed, and the number of agents required for horizontal movement ($\boldsymbol{n_h}$) has reached the devices' location, the agents adopt their handling position (as represented by their attachment to the points specified in Table 6-5) and move off at the required speed. The gender of the handling team informs the preparation times and horizontal speeds adopted; if any member of the team is female, they will adopt an all-female preparation time and horizontal speed.

Once moving with a device, the handlers are rigidly attached to the device in their handling locations. A horizontal travel algorithm is applied to progress the devices' movement, and a door transition model is applied whenever a door is encountered on the route. These are described in sections 6.5 and 6.6. Once a device team has reached two metres of a staircase on their evacuation route, the transition to vertical movement occurs. The operators move to their vertical attachment positions and employ the vertical movement algorithm described in section 6.7. Other agents' evacuation alongside a device is represented by their occupation of unoccupied nodes surrounding the device and as such overtaking is not specifically identified; however, the existing pedestrian model will allow overtaking under the lane system described in the upcoming sections.

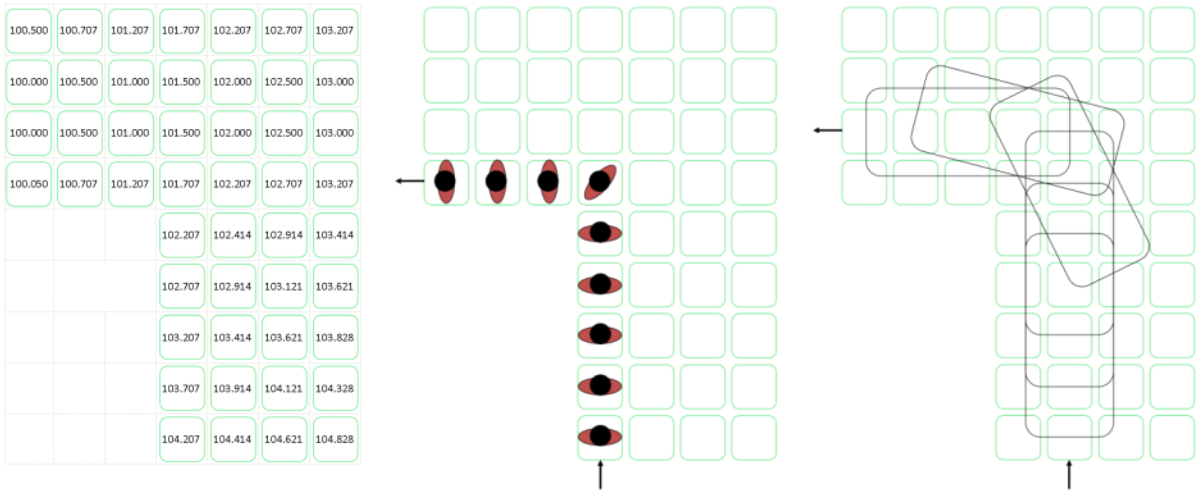
6.5 Horizontal Travel

For navigational purposes, objects use a version of the bEX potential map with a default path towards an exit. However, as the use of these devices are highly subject to a designated procedure, it is more likely that itineraries are used to represent the procedural aims, i.e. the devices will not necessarily look for an exit, but instead navigate towards a predetermined point as determined by the tasks allocated to their handling teams. This is appropriate for modelling the progressive horizontal evacuation procedure that is widely used in hospitals [2], where devices are led to an adjacent compartment for safety, which is not necessarily along the route towards the nearest exit. In other types of buildings, the same principle of a

targeted route can apply to muster/assembly areas where, for example, wheelchair users travel to a designated position to await rescue.

In bEX, the space is decomposed such that every agent is positioned on one node, and travels along connecting arcs to reach their next node, progressively moving around the space depending on procedural objectives and behavioural rules. Movement is typically governed by a potential field that is superimposed onto the geometry. This assigns a value to each node, based on its shortest distance (from measuring the collective distance of the connecting arcs) to a target. Therefore, in many evacuation simulations the nearest external exit acts as the seed value. In order to ensure that objects interact effectively with the established model functionality, they also navigate on the nodal system, moving from node to node like agents do, but occupying surrounding nodes according to the extra space that is taken up. Although the nodes are often visualised as a grid (for example in Figure 6-7), they hold no area as they are solely positional points.

The potential field for agent movement is delineated irrespective of the size of the agent. As depicted in Figure 6-7 (i) and (ii), the expected route of an agent is well-represented by choosing the smallest potential value at each step. However, the expected route of a device Figure 6-7 (iii) cannot be positioned directly adjacent to a boundary because of its size. Therefore, the navigation taken by the device must initially consider the boundaries.



(i) Numerical Potential **(ii) Agent Route** **(iii) Device Route**

Figure 6-7: Suitability of current numerical potential field for device navigation.

As depicted in the first box of the flowchart in Figure 6-8 when an individual agent is positioned on a node, there are typically eight choices for the next step of movement. These are defined as the surrounding nodes that can be moved to within a single step; i.e. are connected directly by one arc. Here, each of these surrounding nodes has label $x = 0,1,2,3\ etc$, with the convention of labelling the node immediately in front (positioned immediately ahead in the current direction of movement) as 0, and then numbered consecutively clockwise from this point. According to the extant potential map calculations, each of these surrounding nodes also has an associated potential value: P_x. The node with the Lowest Node Potential (LNP) $= \min\{P_0, P_1, P_2, P_3, P_4, P_5, P_6, P_7\}$ represents the ideal movement choice of an individual agent as it signifies the closest step to the agent's next target; e.g. in an evacuation, this is typically the nearest exit.

For objects travelling within this nodal system, the same choice of single-step movements are considered, however this scheme of navigation must be altered to account for the larger size of the object. For an agent, their location also signifies the space that they occupy: they have one location and occupy that one node. The position of an object is defined by its nodal location, paired with the angle at which it is situated, and can occupy multiple nodes. For navigational purposes, the location of an object can be considered in the same way as the location of an agent: as defined by its occupation of one node. Therefore this point is modelled as the

centre of its foremost edge (i.e. the leading face of the object in its direction of travel).

For this navigation model, three types of node are considered: Floor Nodes (typical horizontal movement nodes), Boundary Nodes (positioned on the geometry's boundary), and Doorway Nodes (positioned on the threshold of a doorway). For an object, the three lowest potential values (LNP_1, LNP_2, LNP_3) are considered. These are allocated as per the following four steps:

1) List p values in numerical order.
2) If there is one p value with the minimum value in the list it is named LNP_1 and removed from the list. If there is more than one p value with the minimum value in the list, choose one at random, name it LNP_1 and remove it from the list.
3) If there is one p value with the minimum value in the list it is named LNP_2 and removed from the list. If there is more than one p value with the minimum value in the list, choose one at random, name it LNP_2 and remove it from the list.
4) If there is one p value with the minimum value in the list it is named LNP_3 and removed from the list. If there is more than one p value with the minimum value in the list, choose one at random, and name it LNP_3.

Of those, the lowest value that is neither on a boundary nor at the edge of a doorway is selected if possible as depicted in the flow chart in Figure 6-8.

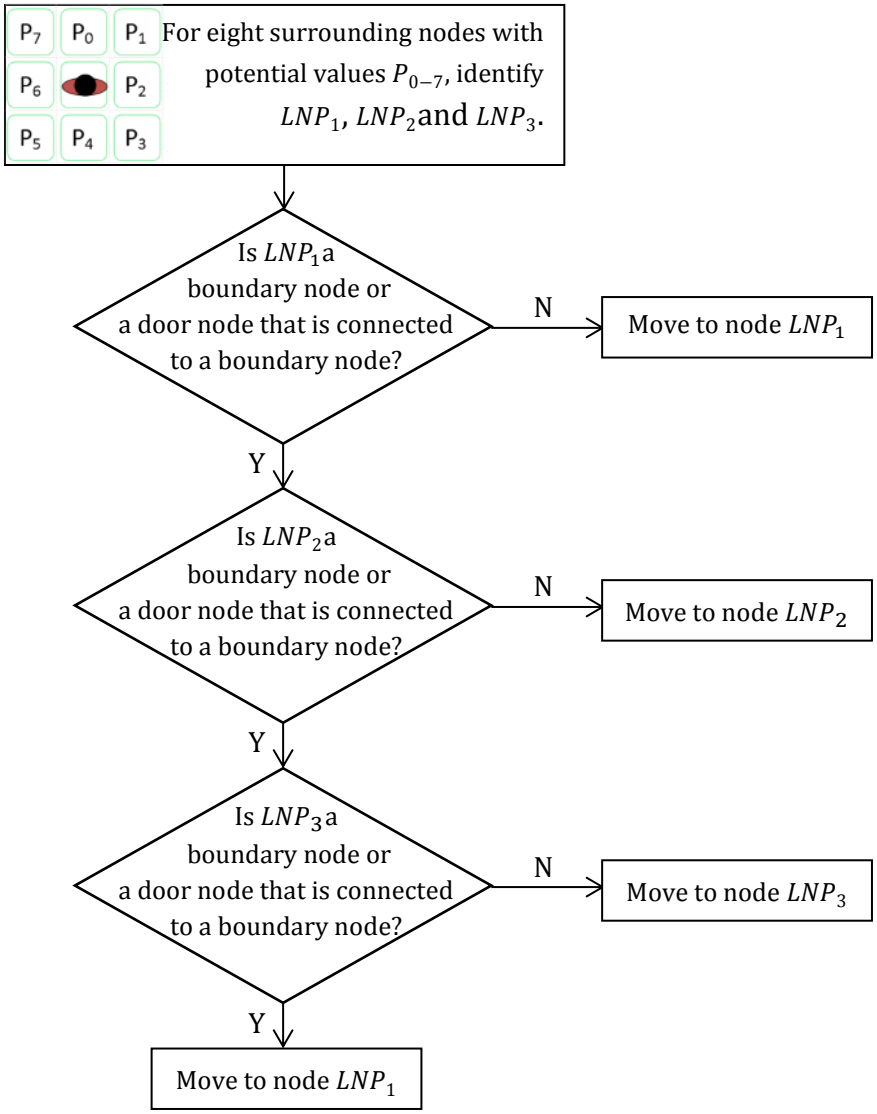


Figure 6-8: Lowest potential navigation for objects

Considering three of the possibilities, instead of eight, ensures that boundary nodes are only selected as a last resort, yet the device will make forward progress. This is vital for ensuring that when presented with a doorway, which by definition will be preceded by boundary nodes, the object does not navigate away from its goal. Two example doorway and boundary configurations are depicted in Figure 6-9, alongside the route taken when object navigate based on their three LNP choices.

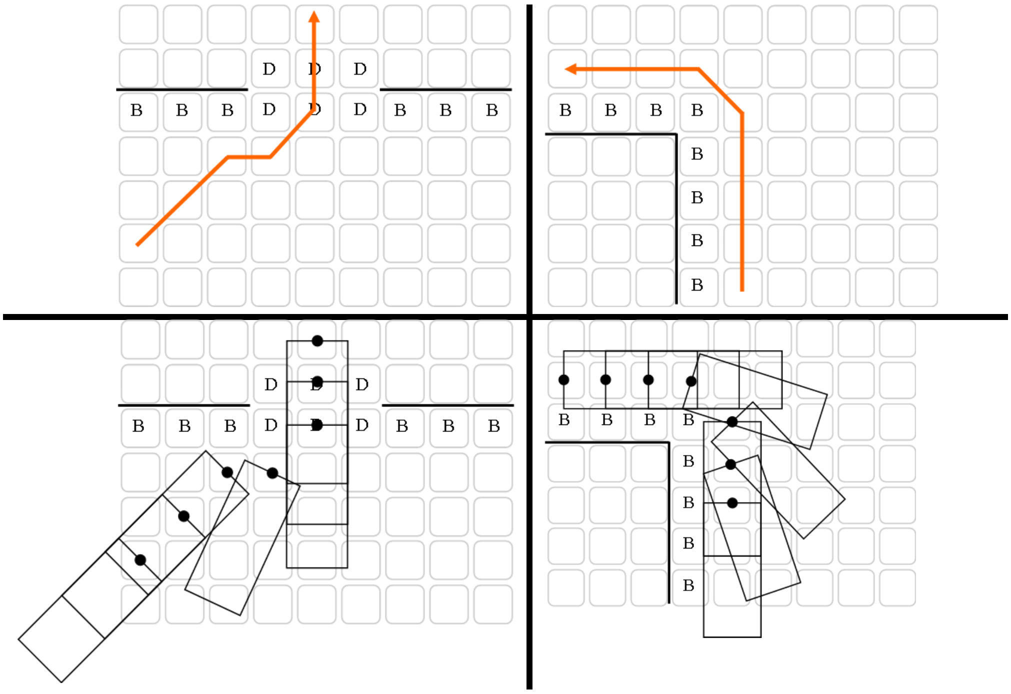


Figure 6-9: Object navigation of boundaries and doorways

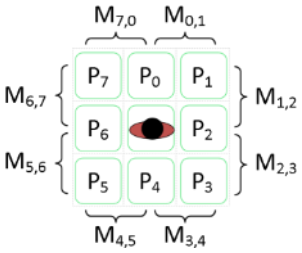
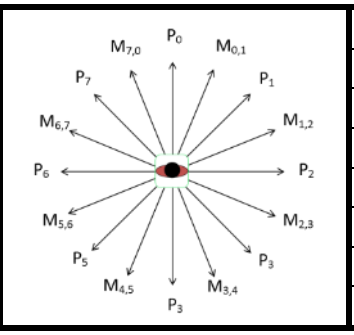
The object travels at the user-specified horizontal travel speed (s_h), unless on a doorway node, in which case its speed is reduced as described in the next section (6.6). For the movement devices investigated in this thesis, the horizontal speed from the Ghent trials are used (Table 4-5). Using the extant navigation model, the object's speed is represented by the time spent on each successive node, recalibrated in bEX every 6th of a second.

Once the device has established the next step of its evacuation path, a further modelling consideration is the position, or angle, of the device at that step. In movement, carried and wheeled objects are positioned with their forward edge aiming towards their target, given that their forward edge is defined by their direction of travel on the horizontal. The direction in which they face in movement, therefore, can be modelled using the information that describes their directional aim.

Here, it is considered that objects can be orientated at one of 16 regular angles: eight of which correspond to the nodal options described in the first figure in Table 6-6 by their associated potential value: P_x. Bisecting these, a further eight angles are considered to enable a more realistic scope of object movement. These are

labelled as $M_{i,j}$, where i and j are the two nodes bisected. P values are the potential values of the surrounding nodes, M values are the mean value of the two adjacent P values. aP and aM values are then all of the associated angles, as specified in Table 6-6.

Table 6-6: Object orientation parameters and corresponding potential field.

		aP_0= 0°	$aM_{0,1}$= 22.5°
		aP_1= 45°	$aM_{1,2}$= 67.5°
		aP_2= 90°	$aM_{2,3}$= 112.5°
		aP_3= 135°	$aM_{3,4}$= 157.5°
		aP_4= 180°	$aM_{4,5}$= 202.5°
		aP_5= 225°	$aM_{5,6}$= 247.5°
		aP_6= 270°	$aM_{6,7}$= 292.5°
		aP_7= 315°	$aM_{7,0}$= 337.5°

The calculation taken to determine a devices' angle at a given point is based on the potential values surrounding the *next* point on its path; i.e. the nodal location as established by the movement algorithm. In this way, any upcoming turns are anticipated in advance. Considering the potential field, and extrapolating more accurate directional information by taking the mean of each, enables a movement algorithm to be implemented in order to smoothly orientate objects during movement. The flow chart in Figure 6-10 depicts this angle selection, with the eight P values as input and angles of orientation (P_{choice} *or* M_{choice}) as output.

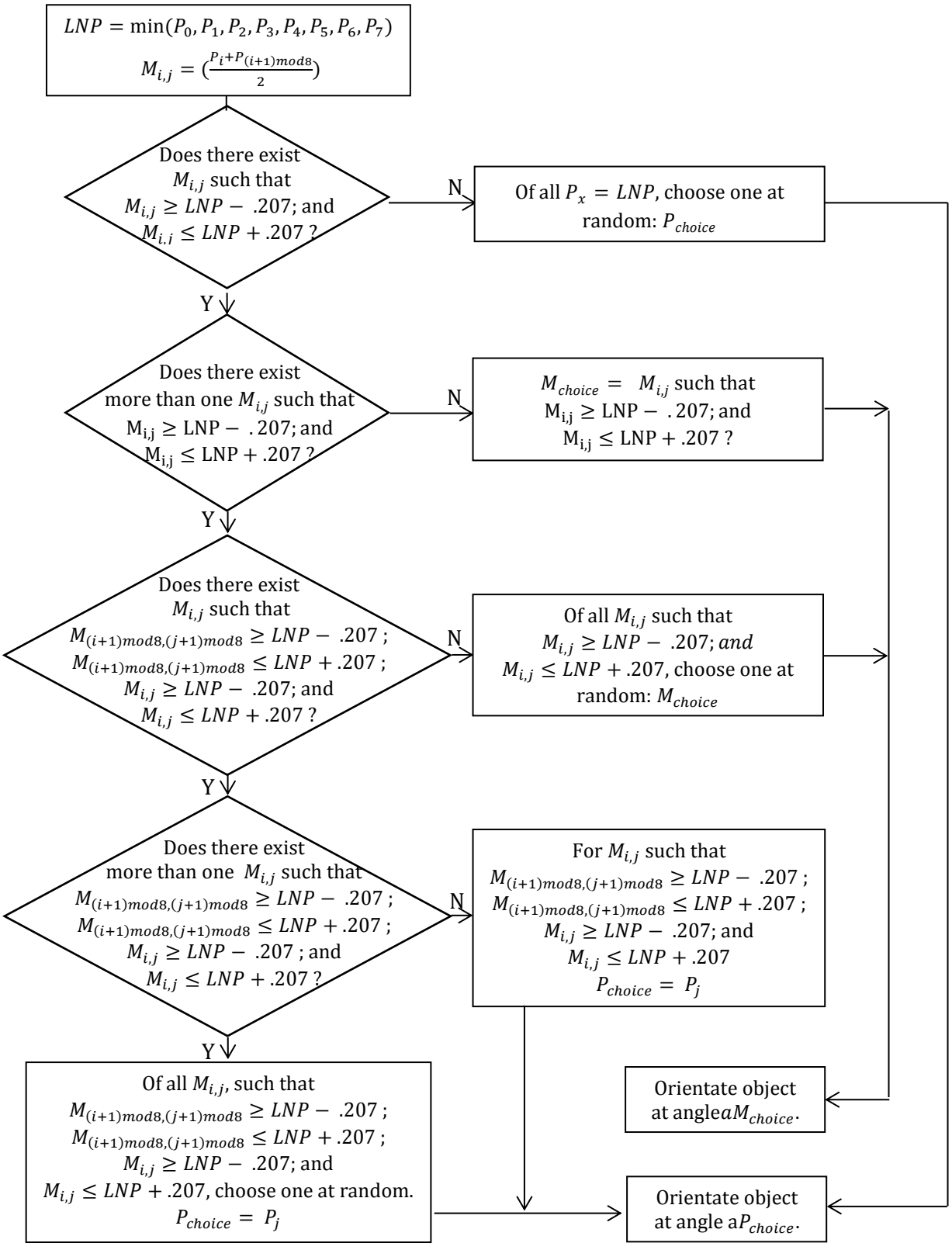


Figure 6-10: Horizontal object orientation flowchart

Initially, M values are calculated as the mean of successive P values, and a comparison is made to detect whether any are within 0.207 of the LNP, indicating

a directional bias towards the M value's associated angle. The value 0.207 is used for the range in this comparison of potential values as it is the typical difference between horizontal and diagonal arc lengths based on a $0.5m$ x $0.5m$ nodal grid, i.e. $0.707 - 0.5$. If there are no M values that satisfy this condition, the LNP or random equivalent node is selected. Where there is only one M value that satisfies this condition, this variable is selected. Where there is more than one M value that satisfies the condition, the algorithm checks whether these form any adjacent pairs; i.e. in the case that they share a P value in their initial mean calculation; $i = j$. If there are no pairs, one M value is randomly selected as the output variable, with a preference for maintaining the current angle. If there is more than one pair, then one is selected at random, with a preference for maintaining the current angle. In this case, where consecutive M values fall within range of the LNP, their common P value is the output variable. The resulting angle will correspond to the directional aim of the object, while aligning with its navigation and spatial objectives. It is notable that, unlike the navigation model, there is no need to specifically account for boundary nodes or door nodes within this calculation as their potential values still effectively inform the directional information.

To demonstrate these algorithms, six steps of an object moving around a 2 x 2 metre corner are calculated using the navigational and orientation models. The spread sheet calculations for this are in Appendix N. Figure 6-11 depicts an object approaching from the south, with potential distances based on an assumed exit in the west. Presented are the four paths that an object can undertake, all of which are equally likely under the algorithm employed. Furthermore, repeated simulation of the same scenarios may yield a variety of results based on the different routes that may be adopted which may provide a more comprehensive analysis of the performance of the objects and agent interaction. Should further data come to light regarding the movement of objects, the nature of the algorithm is such that movement preferences can be easily implemented. For example, if it is apparent that certain objects will hug corner geometries, i.e. in the first route in Figure 6-11, then the LNP choice could be specified as the minimum distance from the previous choice, which would avoid the diagonal movement displayed in the other three route possibilities. In the same way, if objects are deemed to take a

corner widely, and spread across the whole space in a 90° turn, the preference could be to select the LNP that is the maximum distance from the previous choice. More data are required in order to establish the expected routes of generic objects, and it may be the case that this cannot be realistically generalised. A useful feature of this functionality is that the impact of varying routes can be tested.

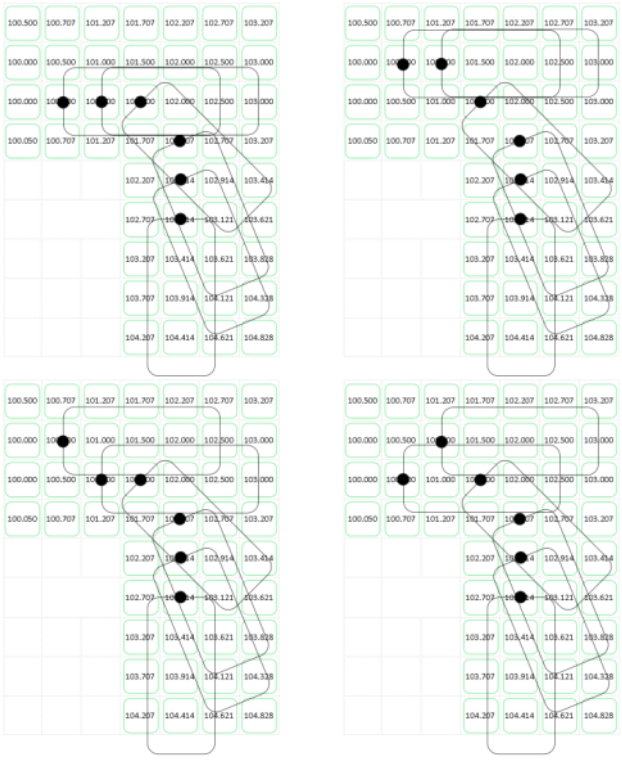


Figure 6-11: Test outcomes of navigation and orientation algorithm

6.6 Door Transition

The horizontal algorithm specified in the previous section enables objects to move through doorways using the potential field for navigation and orientation. However, data from the Ghent trials indicates that devices reduce their speeds in order to travel through doorways. As presented in Table 4-8, times were recorded for teams of males and females to traverse doors of different types. In hospitals, double swing doors are most appropriate for movement of devices such as beds and doors on the evacuation should open outwards in the direction of the evacuation route [2]. However, this is not always possible, as progressive horizontal evacuation will often require movement in both directions. For this reason, two different door types are introduced to bEX: Door Type 1 in which the

double leaves open towards the object, and Door Type 2 in which the double leaves open away from the object: these correspond to Door 2 and Door 3 in the Ghent experiment: Table 4-8.

In bEX, door nodes are used to specify agent flow through doorways. They have size attributes, signage indicators, and can be open or closed. By recognising these node types as in the extant agent model, objects can detect whether or not the next node is a "doorway node". Therefore, objects will adopt a new speed when they are positioned on door nodes, and revert to horizontal speeds when they are positioned only on floor nodes.

Data from the Ghent trials and the Greenwich Door Transition Experiment (Appendix I) indicated the number of seconds required for male and female teams to travel through the doors: $\boldsymbol{d_{d1}}$seconds for the first door type, and $\boldsymbol{d_{d2}}$seconds for the second door type. However, the speed associated with this delay is dependent on the length of the device ($\boldsymbol{m_l}$), as the distance travelled at the reduced speed will be greater for longer devices. Therefore the following directive is employed: if an object's next step will result in any part of the object being positioned on a door node of door type i, it will adopt speed: $D_{Speed} = \frac{\boldsymbol{m_l}}{\boldsymbol{d_{di}}}$ (m/s) for $\boldsymbol{d_{di}}$seconds.

For the movement devices, the speed adopted for door transition is presented in Table 6-7. There is no data available for the door transition times for the carry chair, so it is assumed for this model that they incur the same delay time as the other wheeled device: the evacuation chair.

Table 6-7: buildingEXODUS Movement Device Door Transition Speed (m/s)

Door Type	Stretcher $\boldsymbol{m_l}$ = 1.66		Rescue Sheet $\boldsymbol{m_l}$ = 2.00		Evacuation Chair $\boldsymbol{m_l}$ = 0.77		Carry Chair* $\boldsymbol{m_l}$ = 0.61	
	M	F	M	F	M	F	M	F
1	0.25	0.24	0.24	0.17	0.15	0.13	0.12	0.10
2	0.34	0.37	0.33	0.27	0.18	0.13	0.15	0.10

*Note: due to lack of data, the door transition time for the carry chair is based on door transition time for the evacuation chair. The horizontal performance and door transition technique of these two chair devices were similar.

6.7 Vertical Travel

When considering the performance of movement devices in vertical travel, it was found that the places in which those manoeuvring the objects stopped on the stairwell, to rest or to adjust handling positions, typically predicted speed per floor (see Table 4-12). Therefore, in modelling the vertical movement of objects, a stopping model is introduced.

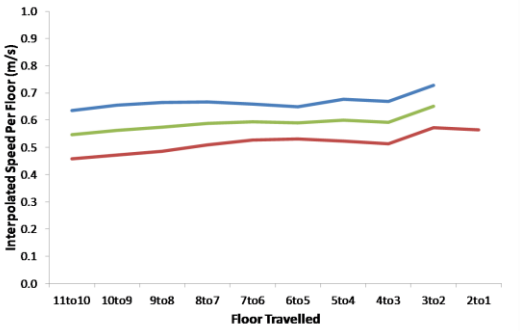
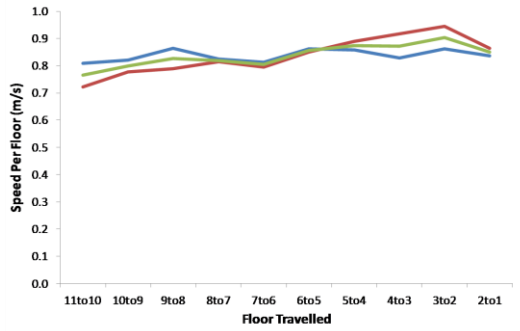
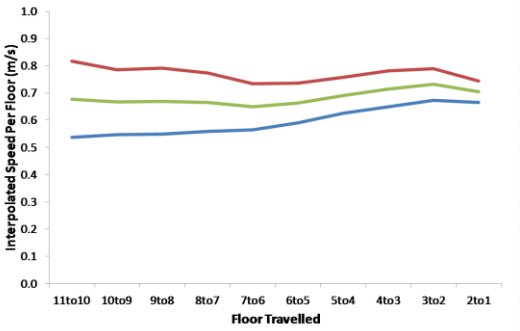
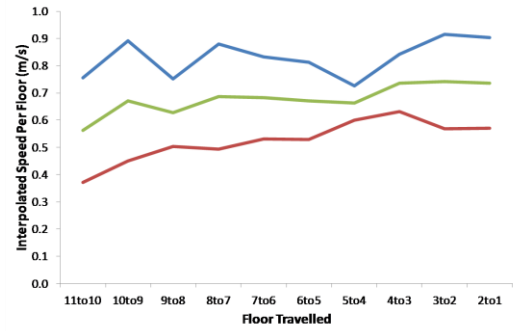
6.7.1 Interpolated Vertical Speeds

The vertical speeds presented in Table 4-9 (section 4.5) incorporated the times in which the devices stopped in the stairwell portion during the Ghent trials. However, this alone is not sufficient to model the movement of devices in stairwells. The intermittent delays on the stairwells cannot be explicitly represented when travel is aggregating into an average speed. This is because the position and duration of stoppages during the trials had a direct impact on the movement of other evacuating pedestrians; e.g. the stretcher device entirely blocked the stair lanes, but when stopping on a landing, it allowed pedestrians to overtake it.

Therefore, in order to simulate the devices periodically stopping within bEX, speed variables are interpolated to represent each speed without stoppages, and thus the stops can be represented as intermittent delays. To remove the effect of the stoppages from the observed vertical speeds, the speeds associated with the floors in which stoppages occurred are removed, and the gaps in data are interpolated as an average from the surrounding data points. It is more effective to aggregate the speeds per floor, than per sub-floor, because of the complex positioning of the stoppages. The remaining data are tabulated in Appendix O. The average speeds are thus increased accordingly, as presented in Table 6-8. These figures indicate that the interpolated speed curves fluctuate less than the raw data, thus indicating that on the floors in which the devices did not stop, the travel speeds were less variable. For modelling these speeds, within the data range of 1-11 floors, this suggests each device and gender is representable by a single average variable: interpolated vertical speed (s_v).

It is vital, however that this is employed alongside the associated stopping model in section 6.7.3 that periodically delays devices in their progress on the stairwell, as it will only produce credible results when these delays are present.

Table 6-8: Interpolated vertical speeds (m/s) with stopping influence removed

(i) Stretcher		(ii) Evacuation Chair	
Male Average	*0.67 ± 0.05*	*Male Average*	*0.84 ± 0.02*
Female Average	*0.51 ± 0.05*	*Female Average*	*0.84 ± 0.07*
Overall Average	*0.60 ± 0.09*	*Overall Average*	*0.84 ± 0.04*
			
(iii) Carry Chair		**(iv) Rescue Sheet**	
Male Average	*0.58 ± 0.07*	*Male Average*	*0.82 ± 0.09*
Female Average	*0.77 ± 0.09*	*Female Average*	*0.54 ± 0.07*
Overall Average	*0.68 ± 0.13*	*Overall Average*	*0.69 ± 0.16*
			

6.7.2 Stairway Movement in Lanes

It is established in pedestrian analysis of staircases [221] that people typically form lanes in stairs when in crowds and therefore flow on stairwells is often modelled in terms of lanes. In bEX, stairwells are categorised as "transit nodes" and are defined by their entry and exit points, their physical dimensions, and the number of stair lanes that are used by individually moving agents. For objects, this convention can be utilised to represent the movement of devices in terms of their

position in a number of lanes on a staircase. During the Ghent trials, the stairwell used was 1.4m wide and two distinct lanes were formed when using the chair devices alongside evacuating pedestrians.

Analysis of the devices movements during the Ghent trials indicates that there are three stair lanes positions that the devices adopt in the stairwells. For the duration of the experiment, the devices did not deviate from their lane position in the dog-leg staircase, unless they had stopped in the stairwell. As depicted in Figure 6-12, the lanes used on the stairs were SL1 (inside lane), SL2 (centre of staircase, occupying two lanes), and SL3 (outside lane). Similarly, the three landing lanes (LL) are specified as: LL1 (inside lane), LL2 (middle lane), and LL3 (outside lane).

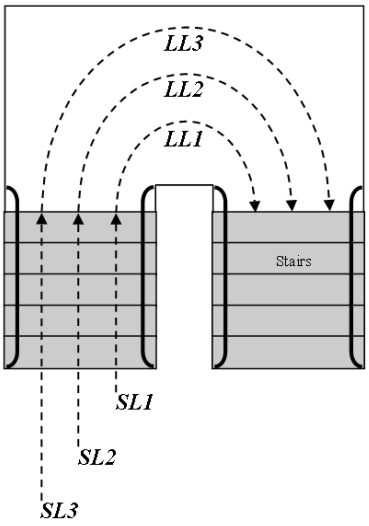
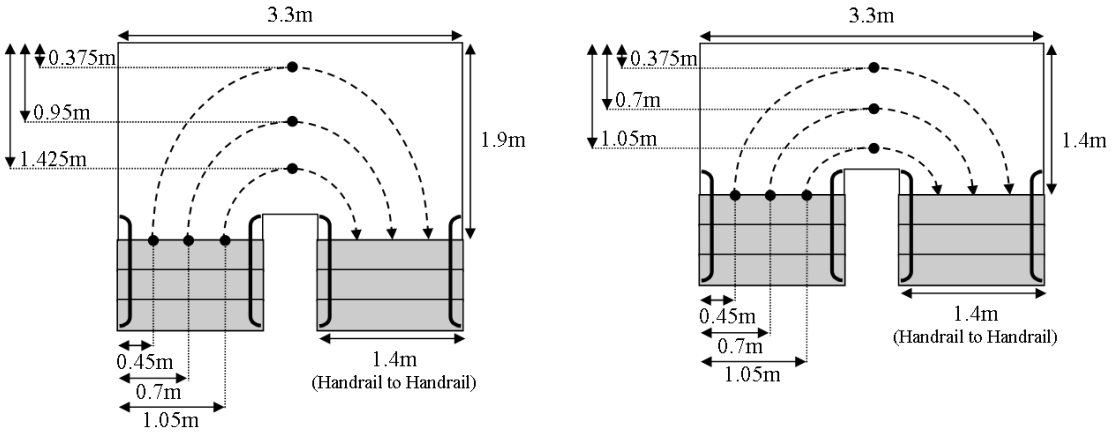


Figure 6-12: Stair and landing lanes

Depicted in Figure 6-13 are the approximate measurements of the entry points onto each main and sub landing, based on the video observations, the midpoints and quartiles of the stair width, as well as the device dimensions. These entry positions remain constant when the width of the staircase is constant, and this is likely to be the case for most stairwells. However, the devices' positioning on the landing is dependent on the landing depth, which is more likely to be variable. In the Ghent experiment, there were larger landings at each floor and smaller sub-landings in between. For these landings, the effective turning depth for the devices was 1.9 m and 1.4 m respectively. The landing position is considered to be the

closest point at which the device is positioned to the external wall of each landing; i.e. the wall non-adjacent to either staircase.

The carry chair with four female operators and the stretcher with four operators, of either gender, travelled in the middle of the stairway, spanning both lanes and blocking the full path. Its entry point to the landing was in the central position of the staircase, i.e. 0.7 m from the outside wall, and the landing position was half of the landing depth: 0.95 m for the main landing and 0.7 m for the sub landing. The carry chair with three male operators, as well as the evacuation chair with two operators, of either gender, travelled on the inside lane of the stairway, occupying only one lane. Its entry point to the landing is the midpoint of the inner lane, i.e. 1.05 m from the outside wall, and the landing position is the boundary of the third and fourth quartile of the landing depth: 1.425 m for the main landing and 1.05 m for the sub landing.



(i)

Main landing device position measurements

(ii)

Sub landing device position measurements

Figure 6-13: Entry and landing positions in two-lane staircases for (i) main landing of effective depth 1.9m and (ii) sub-landing of effective depth 1.4m.

The rescue sheet with two operators, of either gender, travelled on the outside lane of the stairway, but it occupied more than one lane because of its larger width (0.75 m) and its edge was typically 0.05 m - 0.10 m from the outside wall. Furthermore, this width was not static as with the other metal devices as the rescue sheet bound the edges of a mattress that was tighter or looser depending on

the way it was prepared and the position of the PRM inside. Therefore, its entry position was variable and thus approximated at 0.45 m from the outside wall: half its width, plus the approximate 0.075 m distance from the wall. However, unlike its position on the stairs, when travelling on the outside lane of the landing, it typically touched the outside wall, and thus its landing position is calculated as half the mattress width: 0.375 m.

Table 6-9 outlines the lane occupancy of each device as observed during the Ghent trials; i.e. a two-lane staircase. If the devices stop during their descent, they stop on at the bottom of a staircase, and only occupy one lane when stopped. The data indicate that devices that travel in the inside lane will stop in the inside lane, and those that travel in either the outside lane or the centre of the stairs will stop in the outside lane.

Table 6-9: Object lane occupancy in stairwells

	Stretcher (M/F)	**Evacuation Chair (M/F)**	**Carry Chair (M)**	**Carry Chair (F)**	**Rescue Sheet (M/F)**
No. Stair lanes occupied	2	1	1	2	1.5
Stair Lane (SL)	Middle of 2 lanes (SL2)	Inside lane (SL1)	Inside lane (SL1)	Middle of 2 lanes (SL2)	Outside lane (SL3)
Landing lane (LL)	Middle of 2 lanes (LL2)	Inside lane (LL1)	Inside lane (LL1)	Middle of 2 lanes (LL2)	Outside lane (LL3)
Position when stopped	Outside Lane (LL3)	n/a	Inside lane (LL1)	Outside Lane (LL3)	Outside Lane (LL3)
Overtaking on stairs	No	Yes, on the outside lane	Yes, on the outside lane	No	Yes, on the inside lane
Overtaking on landing	Yes, on the inside lane when the device has stopped	Yes, on the outside lane at any time	Yes, on the outside lane at any time	Yes, on the inside lane when the device has stopped	Yes, on the inside lane at any time, but more often when device has stopped

Transit nodes in bEX operate alongside the nodal system: a staircase can be attached to nodes to link horizontal and vertical movement. In the case of devices, the horizontal movement algorithm, as described in section 6.5, is employed until a transit node is encountered. Using the lane information in Table 6-9, when the object detects that it is heading towards a transit node, i.e. when it is within 2.0 m

of a transit note, its itinerary function sends it to the correct entrance point, depending on the lane attribute of the device. For example, when approaching a two-lane stairway, the stretcher will aim for the centre of the staircase and travel down the two lanes, and the evacuation chair will aim for the inside stairs and remain in lane. Once on a transit node, the device employs its interpolated vertical speed, as outlined in section 6.7.1, and the stopping algorithm outlined in the next section (6.7.3). Once a device reaches a landing from a transit node, it has travelled in a straight line and thus its entrance position is maintained. The path travelled on the landing approximately follows a segment of an elliptic shape as previously depicted in Figure 6-12. For a clockwise dog leg staircase, the parametric Equation 6-5 models this curve as bounded by the variables: entrance position (E), landing position (L_P), landing width (L_W), and landing depth (L_D).

Equation 6-5

$$\mathrm{x} = \left(\frac{L_W}{2} - E\right)(\cos(\pi - \tau) + 1)$$

$$\mathrm{y} = (L_D - L_P)\sin(\pi - \tau)$$

$$0 \leq \tau \leq \pi$$

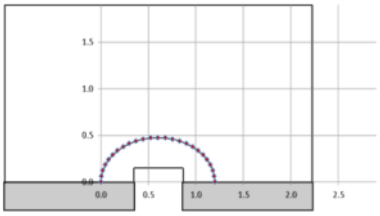
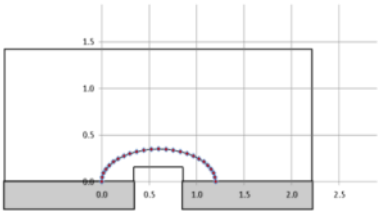
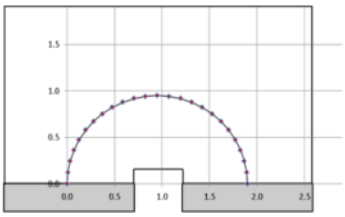
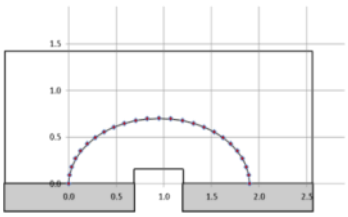
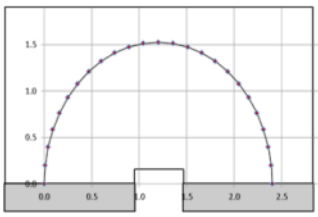
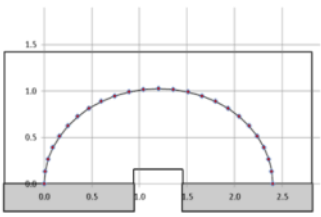
Table 6-10 depicts the path for each device, calculated using Equation 6-5 on a local Cartesian grid. The origin is the entry point, for this local coordinate system, in which the device navigates irrespective to its global position. Therefore the entry position (x,0) is categorised as the distance between the centre of the lane, and the closest adjacent external wall.

In addition to the continuous paths described in Table 6-10, the turning motion A of each device can be modelled using the gradient of its path, as per Equation 6-6 (in radians):

Equation 6-6

$$A = tan^{-1}\left(\frac{-(L_D - L_P)^2\left(x - \frac{L_W}{2} + E\right)}{\left(\frac{L_W}{2} - E\right)^2 y}\right)$$

Table 6-10: The continuous path of each device on main landings and sub landings

Devices/Position	Main Landing $L_W = 3.3, L_D = 1.9$	Sub landing $L_W = 3.3, L_D = 1.4$
Evacuation chair & carry chair (M)/ SL1-LL1	$(E = 1.05; L_P = 1.425)$ 	$(E = 1.05; L_P = 1.05)$ 
Stretcher & carry chair (F)/ SL2-LL2	$(E = 0.7; L_P = 0.95)$ 	$(E = 0.7; L_P = 0.7)$ 
Rescue Sheet SL3-LL3	$(E = 0.45; L_P = 0.375)$ 	$(E = 0.45; L_P = 0.375)$ 

To model devices in a discrete event simulation engine, their paths on landings must be discretised into a number of steps. Clearly, as this number increases, the motion of the path will appear smoother in the model; however, it is bound by the speed of the device in relation to the time-steps used: in bEX every $1/6^{th}$ second. The data indicate that, on average, the longest time a device will spend on a landing is 10.3 seconds (trial 17: Male Carry Chair team – see Appendix P for raw data). Therefore, a maximum of 62 discrete steps will be used when any device is moving. For all the devices considered as part of this work it is therefore proposed that 62 discrete steps (n) will be modelled: $n = 0, 1, \ldots . 61$.

The position of the device at step n is (x_n, y_n), where:

$$x_n = \left(\frac{L_W}{2} - E\right)(\cos(\pi - \tau_n) + 1)$$

$$y_n = (L_D - L_P)\sin(\pi - \tau_n)$$

$$\tau_n = \frac{\pi n}{61}$$

The device's angle in degrees at position (x_n, y_n) is:

$$\theta° = 90 - \frac{180}{\pi} tan^{-1}\left(\frac{-(L_D - L_P)^2\left(x_n - \frac{L_W}{2} + E\right)}{\left(\frac{L_W}{2} - E\right)^2 y_n}\right)$$

The time at which the device enters the landing is recorded as T_n (when $n = 0$)
Then the time at each subsequent step T_n (when $n > 0$) is simply the distance travelled divided by the interpolated vertical speed (s_v):

$$T_n = T_{n-1} + \frac{\sqrt{(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2}}{s_v}$$

As each successive time-step elapses in bEX, the device moves to the step with the highest T_n value below the time on the simulation clock, and is orientated according to the equations above.

Because of the nature of the movement on stairs (in lanes), each device enters the landing perpendicular to the landing. Its angle with respect to the landing geometry begins at 0° and ends at 180°. However, because of the length of the device, it may still turn on the stairway given that its front position is turning as prescribed on the landing.

6.7.3 Vertical Stopping Algorithm

To represent the sequence of stops that devices will undertake during a ten floor journey, the following parameters are introduced:

- $\boldsymbol{d_s}$ = (Vertical) Stoppage duration (seconds)
- $\boldsymbol{m_s}$ = (Vertical) Stopping Frequency: distance travelled (metres)

Table 6-11 presents the corresponding data for these: the average stopping duration for the stretcher, carry chair and rescue sheet as recorded in the Ghent experiment, and the average distance that teams travelled between stops. The evacuation chair did not stop in any of the trials; therefore, it is not included in the stopping model presented.

Table 6-11: Vertical stopping model data

Stretcher	**Variable**	**Male**	**Female**
Average No. of Stops		2	4.5
Average Duration of Stops (Seconds)	$\boldsymbol{d_s}$	10.24	14.08
Average Metres Travelled before Stopping	$\boldsymbol{m_s}$	70.57	30.52
Carry Chair		**Male**	**Female**
Average No. of Stops		4.5	3
Average Duration of Stops (Seconds)	$\boldsymbol{d_s}$	7.94	10.79
Average Metres Travelled before Stopping	$\boldsymbol{m_s}$	27.72	39.38
Rescue Sheet		**Male**	**Female**
Average No. of Stops		0.5	1.5
Average Duration of Stops (Seconds)	$\boldsymbol{d_s}$	8.04	3.07
Average Metres Travelled before Stopping	$\boldsymbol{m_s}$	129.85	14.67

As depicted in the flowchart in Figure 6-14, when teams progress down the stairs at their vertical speeds ($\boldsymbol{s_v}$), bEX records the distance travelled in the stairwells as a dynamic attribute: metres travelled in a staircase ($\boldsymbol{m_t}$). At any time in which the device travels within a stairway during the simulation, the variable cumulatively updates as the sum of all distances travelled on stair (transit) nodes and landing nodes. When this distance travelled is greater than the devices stopping distance variable ($\boldsymbol{m_s}$), it is time for the device to stop at the next opportunity. Both the distances travelled on the stairwell and the devices' stopping distances were calculated using the Pythagorean diagonal distance taken down the stairs.

Once the decision is made to stop, the device continues travelling to the next landing (to their $\boldsymbol{LLP}$) and delays for a period of $\boldsymbol{d_s}$ seconds. After a stop, the distance variable ($\boldsymbol{m_t}$) is reset to zero and the distance accumulates once more until enough time has elapsed for the next stop to occur. The time taken when stopping incorporates the time taken to move to the stopping position.

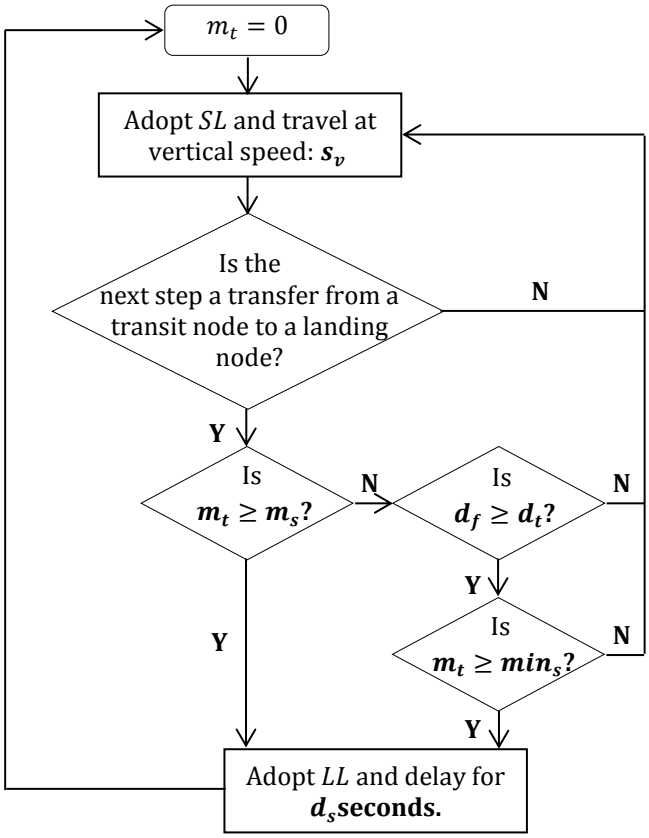


Figure 6-14: Object vertical stoppage model flow chart

During the Ghent trials, it was found that other evacuating agents could more easily overtake the devices when they were stopped on the landings. Furthermore, in the case of the stretcher and the carry chair with a female handling team, the only times in which others could overtake were during these stop periods. In an evacuation scenario, devices may opt to stop in order to allow overtaking; therefore this model incorporates an optional user-set variable in which to represent this condition. The decision to allow overtaking is based on the density of the queue that is building up behind the device. Therefore the user can specify a density tolerance ($\boldsymbol{d_t}$) in people per metres squared. When the density in the stairwell behind the device ($\boldsymbol{d_f}$) exceeds the tolerance level, then the device opts to stop (travelling to its $\boldsymbol{LP}$ first and then delaying for a period of $\boldsymbol{d_s}$ seconds as before).

These models are combined in the flowchart in Figure 6-14, where the accumulated distance is monitored as well as the stairwell density. In cases of very congested stairways, the density tolerance may always flag the need for a stop.

Therefore, a minimum distance between stops is introduced ($\boldsymbol{min_s}$ metres) to set a limit on the number of stops that will occur. This is a user-set parameter that can represent the willingness of devices to stop in order to let people pass, and to ensure that the devices continues to progress in a realistic manner. For example, if it is assumed that the devices will only allow people to pass when they would have stopped anyway, then $\boldsymbol{min_s} \geq \boldsymbol{m_s}$, or if it is assumed that devices will stop twice as often as desired in order to allow passing, then $\boldsymbol{min_s} = \frac{\boldsymbol{m_s}}{\boldsymbol{2}}$.

6.8 Horizontal and Vertical Model Interactions

Objects can be specified in bEX with a different number of agents required for horizontal travel ($\boldsymbol{n_h}$) and for vertical travel ($\boldsymbol{n_v}$). Therefore, when moving between the horizontal node system and the vertical transit node system, agents may be required to attach and detach from the devices. The number of agents currently attached to the device ($\boldsymbol{n_a}$) is a dynamic attribute. The device will wait at a nodal location for the correct number of attachments before moving in horizontal or vertical evacuation.
Figure 6-15 depicts an overview of the process at each time step, considering the next step the object intends to make.

This accords with the itineraries allocated to device handlers as described in section 6.4: the location of a device is specified by the nodes on which it resides and these represent location targets for agents. As such, tasks can be assigned for agents to: pick up the device; delay while preparing once the minimum number of handlers are present; utilise the horizontal movement algorithm once the required handlers are attached to the device via the prescribed points; and utilise the vertical descent model, including stoppages.

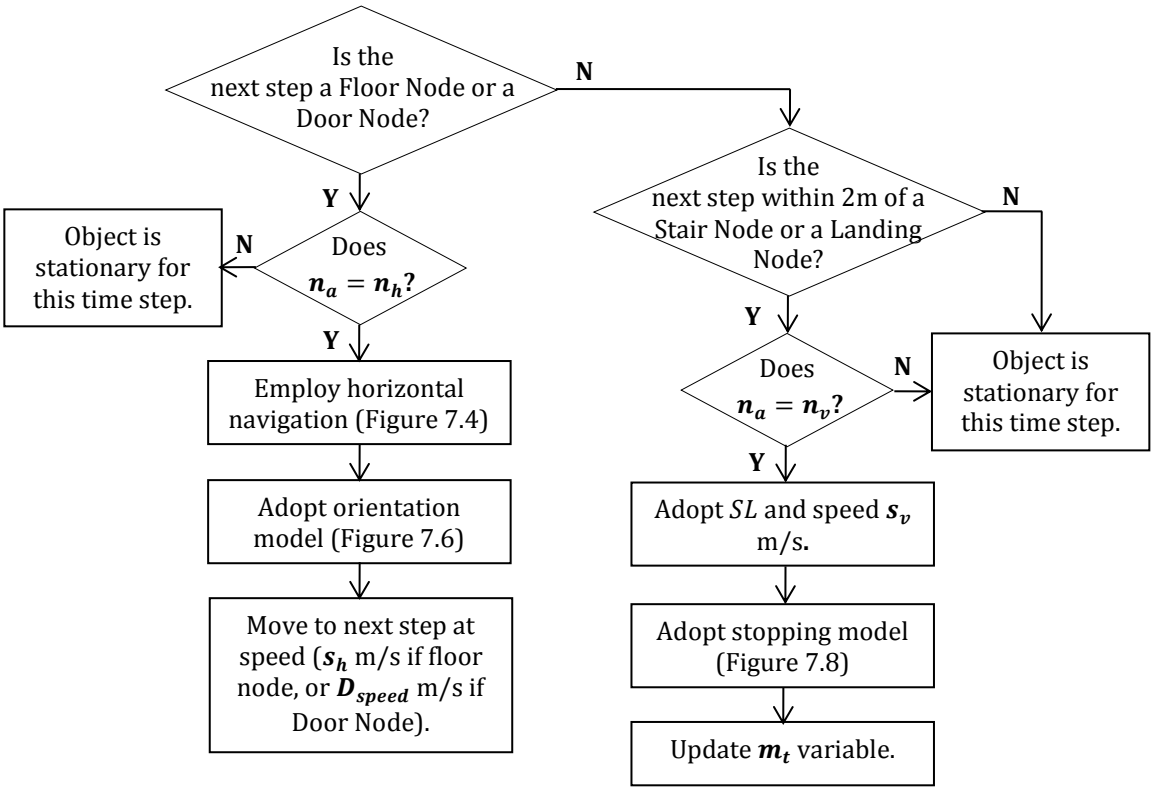


Figure 6-15: Horizontal and Vertical Model Interaction

This section presented a detailed specification of a theoretical model, designed to explicitly represent movement devices within an agent-based evacuation model. This theoretical model, and hence the simulated performance of the movement devices, was designed in accordance with the data collected as part of this research (see Chapters 3 and 4). It represented the key qualitative factors that influenced performance that were identified during this data collection, and then embedded representative data to quantify performance. This theoretical model has been specified such that it might be implemented in an evacuation model with the required functionality (Chapter 2.2.2). The theoretical model has been implemented within the bEX evacuation model, using the specification presented in this section, by Dr Lawrence and the bEX development team, in order to test the effectiveness of the model. The specification was such that the implemented theoretical model complimented, exploited and significantly extended the existing functionality within bEX. The following section presents component testing of this model within bEX software in order to determine that the model specification was implemented accurately, and that the implemented model performed as expected.

Following this, Chapter 8 discusses the key elements of the theoretical model and findings from the testing conducted, by addressing the research questions posed in Chapter 1.

7 VALIDATION AND VERIFICATION

The sections in this chapter present a number of test cases to evaluate the theoretical models described in this thesis. Unlike maritime evacuation models [161], there are not yet definitive standards for the verification and validation of building evacuation simulations. Some generalised examples of tests for agent-based evacuation simulations are available (e.g. ISO/TR 16730-5:2013 [162] and NIST [163]). However, these do not specifically address healthcare environments. While many of the tests may be extended to represent aspects of hospital evacuation simulation (e.g. NIST include a verification test for the representation of wheelchair users [163]), new tests are presented here to explicitly quantify the movement of beds and movement devices, in both horizontal and vertical evacuations.

Guidance document MSC/Circ.1238 [255] has been recently developed by the International Maritime Organisation to evaluate the performance of evacuation models in the maritime environment. While this does not translate directly to the built environment, it still represents the most comprehensive regulatory guidance for evacuation models to date. Therefore, the testing presented here will largely follow the structure suggested for maritime and building evacuation modelling [256]: *Component Testing*, where individual components of the theoretic model are tested to ensure they function as intended; and *Functional Verification*, where the model's ability to perform simulations of hospital evacuation is analysed. For each test, *Qualitative or Quantitative Verification* is conducted to compare the simulation model against experimental data presented in this thesis.

For ease of reference, the component tests outlined here correspond directly to the sections outlined in the theoretical model: Route Assessment, Object Specification, Agent-Device Interaction, Horizontal Travel, Door Transition, and Vertical Travel. Each test will outline:

- the purpose of the test;

- the method utilised in the test, including the parameters used and the data they are derived from;
- the results that are expected from the test, based on data or functional requirements;
- the actual results that were observed from the test, tabulated according to the device used and the attributes allocated; and
- a statement of either qualitative or quantitative verification of the sub-model or model in question.

7.1 Route Assessment: Component Testing

As outlined in the theoretical model, hospital plans are analysed to detect 90° turns in the evacuation routes taken by devices. This functionality allows a simple calculation to be made to determine whether beds, movement devices and other objects larger than people can fit around the corners within a geometry, therefore establishing viable routes for devices to take. To test this component of the theoretical model, 12 test cases are developed.

While UK building codes specify that the effective width of hospital corridors should be at least 2150mm and doors 1550mm, there are cases in the literature (e.g. the Royal Marsden evacuation [59]) where the effective width of doors on the exit route was too small to accommodate devices (i.e. less than 1550mm). Therefore, the tests presented here use conservative values for the size of corridors and doors (between 1000mm and 2000mm), as well as larger configurations (between 2000mm and 6000mm).

The purpose of these tests is to identify an extensive range of configurations of right angle routes that are possible in a realistic hospital environment, to demonstrate that the expected results (the correct identification of right angles) are met by this model. Evacuation paths are considered as a sequence of straight-line and right-angled routes, as outlined in Figure 7-1. Tests 1-2 each investigate one right-angled corridor (an L-shape) with varying dimensions. Test 3-9 each investigate two right-angles. As depicted in Figure 7-1 (ii), this combination will invariably result in a “dog-legged” or “snake” configuration: all other possible

combinations are a reflection, rotation or transpose of these shapes. In test 10, a case is identified where two corners intersect (i.e. when they overlap with each other), and there is no demonstrable 90° turn. For this test, the ideal outcome is for a corner not to be identified.

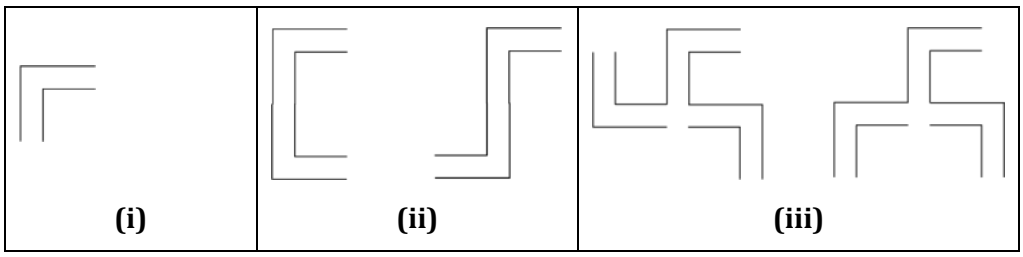


Figure 7-1: Test configurations for corridors with (i) one right angle, (ii) two right angles, and (iii) three right angles

Combining three right angles will lead to the two shapes identified in Figure 7-1 (iii): all other combinations will be made up of one or more of the previous shapes and are therefore already accounted for in the testing schedule. These are investigated in tests 11-12, where a mixture of definitive corners is tested, alongside an intersecting (overlapping) corner.

For each of these configurations, various dimensions are tested to establish the performance of the algorithm: when the route passes through corridors of identical and varying widths; when the right angled turns are far away from each other, close to each other, or overlapping each other; and where the spaces in which to turn are small ($< 1.0m$), big ($> 5.0m$), or of varying dimensions. As previously demonstrated (Figure 6-3) doorways are treated in the same way as open space using the medial axis transform, therefore it is not necessary to test these separately: the case of a 90° turn from a doorway is encompassed by these tests. The model identifies the change in angle along a given route, where the user identifies the start and finish points. Each route was tested twice, once in either direction (i.e. the start and end point is swapped), but it was found that there was no difference in any case between these detection capabilities, therefore only one direction for each test is presented here. Additionally, as it is clear from all of the tests that corners aren't identified in straight spaces there is no need to specify this elementary test.

7.1.1 Component Tests 1 – 2: identifying one corner

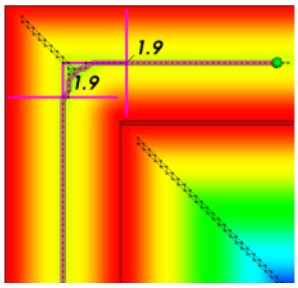
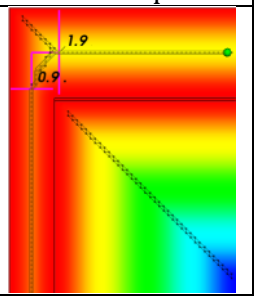
Purpose: To test the identification of simple 90° routes in corridors with equal dimensions and unequal dimensions.

Method: Import plans of equal (2.0m, 2.0m) and unequal (1.0m, 2.0m) corners into the proximity field generator (PFG) and observe the recorded corner dimensions.

Expected Results: In each case, the PFG automatically detects one right-angle, and correctly reports the corridor dimensions, within the expected error: $\varepsilon \leq 0.2m$.

Test Results: As demonstrated in Table 7-1, the automatic detection yields the expected results.

Table 7-1: Component Tests 1 – 2: identifying one corner

Test 1	PFG Output	Test 2	PFG Output
1 corner; equal dimensions		1 corner; unequal dimensions	
REAL: Corner 1 (2.0m, 2.0m)		REAL: Corner 1 (1.0m, 2.0m)	
PFG: Corner 1 (1.9m, 1.9m)		PFG: Corner 1 (0.9m, 1.9m)	
ε Corner 1 (0.1m, 0.1m)		ε Corner 1 (0.1m, 0.1m)	

Quantitative Verification: This test satisfies the conditions set in that a right-angled corner is correctly identified within expected dimensions, and to an appropriate degree of accuracy.

7.1.2 Component Tests 3 – 5: identifying two corners in a dog-leg configuration

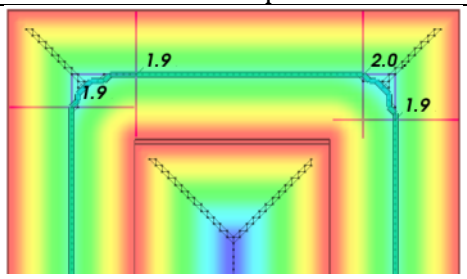
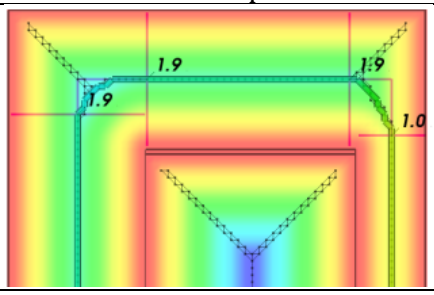
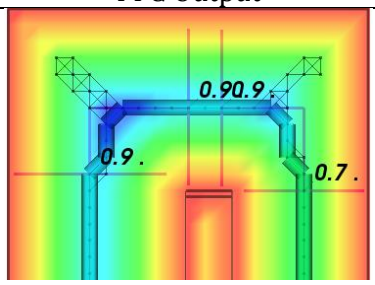
Purpose: To test the identification of routes consisting of two 90° turns in a dog-leg configuration in corridors with equal dimensions and unequal dimensions, and where the distance between the turns is either short or long.

Method: Import plans of equal (1.0m, 1.0m; 2.0m, 2.0m) and unequal (1.0m, 2.0m; 1.0m, 0.75m) corners into the proximity field generator (PFG) and observe the recorded corner dimensions.

Expected Results: In each case, the PFG automatically detects two right-angles, and correctly reports the corridor dimensions, within the expected error: $\varepsilon \leq 0.2m$.

Test results: As demonstrated in Table 7-2: Component Tests , the automatic detection yields the expected results.

Table 7-2: Component Tests 3 – 5: identifying two corners in a dog-leg configuration

Test 3		PFG Output
2 corners; both equal dimensions		
REAL: Corner 1 (2.0m, 2.0m)	REAL: Corner 2 (2.0m, 2.0m)	
PFG: Corner 1 (1.9m, 1.9m)	PFG: Corner 2 (2.0m, 1.9m)	
Ɛ Corner 1 (0.1m, 0.1m)	Ɛ Corner 2 (0.0m, 0.1m)	
Test 4		PFG Output
2 corners; one equal and one unequal dimensions		
REAL: Corner 1 (2.0m, 2.0m)	REAL: Corner 2 (2.0m, 1.0m)	
PFG: Corner 1 (1.9m, 1.9m)	PFG: Corner 2 (1.9m, 1.0m)	
Ɛ Corner 1 (0.1m, 0.1m)	Ɛ Corner 2 (0.1m, 0.0m)	
Test 5		PFG Output
2 corners; one equal and one small unequal dimensions; close together (i.e. “U-turn”)		
REAL: Corner 1 (1.0m, 1.0m)	REAL: Corner 2 (1.0m, 0.75m)	
PFG: Corner 1 (0.9m, 0.9m)	PFG: Corner 2 (0.9m, 0.7m)	
Ɛ Corner 1 (0.1m, 0.1m)	Ɛ Corner 2 (0.1m, 0.05m)	

Quantitative Verification: This test satisfies the conditions set in that two right-angled corners are correctly identified within expected dimensions, and to an appropriate degree of accuracy.

7.1.3 Component Tests 6 - 9: identifying two corners in a snake configuration

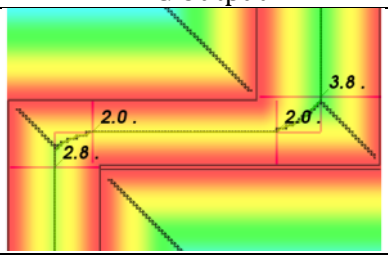
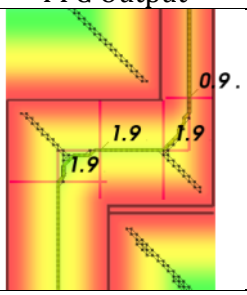
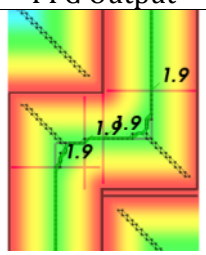
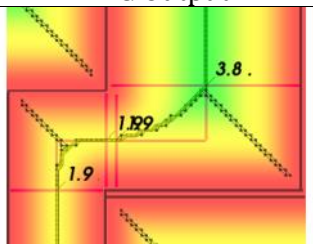
Purpose: To test the identification of routes consisting of two 90° turns in a snake configuration in corridors with equal dimensions and unequal dimensions, and where the distance between the turns is either short or long.

Method: Import plans of equal (2.0m, 2.0m) and unequal (1.0m, 2.0m; 2.0m, 4.0m) corners into the proximity field generator (PFG) and observe the recorded corner dimensions.

Expected Results: In each case, the PFG automatically detects two right-angles, and correctly reports the corridor dimensions, within the expected error: $\mathcal{E} \leq 0.2m$.

Test results: As demonstrated in Table 7-3, the automatic detection yields the expected results.

Table 7-3: Component Tests 6 - 9: identifying two corners in a snake configuration

<table>
<tr><td colspan="2">Test 6</td><td>PFG Output</td></tr>
<tr><td colspan="2">2 corners; both unequal (large) dimensions;</td><td rowspan="4"> 
</td></tr>
<tr><td>REAL: Corner 1
(3.0m, 2.0m)</td><td>REAL: Corner 2
(2.0m, 4.0m)</td></tr>
<tr><td>PFG: Corner 1
(2.8m, 2.0m)</td><td>PFG: Corner 2
(2.0m, 3.8m)</td></tr>
<tr><td>Ɛ Corner 1
(0.2m, 0.0m)</td><td>Ɛ Corner 2
(0.0m, 0.2m)</td></tr>
<tr><td colspan="2">Test 7</td><td>PFG Output</td></tr>
<tr><td colspan="2">2 corners; one equal and one unequal with small dimensions;</td><td rowspan="4"> 
</td></tr>
<tr><td>REAL: Corner 1
(2.0m, 2.0m)</td><td>REAL: Corner 2
(2.0m, 1.0m)</td></tr>
<tr><td>PFG: Corner 1
(1.9m, 1.9m)</td><td>PFG: Corner 2
(1.9m, 0.9m)</td></tr>
<tr><td>Ɛ Corner 1
(0.1m, 0.1m)</td><td>Ɛ Corner 2
(0.1m, 0.1m)</td></tr>
<tr><td colspan="2">Test 8</td><td>PFG Output</td></tr>
<tr><td colspan="2">2 corners; both equal (small) dimensions; close proximity</td><td rowspan="4"> 
</td></tr>
<tr><td>REAL: Corner 1
(2.0m, 2.0m)</td><td>REAL: Corner 2
(2.0m, 2.0m)</td></tr>
<tr><td>PFG: Corner 1
(1.9m, 1.9m)</td><td>PFG: Corner 2
(1.9m, 1.9m)</td></tr>
<tr><td>Ɛ Corner 1
(0.1m, 0.1m)</td><td>Ɛ Corner 2
(0.1m, 0.1m)</td></tr>
<tr><td colspan="2">Test 9</td><td>PFG Output</td></tr>
<tr><td colspan="2">2 corners; one equal and one unequal with small dimensions; close proximity</td><td rowspan="4"> 
</td></tr>
<tr><td>REAL: Corner 1
(2.0m, 2.0m)</td><td>REAL: Corner 2
(2.0m, 4.0m)</td></tr>
<tr><td>PFG: Corner 1
(1.9m, 1.9m)</td><td>PFG: Corner 2
(1.9m, 3.8m)</td></tr>
<tr><td>Ɛ Corner 1
(0.1m, 0.1m)</td><td>Ɛ Corner 2
(0.1m, 0.2m)</td></tr>
</table>

Quantitative Verification: This test satisfies the conditions set in that two right-angled corners in a snake configuration are correctly identified within expected dimensions, and to an appropriate degree of accuracy.

7.1.4 Component Test 10: not identifying any corner in an intersecting snake configuration

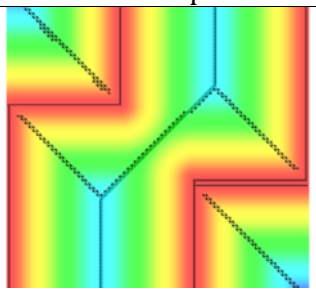
Purpose: To test the identification of routes consisting of two 90° turns in a snake configuration where the corners "overlap"; i.e. they are connected and therefore there is no demonstrable 90° turn.

Method: Import plans of equal (2.0m, 5.0m) intersecting corners into the proximity field generator (PFG) and observe any recorded corner dimensions.

Expected Result: The PFG does **not** automatically detect any right angle.

Test result: As demonstrated in Table 7-4 the automatic detection yields the expected results.

Table 7-4: Component Test 10: not identifying any corner in an intersecting snake configuration

<table>
<tr><td colspan="2">Test 10</td><td>PFG Output</td></tr>
<tr><td colspan="2">2 corners; both equal (large) dimensions; intersecting, i.e. no distance between corners</td><td rowspan="3">  </td></tr>
<tr><td>REAL: Corner 1
(5.0m, 2.0m)</td><td>REAL: Corner 2
(2.0m, 5.0m)</td></tr>
<tr><td>PFG: Corner 1
Unidentified</td><td>PFG: Corner 2
Unidentified</td></tr>
</table>

Quantitative Verification: This test satisfies the conditions set in that two right-angled corners in an overlapping snake configuration are correctly unidentified within expected dimensions.

7.1.5 Component Tests 11 (i), (ii), and (iii): identifying three corners

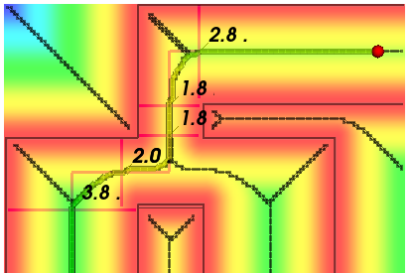
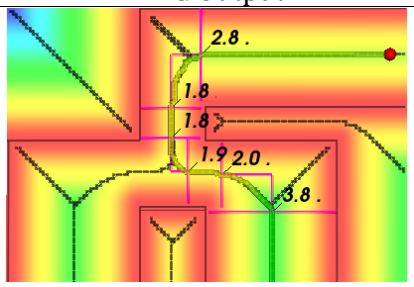
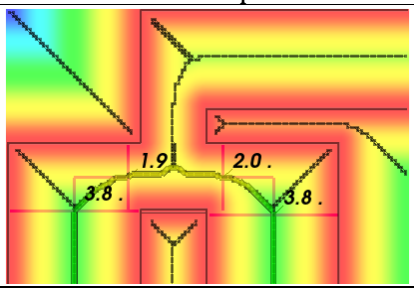
Purpose: To test the identification of routes consisting of three 90° turns in a corridors with equal dimensions and unequal dimensions, and varying distances between the turns.

Method: Import plans of equal (2.0m, 2.0m) and unequal (2.0m, 3.0m; 2.0m, 4.0m) corners into the proximity field generator (PFG), run three sets of possible routes and observe the recorded corner dimensions.

Expected Results: In each case, the PFG automatically detects two right-angles, and correctly reports the corridor dimensions, within the expected error: $\mathcal{E} \leq 0.2m$.

Test results: As demonstrated in Table 7-5, the automatic detection yields the expected results.

Table 7-5: Component Tests 11 (i), (ii), and (iii): identifying three corners

<table>
<tr><td colspan="3">Test 11: Route (i)</td><td>PFG Output</td></tr>
<tr><td colspan="3">3 corner configuration – varying dimensions (see below)</td><td rowspan="4"> 
</td></tr>
<tr><td>R: Corner 1
(4.0m, 2.0m)</td><td>R: Corner 2
(2.0m, 2.0m)</td><td>R: Corner 3
(2.0m, 3.0m)</td></tr>
<tr><td>PFG: Corner 1
(3.8m, 2.0m)</td><td>PFG: Corner 2
(2.0m, 1.8m)</td><td>PFG: Corner 3
(1.8m, 2.8m)</td></tr>
<tr><td>Ɛ Corner 1
(0.2m, 0.0m)</td><td>Ɛ Corner 2
(0.0m, 0.2m)</td><td>Ɛ Corner 3
(0.2m, 0.2m)</td></tr>
<tr><td colspan="3">Test 11: Route (ii)</td><td>PFG Output</td></tr>
<tr><td colspan="3">3 corner configuration – varying dimensions (see below)</td><td rowspan="4"> 
</td></tr>
<tr><td>R: Corner 1
(3.0m, 2.0m)</td><td>R: Corner 2
(2.0m, 2.0m)</td><td>R: Corner 3
(2.0m, 4.0m)</td></tr>
<tr><td>PFG: Corner 1
(2.8m, 1.8m)</td><td>PFG: Corner 2
(1.8m, 1.9m)</td><td>PFG: Corner 3
(2.0m, 3.8m)</td></tr>
<tr><td>Ɛ Corner 1
(0.2m, 0.2m)</td><td>Ɛ Corner 2
(0.2m, 0.1m)</td><td>Ɛ Corner 3
(0.0m, 0.2m)</td></tr>
<tr><td colspan="3">Test 11: Route (iii)</td><td>PFG Output</td></tr>
<tr><td colspan="3">2 corner configuration – varying dimensions (see below)</td><td rowspan="4"> 
</td></tr>
<tr><td colspan="2">R: Corner 1
(4.0m, 2.0m)</td><td>R: Corner 2
(2.0m, 4.0m)</td></tr>
<tr><td colspan="2">PFG: Corner 1
(3.8m, 1.9m)</td><td>PFG: Corner 1
(2.0m, 3.8m)</td></tr>
<tr><td colspan="2">Ɛ Corner 1
(0.2m, 0.1m)</td><td>Ɛ Corner 1
(0.0m, 0.2m)</td></tr>
</table>

Quantitative Verification: This test satisfies the conditions set in that three right-angled corners are correctly identified within expected dimensions, and to an appropriate degree of accuracy.

7.1.6 Component Tests 12 (i), (ii), and (iii): identifying two corners in a three-corner configuration with one intersecting corner

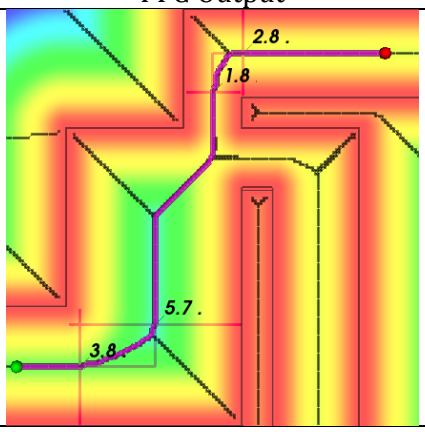
Purpose: To test the identification of routes consisting of three 90° turns in a corridors, with equal dimensions and unequal dimensions, and varying distances between the turns, where one of the turns is a intersecting (overlapping) corner,

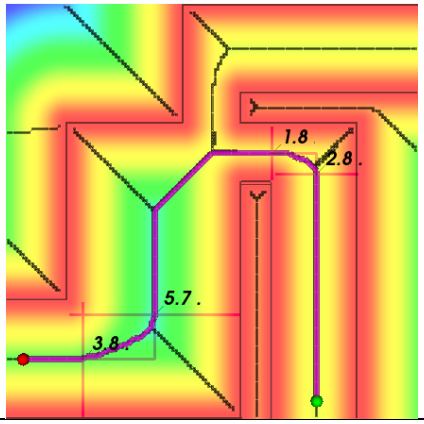
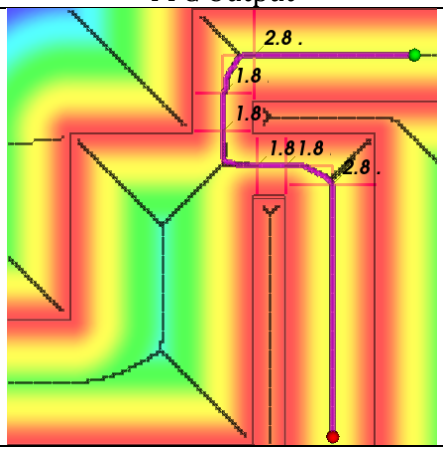
Method: Import plans of equal (2.0m, 2.0m) and unequal (2.0m, 3.0m; 2.0m, 6.0m) corners into the proximity field generator (PFG), run three sets of possible routes and observe the recorded corner dimensions.

Expected Results: In each case, the PFG automatically detects two right-angles, and correctly reports the corridor dimensions, within the expected error: $\mathcal{E} \leq 0.2m$.

Test results: As demonstrated in Table 7-6, the automatic detection yields the expected results, with the exception of a larger error in the first instance ($\mathcal{E} = 0.3m$). As described in chapter 6.2, this is to be expected with larger geometries because of the algorithm employed. This is not an issue because the turning position within a large 90° turn is so wide that it is essentially an area of open space. This is demonstrated in this example (where the turn is 4m by 6m) as in terms of bed and device movement, it is no longer a turn on a route, but a large space configuration that happens to have an l-shape.

Table 7-6: Component Tests 12 (i), (ii), and (iii): identifying two corners in a three-corner configuration with one intersecting corner

<table>
<tr><td colspan="3">Test 12: Route (i)</td><td>PFG Output</td></tr>
<tr><td colspan="3">3 corner configuration from Test 11 with one intersecting corner</td><td rowspan="4"> 
</td></tr>
<tr><td>R: Corner 1
(4.0m, 6.0m)</td><td>Intersecting
“Corner 2”</td><td>R: Corner 3
(2.0m, 3.0m)</td></tr>
<tr><td>PFG: Corner 1
(3.8m, 5.7m)</td><td>PFG: Corner 2
Unidentified</td><td>PFG: Corner 3
(1.8m, 2.8m)</td></tr>
<tr><td>Ɛ Corner 1
(0.2m, 0.3m)</td><td></td><td>Ɛ Corner 3
(0.2m, 0.2m)</td></tr>
</table>

<table>
<tr><td colspan="3">Test 12: Route (ii)</td><td>PFG Output</td></tr>
<tr><td colspan="3">3 corner configuration from Test 11 with one intersecting corner</td><td rowspan="4"> 
</td></tr>
<tr><td>R: Corner 1
(4.0m, 6.0m)</td><td>Intersecting
“Corner 2”</td><td>R: Corner 3
(2.0m, 3.0m)</td></tr>
<tr><td>PFG: Corner 1
(3.8m, 5.7m)</td><td>PFG: Corner 2
Unidentified</td><td>PFG: Corner 3
(1.8m, 2.8m)</td></tr>
<tr><td>Ɛ Corner 1
(0.2m, 0.3m)</td><td></td><td>Ɛ Corner 3
(0.2m, 0.2m)</td></tr>
<tr><td colspan="3">Test 12: Route (iii)</td><td>PFG Output</td></tr>
<tr><td colspan="3">3 corner configuration from Test 11 with one intersecting corner</td><td rowspan="4"> 
</td></tr>
<tr><td>R: Corner 1
(3.0m, 2.0m)</td><td>R: Corner 2
(2.0m, 2.0m)</td><td>R: Corner 3
(2.0m, 3.0m)</td></tr>
<tr><td>PFG: Corner 1
(2.8m, 1.8m)</td><td>PFG: Corner 2
(1.8m, 1.8m)</td><td>PFG: Corner 3
(1.8m, 2.8m)</td></tr>
<tr><td>Ɛ Corner 1
(0.2m, 0.2m)</td><td>Ɛ Corner 2
(0.2m, 0.2m)</td><td>Ɛ Corner 3
(0.2m, 0.2m)</td></tr>
</table>

Quantitative Verification: This test satisfies the conditions set in that right-angled corners are correctly identified within expected dimensions (to an appropriate degree of accuracy), and not identified in large areas of space.

7.2 Object Specification: Component Testing

As outlined in the theoretical model, movement devices and other objects are specified as rectangular shapes. Two tests are identified here to ensure that a device, as intended by its dimensions, occupies the correct amount of space.

7.2.1 Component Test 13: Representation of Device Size

Purpose: To ensure that the size of the device is correctly represented in respect to the scale of the geometry.

Method: Four devices are tested: stretcher (ST), evacuation chair (EC), carry chair (CC), and rescue sheet (RS). Each device is specified in bEX as a rectangular shape

of length l and width w. Initially, for test 13(i), the device is placed outside a room in the geometry of length l and width w, to establish comparable dimensions (see Figure 7-2). Then, for test 13(ii) the device is placed within the geometry of length l and width w, to demonstrate that it fully and exactly occupies the space specified (see Figure 7-2).

Test 13(i): Stretcher outside geometry **Test 13(ii): Stretcher inside geometry**

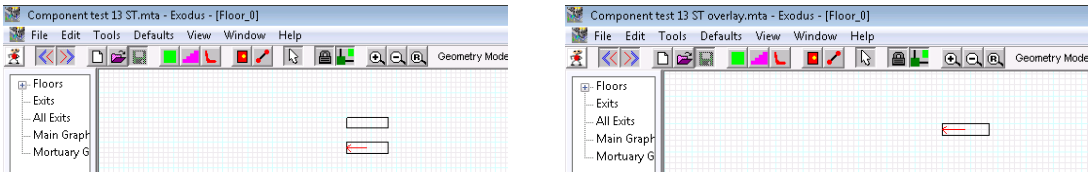


Figure 7-2: Tests 13(i) and 13(ii) demonstrating the correct geometric specification of the stretcher device

Expected Results: For test 13(i), the device has been correctly specified if it presents identical dimensions to the shape of the geometry. For test 13(ii), the device has been correctly specified if, when placed within the geometry, its shape exactly matches the shape of the geometry.

Test results: As demonstrated in Table 7-7, the test yields the expected results: the devices occupy the specified dimensions in relation to the bEX geometry.

Table 7-7: Component Test 13: Representation of Device Size

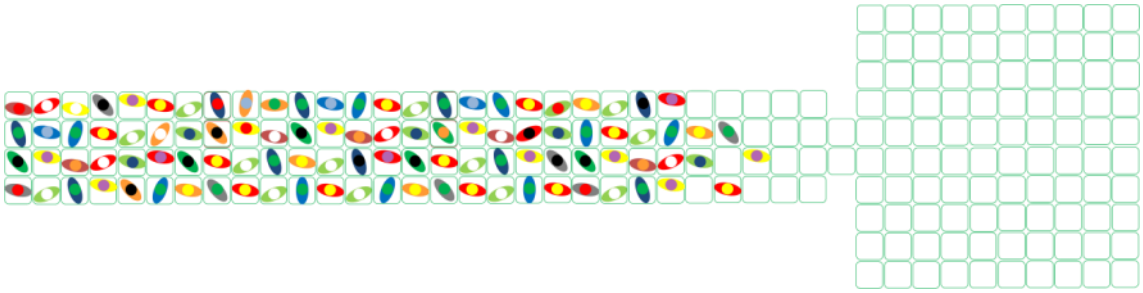
Device	Device Specification (m)		Geometry Specification (m)		Test 13(i) bEX output	Test 13(ii) bEX output
	l	***w***	***l***	***w***		
ST	1.66	0.43	1.66	0.43	Identical dimensions	Exact overlay
EC	0.77	0.52	0.77	0.52	Identical dimensions	Exact overlay
CC	0.61	0.48	0.61	0.48	Identical dimensions	Exact overlay
RS	2.00	0.75	2.00	0.75	Identical dimensions	Exact overlay

Qualitative Verification: This test satisfies the conditions set in that the dimensions prescribed for each device align with (and directly scale to) the dimensions of other geometric shape within the model.

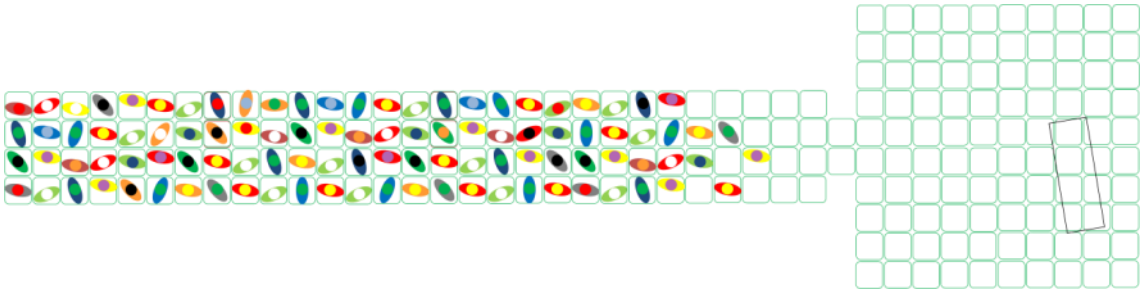
7.2.2 Component Test 14: Representation of Device Area

Purpose: To ensure that the area occupied by a device is correctly represented in relation to the surrounding geometry and other occupants.

Method: As depicted in Figure 7-3, a room is specified in the geometry of length $5.0m$ and width $5.0m$ and is connected by a door to a large corridor. 101 agents are randomly positioned in the corridor and the model is calibrated so that a maximum density of $4ppm^2$ is specified. The agents are given itineraries to travel towards a node positioned at the back of the room: this ensures that they all aim to fill the room. As depicted in Figure 7-3, the first test represents the base case, where no device is present. Agents pile into the room and it is observed that exactly 100 agents fit into the space (with exactly one agent remaining in the corridor). Then four devices are tested in turn: stretcher (ST), evacuation chair (EC), carry chair (CC), and rescue sheet (RS). Each device is specified in bEX as a rectangular shape of length l and width w and placed into the room at a number of orientations (including vertical, horizontal and diagonal orientations). The number of agents that can fit into the room alongside the device is counted.



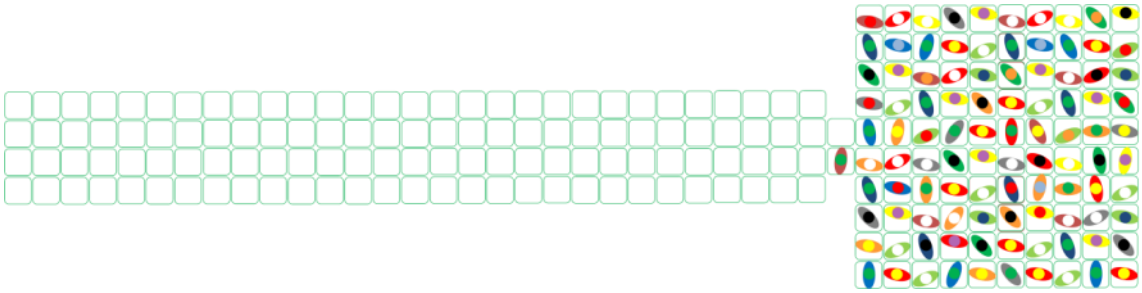
(i) Base case set-up



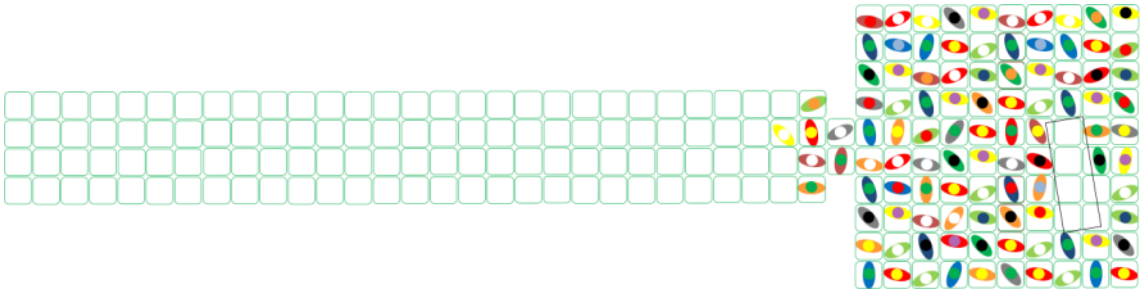
(ii) Device case set-up

Figure 7-3 Scenario for Component Test 14 – Base Case and Device Case

Expected Results: As depicted in Figure 7-4, for the base case (test 14 (i)), it is expected that 100 agents will fit into the room. For the device tests, it is expected that a maximum of 97 agents will be able to fit in with the stretcher, 98 with the evacuation chair, 98 with the carry chair, and 94 with the rescue sheet. These expected population sizes are based on the device areas (the rectangular area of $l * w$) as presented in Table 7-8. The result is expected to vary slightly based on the orientation of the device as this can alter the shape of space available to occupants, but the number of people occupying the room alongside the device must not exceed the maximum specified here because this represented the absolute space occupied by the device.



(i) Base case expected result



(ii) Device case expected result for stretcher of length 1.66m and width 0.43m

Figure 7-4 Expected results for Component Test 14 – Base Case and Stretcher Device Case

Test results: Ten applications of each test were simulated in bEX, with the devices at varying starting positions in each. Varying orientations of the device yielded slightly different results, as demonstrated in Table 7-8. A range was expected as the angle of a device and its proximity to boundaries can alter the availability of surrounding space for agents; for example, in Figure 7-5 the stretcher has displaced four agents when positioned at a 30° orientation and five agents when

positioned at a 65° orientation, both occupying the required minimum of three nodes.

Table 7-8: Component Test 14: Representation of Device Area

Test	Device	Device Specification (m)		Device area (m^2)	Available Space (m^2)	Maximum no. of agents in the room (expected result)	Range of bEX output: no. of agents in the room (test result)
		l	w				
14(i)	None	-	-	-	-	100	100
14(ii)	ST	1.66	0.43	0.71	24.29	97	95-97
14(iii)	EC	0.77	0.52	0.40	24.60	98	97-98
14(iv)	CC	0.61	0.48	0.29	24.71	98	97-98
14(v)	RS	2.00	0.75	1.50	23.50	94	92-94

Figure 7-5: Component Test 14(ii) where the stretcher has displaced four agents in a 30° orientation and five agents in a 65° orientation

Quantitative Verification: This test satisfies the conditions set in that each case demonstrates that the minimum area of the device is unoccupied.

7.3 Agent-Device Interaction: Component Testing

As outlined in section 6.3, a set of itineraries is developed to represent the tasks agents completed in order to evacuate a patient in a device. Agents are sent to a device. When the minimum number of people required to prepare the patient have arrived at the device a preparation delay is incurred. Once that has elapsed, and given that there are enough operators to horizontally transport the device, the

device moves off. It takes two handlers to prepare a patient in a device, and therefore a preparation delay is imposed once two handlers have reached the patient. The test outlined here is designed to test these itineraries, firstly when all the agents arrive at the device at the same time, and secondly when they arrive at different times.

7.3.1 Component Test 15: Agent preparation and collection of device

Purpose: To ensure that the correct delay occurs when a patient is being prepared in a device.

Method: Each of the four devices, with both male and female handling teams, are separately tested as follows. A device is positioned in a room, is allocated a number of attachment points, and assigned a preparation delay. The room is connected to a corridor with an exit at the end. Four agents (labelled agents 1, 2, 3, and 4) are positioned in a group in the corridor and are each given an itinerary to evacuate the device. In the first case (15(i)), agents 1, 2, 3 and 4 are all allocated a pre-evacuation response time of 0 s. In the second case (15(ii)), agents 1, 2 and 3 are allocated a pre-evacuation response time of 0 s, and agent 4 is allocated a pre-evacuation response time of 10s. It is assumed that all agents are required to be at the device before the preparation starts.

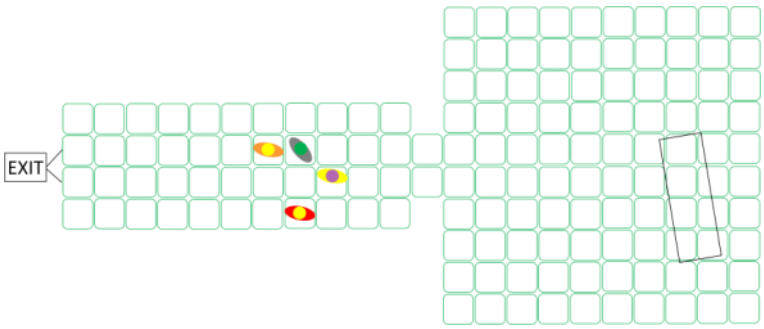


Figure 7-6: Component Test 15 set-up

Expected Results: In the first case (15(i)), when the simulation runs, all four agents immediately walk to the device and the specified preparation delay occurs, then they move off, attached to the device at the four attachment points, towards

the exit. In the second case (15(ii)), when the simulation runs agents 1, 2 and 3 immediately walk to the device and the specified preparation delay begins. Meanwhile agent 4 remains in the corridor. After 10 s elapses, agent 4 walks to the device and once they arrive at the device the preparation time begins. After the specified delay time, all of the agents move off, attached to the device at the four attachment points, towards the exit.

Test results: As depicted in Figure 7-7, the test scenario modelled the agent-device interaction for collection as follows: (i) the initial set-up; (ii) the minimum number of handlers (two) required to prepare the device have arrived at the device; (iii) the preparation time has elapsed and the handlers pick up the device; and (iv) the handlers begin to transport the device.

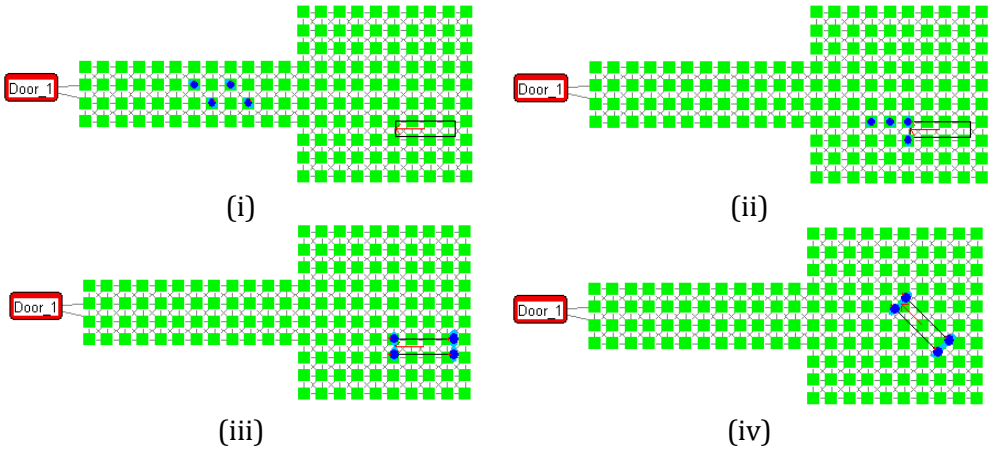


Figure 7-7: Component test 15 for the stretcher with a male team of handlers

To establish the preparation time modelled in each scenario, two key times were noted: the simulation time at which all of the required agents reached the device (S1) and the simulation time at which the device begins moving (S2). The expected delay is the average preparation time observed during the Ghent experiment (Table 4-3) and is compared to the delay observed in the simulation model (S2-S1). As presented in Table 7-9, the test results indicate that the expected delay has incurred.

Table 7-9: Component Test 15: Agent preparation and collection of device

Test/Device/Team (Male/Female)	**Simulation time when all agents reach device (S1)**	**Simulation time when device begins moving (S2)**	**Test result: Simulated preparation delay (S2-S1)**	**Expected delay from data (**Table 4-3**)**	**Did any agent cross device boundary?**
15(i)/ST/M	6.5s	1m14.7s	68.2s	68s	N
15(ii)/ST/M	15.1s	1m23.2s	68.1s	68s	N
15(i)/ST/F	5.8s	1m34.0s	88.2s	88s	N
15(ii)/ST/F	15.0s	1m43.0s	88.0s	88s	N
15(i)/EC/M	3.5s	33.7s	30.2s	30s	N
15(ii)/EC/M	14.3s	44.4s	30.1s	30s	N
15(i)/EC/F	3.7s	39.8s	36.1s	36s	N
15(ii)/EC/F	14.2s	50.3s	36.1s	36s	N
15(i)/CC/M	3.0s	38.2s	35.2s	35s	N
15(ii)/CC/M	14.0s	49.2s	35.2s	35s	N
15(i)/CC/F	3.2s	52.3s	49.1s	49s	N
15(ii)/CC/F	14.2s	1m03.2s	49.0s	49s	N
15(i)/RS/M	3.5s	56.5s	53.0s	53s	N
15(ii)/RS/M	13.5s	1m06.3s	52.8s	53s	N
15(i)/RS/F	3.7s	1m21.5s	77.8s	78s	N
15(ii)/RS/F	13.3s	1m31.5s	78.2s	78s	N

Quantitative and Qualitative Verification: This test satisfies the conditions set in that each case demonstrates that the correct preparation time elapsed (with error: $\varepsilon \leq 0.2s$). It is also noted that the boundaries of the device were observed by the agents.

7.4 Horizontal Travel: Component Testing

As outlined in the theoretical model, movement and navigation algorithms have been developed to represent devices travel on the horizontal. To evaluate the components of these algorithms, three tests are outlined here: first, to establish that a device will travel at a specified speed in a corridor, secondly, to establish that a device can block the path of evacuating agents, and, thirdly, to ensure that the device can navigate corners.

7.4.1 Component Test 16: Speed of Device in a Corridor

Purpose: To ensure that devices travel at the specified speed in a corridor and in the direction of a viable exit.

Method: This test is adapted from the individual walking speed scenario of the IMO test cases [255](MSC/Circ.1239; Test 1), using a device instead of an

individual. As depicted in Figure 7-8, a corridor is constructed that is 60m long and 2m wide, with one device at one end and an exit at the other end. The width of the device is less than the width of the exit. The device is assigned a horizontal travel speed. An operator is, or operators are attached to the device, and no pre-evacuation time or preparation time is allocated. Four devices are tested with both male and female teams: the stretcher (ST), evacuation chair (EC), carry chair (CC) and rescue sheet (RS).

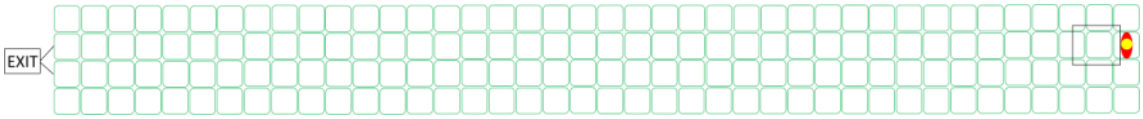


Figure 7-8: Component Test 16 Set-up (not to scale)

Expected Results: The agent and the device travel together at their assigned speed, reaching the exit in in the expected time (distance / speed) as tabulated in Table 7-10.

Test results: As presented in Table 7-10, each device travelled at the specified speed, taking the expected time to traverse the corridor.

Table 7-10: Component test 16: Speed of Device in Corridor

Test/ Device/ Team (M/F)	Simulation time when device crosses 60m line (S1)	Simulation time when device team has exited (S2)	Specified Device Speed (m/s)	Average Expected time taken (range $\pm$ 1SD) (s)	Test time taken seconds (S2-S1)	Test time within range? Y/N
16/ST/M	8.0s	1m03.5s	1.09	55.0 (51.3-59.4)	55.5	Y
16/ST/F	8.2s	1m07.6s	0.99	60.6 (57.1-64.5)	59.4	Y
16/EC/M	2.8s	41.4s	1.55	38.7 (37.3-40.3)	38.6	Y
16/EC/F	2.7s	45.9s	1.39	43.2 (42.3-44.1)	43.2	Y
16/CC/M	2.7s	42.5s	1.54	39.0 (35.9-42.6)	39.8	Y
16/CC/F	2.9s	44.3s	1.46	41.1 (40.0-42.3)	41.4	Y
16/RS/M	5.1s	57.2s	1.16	51.7 (49.2-54.5)	52.1	Y
16/RS/F	6.3s	1m29.3s	0.72	83.3 (66.7-111.1)	83	Y

Quantitative Verification: This test satisfies the conditions set in that each case demonstrates that the correct time elapsed (with error: $\varepsilon \leq 0.8s$, and within one standard deviation of the average).

7.4.2 Component Test 17: Representation of Path Blockage by a Device

Purpose: To ensure that a moving device can block paths for other evacuating agents.

Method: This is a verification test based on a scenario outlined by NIST (Verif2.10) [163], where the path to an exit is defined as two rooms in which the connecting path should be blocked by a wheelchair. As depicted in
Figure 7-9 two rooms are connected by a short corridor. 24 agents are randomly positioned in room 1, all with an unimpeded walking speed of 1.5m/s. One device is positioned at the entrance to the corridor, with associated agents to operate it. Two scenarios are run: test 17 (i), where there is 25 agents and no device (
Figure 7-9); and test 17(ii) where there are 24 agents and a device (Figure 7-10). Four devices are tested in this 1m wide corridor: the stretcher (ST) and the rescue sheet (RS), which should both block the corridor because of their large effective widths when agents are carrying them; and the evacuation chair (EC) and carry chair (CC), which should both not block the corridor when being wheeled by one agent.

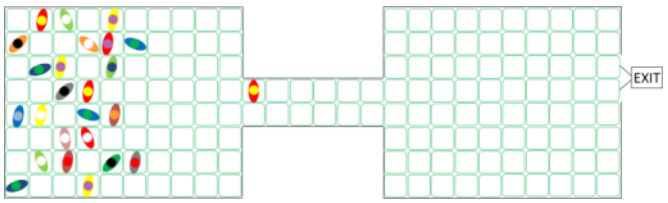
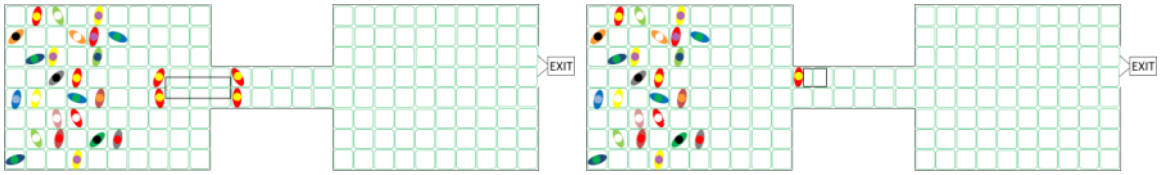


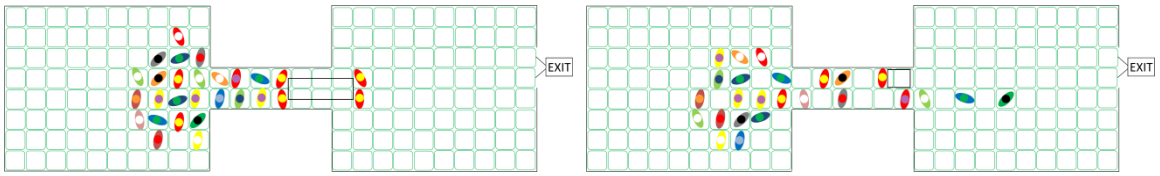
Figure 7-9: Component Test 17(i) Set-Up



(a) (b)

Figure 7-10: Component Test 17(ii) Set-Up for (a) blocking and (b) non-blocking devices

Expected Results: As depicted in Figure 7-11, in the second scenario (17(ii)) the device evacuates ahead of the evacuating population, travelling at reduced speeds, and for the ST and RS, the larger area of the devices will block the corridor. The expected result is that occupants blocked in the corridor in test 17(ii) will reach the exit in less time than occupants in test 17 (i).



(a) (b)

Figure 7-11: Expected results for component Test 17(ii) Set-Up for (a) blocking and (b) non-blocking devices

Test results: As presented in Table 7-11, the presence of a device increased the evacuation time. The evacuation chair and carry chair only slightly increased the evacuation time (by 2.3s-3.1s) as they only blocked one lane in the corridor, and the stretcher and rescue sheets greatly increased the evacuation time (by 6.3s-10.3s) as they blocked the full corridor.

Table 7-11: Component Test 17: Representation of Path Blockage by a Device

Test/Device/Team (Male/Female)	Total evacuation time (s)	Expected blockage	Did the device block the corridor? (Y/N)
17i: base case (no device)	26.3	n/a	n/a
17(ii)/ST/M	32.6	Y	Y
17(ii)/ST/F	34.1	Y	Y
17(ii)/EC/M	28.6	N	N
17(ii)/EC/F	28.9	N	N
17(ii)/CC/M	29.8	N	N
17(ii)/CC/F	29.4	N	N
17(ii)/RS/M	35.3	Y	Y
17(ii)/RS/F	36.9	Y	Y

Quantitative and Qualitative Verification: This test satisfies the conditions set in that each case demonstrates that the devices blocked the corridor as specified, incurring greater evacuation times than the base case.

7.4.3 Component Test 18: Device Navigation around Corners

Purpose: To ensure the devices can navigate around corners without penetrating the boundaries.

Method: This test is adapted from the individual walking speed scenarios in the IMO test cases [255](MSC/Circ.1239; Test 6), using a device instead of individuals. A device approaches and turns a left-hand corner (see Figure 7-12), travelling approximately 20m, depending on the turning arc selected in the movement algorithm.

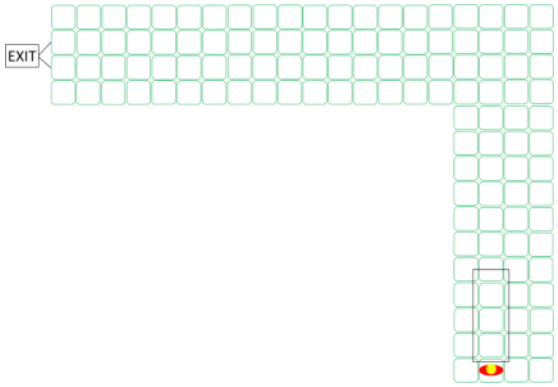


Figure 7-12: Component Test 18 Set-Up (not to scale)

Expected Results: The device will successfully navigate around the corner without penetrating the boundaries.

Test results: As presented in Table 7-12, each device did not cross the boundaries of the geometry. The time taken to traverse the corridor with a right angled corner in it was greater than the time expected to travel approximately the same distance (20m) on a straight corner.

Table 7-12: Component test 18: Device navigation around corners.

Test/Device/Team	Simulation time for device to travel approximately 20m including a turn (s)	Approximate expected time taken for 20m straight path (s)	Did the device cross the boundary? Y/N
18/ST/Male	21.3	18.4	N
18/ST/Female	23.3	20.2	N
18/EC/Male	14.3	12.9	N
18/EC/Female	15.9	14.4	N
18/CC/Male	14.8	13.0	N

18/CC/Female	15.9	13.7	N
18/RS/Male	18.8	17.2	N
18/RS/Female	28.3	27.8	N

Qualitative Verification: This test satisfies the conditions set in that each case demonstrates that the devices do not cross the corridor boundaries when turning at a right angle.

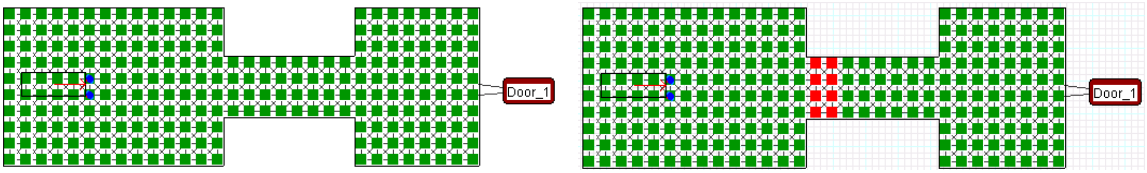
7.5 Door Transition: Component Testing

As outlined in the theoretical model, a door transition model has been developed to represent devices travelling through doors within bEX, informed by the data presented in chapter 4. To evaluate this component, the following test is outlined to evaluate the delay incurred by a device travelling through a double door.

7.5.1 Component Test 19: Device Navigation through Doors

Purpose: To ensure that the correct delay incurs when a device travels through doors.

Method: A device is positioned in a room that has an (open) exit in the adjacent room. It travels through a doorway towards the exit. Speeds and delays are allocated to the devices as in Table 6-7, where it is assumed that the Carry Chair takes the same time as the Evacuation Chair, as there are no door transition data available for this device. A simulation is run with no door between the device and the exit, and another is run with an outward opening door between the device and the exit (see Figure 7-13). The two resulting simulation times are compared.



(i) (ii)

Figure 7-13: Component Test 19 Set-Up, (i) with no internal door, and (ii) with one internal door.

Expected Results: It is expected that, given the delay incurred by manoeuvring a device through a doorway, the simulations with a door included will take longer. The difference in time taken between each pair of simulations should be:

$$dt = \boldsymbol{d_{di}} - \frac{\boldsymbol{m_l}}{\boldsymbol{s_h}},$$

where $\boldsymbol{d_{di}}$ is the number of seconds delay incurred by the door, ($\boldsymbol{m_l}$) is the length of the device in metres, and $\boldsymbol{s_h}$ is the speed of the device on the horizontal.

Test results: As demonstrated in Table 7-13, the expected difference is close to the test difference (error ranging between 0s and 0.4s). This indicates that the correct delay is applied when traversing doors. In each simulation with a door present, the device is seen as effectively targeting the centre of the door, travelling at a reduced speed while travelling through the door, and then resuming the normal horizontal travel speed once fully through the door.

Table 7-13: Component Test 19: Device Navigation through Doors

Test/Device / Team	Simulation time with no internal door (S1)	Simulation time with one internal door (S2)	Expected difference dt (s)	Test difference (S2-S1)	Error ε
19/ST/M	11.1	16.4	5.5	5.3	0.2
19/ST/F	11.9	16.9	5.3	5.0	0.3
19/EC/M	7.9	12.4	4.5	4.5	0.0
19/EC/F	9.1	14.9	5.4	5.8	0.4
19/CC/M	8.4	13.0	4.6	4.6	0.0
19/CC/F	8.7	14.7	5.6	6.0	0.4
19/RS/M	12.7	19.3	6.3	6.6	0.3
19/RS/F	18.7	28.1	9.3	9.4	0.1

Quantitative Verification: This test satisfies the conditions set in that each case demonstrates that the correct time elapses when devices are pushed and carried through doorways (with error: $\varepsilon \leq 0.4s$).

7.6 Vertical Travel: Component Testing

As outlined in the theoretical model, specifications have been developed to represent devices traversing stairs. To evaluate the components of these algorithms, three tests are outlined here: firstly, to establish that a device will

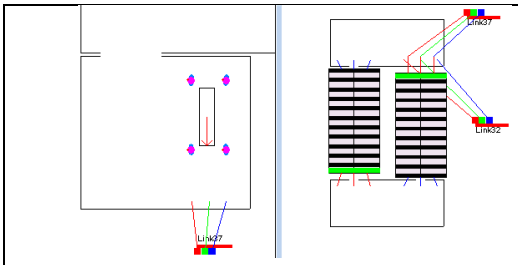
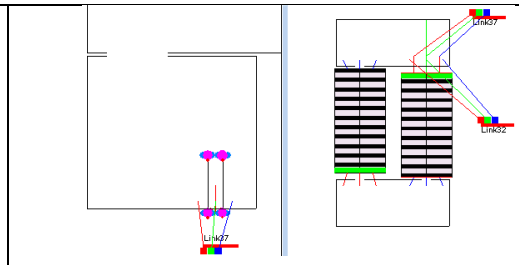
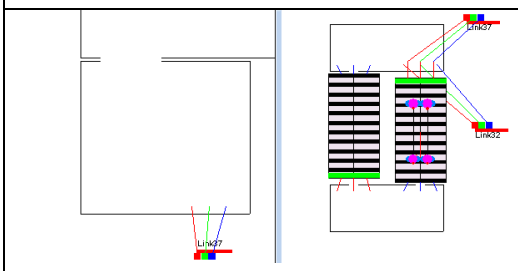
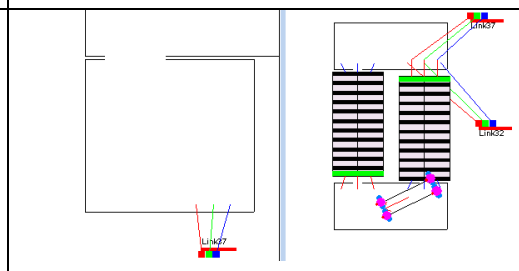
travel at a specified speed in a stairwell, secondly, to establish that devices stop as specified within their stairway descent, and, thirdly, to establish that a device can block the path of evacuating agents where appropriate.

7.6.1 Component Test 20: Speed of Device Descending Stairs

Purpose: To ensure that devices travel at the specified speed, and in the correct lane when travelling down stairs and across landings.

Method: This test is adapted from the individual walking speed tests of the IMO test cases [255](MSC/Circ.1239; Test 3), using a device instead of an individual. As depicted in Table 7-14, a staircase is constructed in a dog-leg configuration. The effective width of the staircase is 1.5 m; there are 12 risers on each stair; and each landing has dimensions 3.4 m by 2.4 m. A device is placed at the top of the stairs and an exit is placed at the end of the staircase. The width of each device is less than the width of the exit. The device is assigned a vertical travel speed. An operator or operators are attached to the device, and no pre-evacuation time or preparation time is allocated. Simulations are run for all four devices with both male and female handling teams, and the first floor of the evacuation progress on the stairs is observed.

Table 7-14: The processes of Component Test 20

	
(i) Handlers approach device	**(ii) Handlers adopt attachment positions and transport the device onto the stairs**
	
(iii) Handlers transport the device down the stairs in the specified lane	**(iv) Handlers turn the device on the landing towards the next stair**

Expected Results: The time taken to traverse one floor of the stairs expected is the distance travelled (10.54 m in the inside lane, 12.88 m in the central lane, and 15.23 m in the outside lane) divided by the speeds allocated (as presented in Table 7-15). The evacuation chair and the carry chair with a male team are expected to travel in the inside lane; the stretcher and the carry chair with a female team are expected to travel in the central lane; and the rescue sheet is expected to travel in the outside lane.

Test results: As presented in Table 7-15 the devices travelled at the specified speed, and in the specified lane, taking the expected time to traverse the stairs.

Table 7-15: Component Test 20: Speed of Device Descending Stairs

Test/ Device/ Team (M/F)	Simulation time when device enters stair (S1)	Simulation time when device team has exited one flight (S2)	Specified Device Speed (m/s)	Average Expected time taken (s)	Test time taken seconds (S2-S1)	Correct stair lane? Y/N
20/ST/M	2.8	21.7	0.67	19.22	18.9	Y
20/ST/F	3.2	27.5	0.52	24.77	24.3	Y
20/EC/M	2.1	14.7	0.84	12.55	12.6	Y
20/EC/F	2.0	14.8	0.84	12.55	12.8	Y
20/CC/M	3.0	21.2	0.60	17.57	18.2	Y
20/CC/F	3.0	19.5	0.77	16.73	16.5	Y
20/RS/M	3.7	22.4	0.83	18.35	18.7	Y
20/RS/F	4.5	34.5	0.52	29.29	30.0	Y

Quantitative and Qualitative Verification: This test satisfies the conditions set in that each case demonstrates that the correct time elapsed (with error: $\varepsilon \leq 0.7s$), and each maintained their specified staircase lane.

7.6.2 Component Test 21: Stopping Frequency in Stairwells

Purpose: To ensure that devices travel stop within the stairwells as expected over a distance of ten floors, and for the correct duration, and in the correct position on the landing.

Method: As in Component Test 20 (section 7.6.1), a staircase is constructed in a dog-leg configuration. It consists of ten floors. The effective width of the staircase

is 1.5 m; there are 12 risers on each stair; and each landing has dimensions 3.4 m by 2.4 m. A device is placed at the top of the stairs and an exit is placed at the end of the staircase. The width of each device is less than the width of the exit. The device is assigned a vertical travel speed. An operator or operators are attached to the device, and no pre-evacuation time or preparation time is allocated. Simulations are run for all four devices with both male and female handling teams, and the stoppages taken on the stairs is observed.

Expected Results: The evacuation time expected is the distance travelled on the full staircase (105.4 m in the inside lane, 128.8 m in the central lane, and 152.3 m in the outside lane) divided by the speeds allocated plus the time taken on the horizontal at the end of the staircase and the time spent stopping; as presented in Table 7-16. The evacuation chair and the carry chair with a male team are expected to travel in the inside lane; the stretcher and the carry chair with a female team are expected to travel in the central lane; and the rescue sheet is expected to travel in the outside lane. All devices are expected to conduct their rest stops on landings and for the prescribed duration.

Table 7-16: Component Test 21: Stopping Frequency in Stairwells

Test/ Device/ Team (M/F)	Simulated Evacuation Time (s)	Expected Evacuation Time (s)	Specified Device Speed (m/s)	Expected distance travelled (m)	No. stops expected	No. stops taken
20/ST/M	213.4	219.7	0.67	133.8	2	2
20/ST/F	305.7	313.3	0.52	133.8	4	4
20/EC/M	132.3	131.4	0.84	110.4	0	0
20/EC/F	132.6	131.4	0.84	110.4	0	0
20/CC/M	212.9	216.0	0.60	110.4	4	4
20/CC/F	203.7	206.8	0.77	133.8	3	3
20/RS/M	204.1	197.5	0.83	157.3	1	1
20/RS/F	317.2	308.5	0.52	157.3	2	2

Test results: As presented in Table 7-16, each device travelled at the specified speed, stopping as frequently as specified and taking the expected time evacuate.

Quantitative and Qualitative Verification: This test satisfies the conditions set in that each case demonstrates that the correct time elapsed (with error: $\varepsilon \leq 3\%$), and each device stopped the prescribed number of times.

7.6.3 Component Test 22: Ability to Overtake Device in Stairwells

Purpose: To establish that agents descending a staircase are able to overtake, or not able to overtake, depending on the lane occupancy of the devices.

Method: As in Component Test 20 (section 7.6.1), a staircase is constructed in a dog-leg configuration. The effective width of the staircase is 1.5 m; there are 12 risers on each stair; and each landing has dimensions 3.4 m by 2.4 m. A device is placed at the top of the stairs and an exit is placed at the end of the staircase. The width of each device is less than the width of the exit. The device is assigned a vertical travel speed. An operator or operators are attached to the device, and no pre-evacuation time or preparation time is allocated. 50 agents are randomly distributed in the room connected to the top landing. Simulations are run for all four devices with both male and female handling teams, and the first floor of the evacuation progress on the stairs is observed.

Expected Results: The evacuation chair and the carry chair with a male team are expected to travel in the inside lane; the stretcher and the carry chair with a female team are expected to travel in the central lane; and the rescue sheet is expected to travel in the outside lane. The devices that occupy two lanes are expected to block the passing agents and the devices that occupy one lane are expected to allow other agents to evacuate alongside the device and overtake.

Test results: Each of the devices performed as expected, allowing agents to overtake or not overtake depending on the lane occupied. This is depicted in Table 7-17 where a device blocks agents in the stairwell and in Table 7-18 where a device allows agents to pass in the stairwell.

Qualitative Verification: This test satisfies the conditions set in that each case demonstrates that the correct devices allowed agents either to overtake or not to overtake on the staircase.

Table 7-17: The stair progression of a blocking device

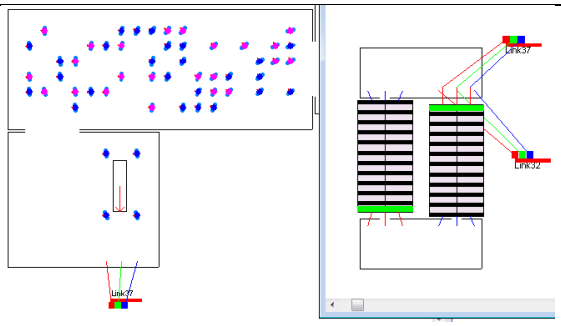
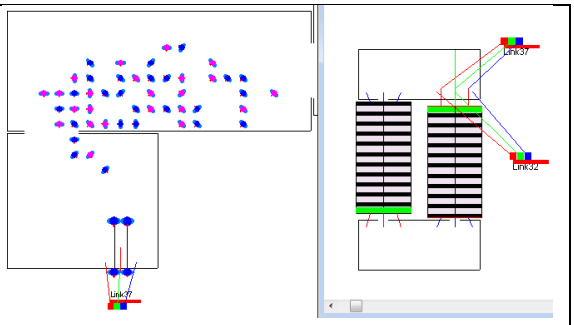
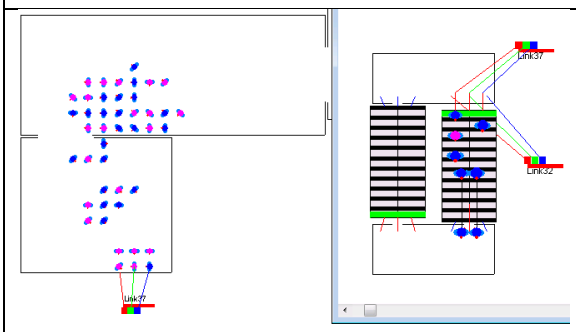
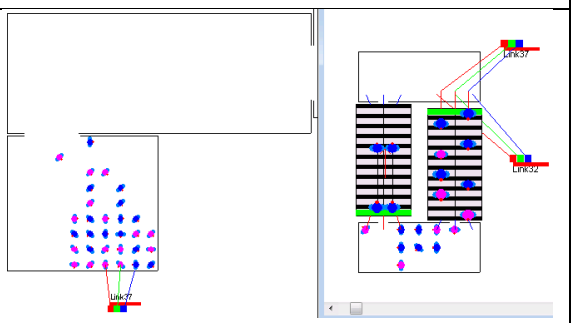
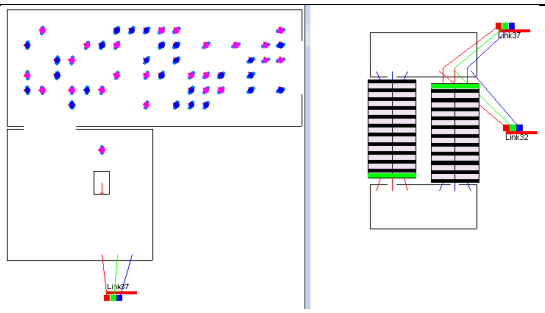
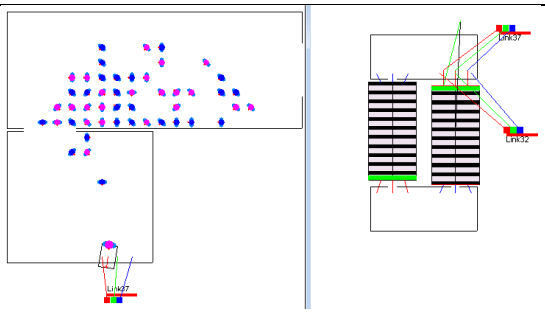
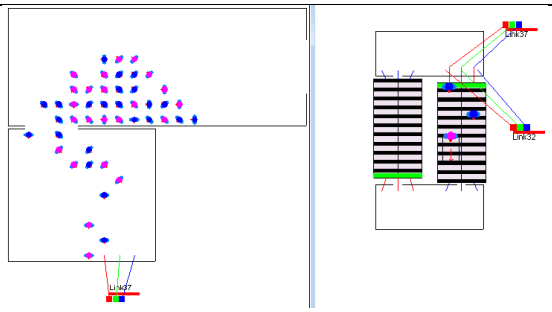
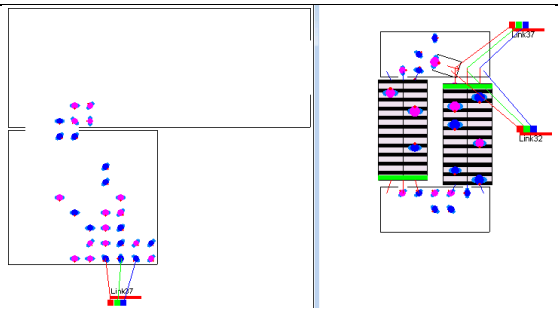
	
(i) Handlers approach device	**(ii) Handlers adopt attachment positions and transport the device onto the stairs**
	
(iii) The device travels along the stairs with agents behind it	**(iv) The agents are not able to overtake the device**

Table 7-18: The stair progression of a non-blocking device

	
(i) Handlers approach device	**(ii) Handlers adopt attachment positions and transport the device onto the stairs**
	
(iii) The device travels in one lane on the stairs; the is space for agents alongside	**(iv) The agents are able to move around and overtake the device**

7.7 Functional Demonstration

The tests presented so far have provided quantitative and qualitative verification of the theoretical model implementation - indicating that the components perform as expected. To quantify the performance of the generalised object functionality, i.e. to further verify the performance of this functionality and validate against expectation where possible, an additional set of demonstrations are presented. This section provides a number of cases in which the model is applied to representative hospital evacuation scenarios - beyond those smaller-scale test cases originally employed. These additional cases demonstrate that the functionality adequately represents the core target scenarios and that it can forecast beyond the test cases presented earlier in this Chapter; i.e. that the model is not limited to the original experimental scenarios. The first case demonstrates the evacuation of hospital wards with day and night staff, in order to verify that the combined functionality performs as expected, and that it produces credible output when compared with available benchmark data. The second case explores the

impact of handling devices when they are not occupied by patients; i.e. the effort required to transport empty devices in repeated evacuation, and the process of transferring patients from devices at an external exit. This expands upon the original functionality tested in case one to demonstrate that the functionality is able to represent a richer set of factors and behaviours than basic implicit representation. The third case demonstrates the ability to extend the model to other devices; a wheelchair is included in a scenario that combines self-evacuating and assisted evacuating down stairs. This test demonstrates the ability to represent different procedural responses given populations with different types of impairments, and apply the model functionality to devices not intended for vertical evacuation. The fourth case demonstrates the ability to represent progressive horizontal evacuation, a key component of hospital evacuation procedures. This test further demonstrates the flexibility of the model to represent the likely procedures in a hospital and thus compare responses; for example, the impact of staffing levels.

It should be noted that genuine validation data are not available. There is no extant data-set that sufficiently documents a full-scale case, including the individual devices used, the scenario, the procedure and the overall evacuation performance for an instructive test to be performed. The current approach has been adopted both to make direct comparisons against benchmark data whilst making equivalent assumptions, i.e. comparing against numerical analysis, and then incrementally including model functionality to represent behavioural and procedural measures. This approach demonstrates the novelty and benefits of explicitly simulating these factors – benefits that enable more underlying factors to be represented and relationships between these factors and emergent outcomes to be established.

7.7.1 Repeated patient collection

The numerical simulation presented in Chapter 5 was based on the Ghent hospital layout, and *implicitly* represented devices as groups of evacuating agents: assembling and disbanding to represent repeated collection, and travelling at

device speeds. In this section, the same scenarios are simulated using the *explicit* object model in buildingEXODUS with the results compared to the numerical simulation. In this instance, the model is allowed to determine the underlying movement characteristics of the device (and associated agents) rather than the user hard-wiring these performance elements. As such, the ability to automatically capture the outcomes hard-wired in the earlier tests is examined. As such, the test is designed to verify the collective performance of the different model components to determine that they function as expected, i.e. that they function in concert with each other, and that they then produce credible output when compared to the manually configured simulation performed earlier.

Purpose: To ensure that the process of patient collection, preparation, horizontal movement, movement through doors, and vertical movement, is simulated as expected and that the outcomes are comparable to the benchmark data available.

Method: As depicted in Figure 7-14, a ward is situated on the 11th floor of a hospital building, based on the Ghent University Hospital Dermatology/Pain Clinic ward (see Figure 5-1). There are two emergency staircases, each constructed in a dog-leg configuration. It consists of ten floors. The effective width of the staircase is 1.5 m; there are 12 risers on each stair; and each landing has dimensions 3.4 m by 2.4 m.

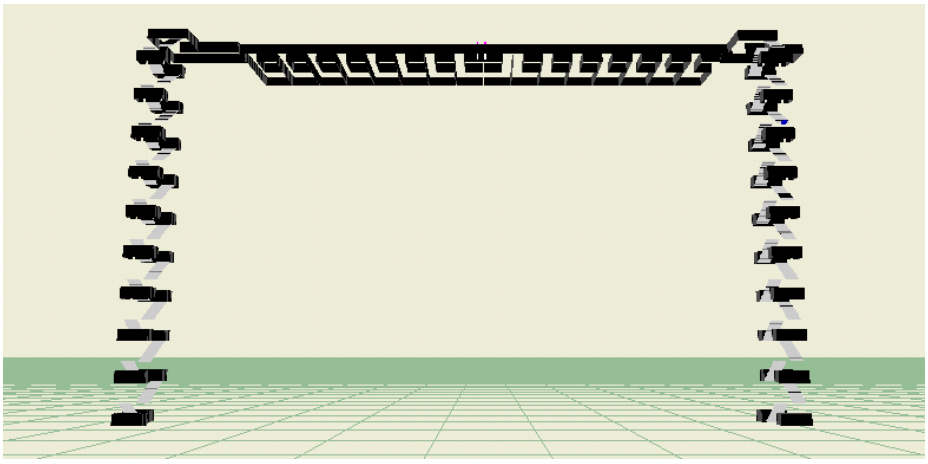


Figure 7-14: Functional Demonstration Geometry

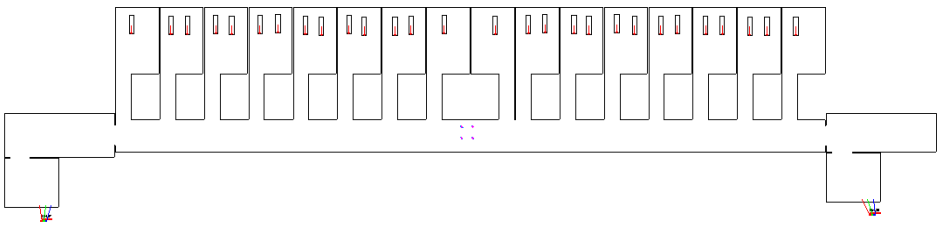
It is assumed that the ward is fully occupied with 28 patients and that all patients have reduced mobility, requiring full assistance to evacuate, and that only members of ward staff are available to assist in the evacuation. In accordance with Ghent Hospital rotas, during a day shift there are seven staff members while during a night shift there are four staff members. The four movement devices are used in turn to evacuate the entire ward. As presented in Table 7-19, 16 scenarios are simulated including: each of the four devices; all-male and all-female teams; and day and night staff availability. The impact of these factors upon the overall performance can then be examined.

Table 7-19: Scenarios for Functional Demonstration

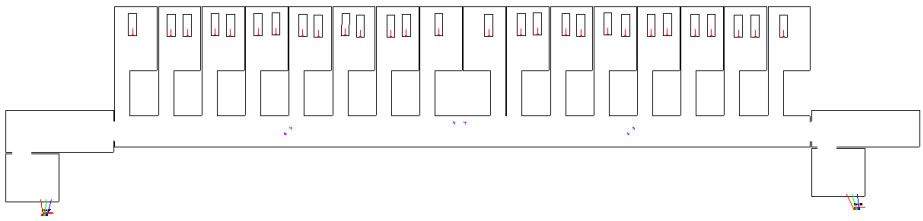
Test	Device	Staff Rota	No. Teams	No. Members per Team	No. Members left on ward
23(i)/ST/M	Stretcher	Day	1	4	3
23(i)/EC/M	Evacuation Chair	Day	6	1	1
23(i)/CC/M	Carry Chair	Day	2	3	1
23(i)/ST/M	Rescue Sheet	Day	3	2	1
23(ii)/ST/M	Stretcher	Night	1	4	0
23(ii)/EC/M	Evacuation Chair	Night	3	1	1
23(ii)/CC/M	Carry Chair	Night	1	3	1
23(ii)/ST/M	Rescue Sheet	Night	2	2	0
23(i)/ST/F	Stretcher	Day	1	4	3
23(i)/EC/F	Evacuation Chair	Day	6	1	1
23(i)/CC/F	Carry Chair	Day	1	4	3
23(i)/ST/F	Rescue Sheet	Day	3	2	1
23(ii)/ST/F	Stretcher	Night	1	4	0
23(ii)/EC/F	Evacuation Chair	Night	3	1	1
23(ii)/CC/F	Carry Chair	Night	1	4	0
23(ii)/ST/F	Rescue Sheet	Night	2	2	0

Staff are allocated into handling teams and assigned a list of patients to collect, beginning with the patient closest to their starting position, and then returning to prepare and evacuate the next nearest patient; continuing until the ward is fully evacuated in which the teams exit the hospital. Figure 7-15 shows the varying starting positions for the scenarios. As in the numerical simulation presented in Section 5.2, the team members left on the ward are assumed to aid in the preparation of patients if there are enough available; i.e. two or more handlers are required to prepare each patient. In the numerical simulations, the tasks assigned to the assisting staff were delineated in detail and the device itself was not

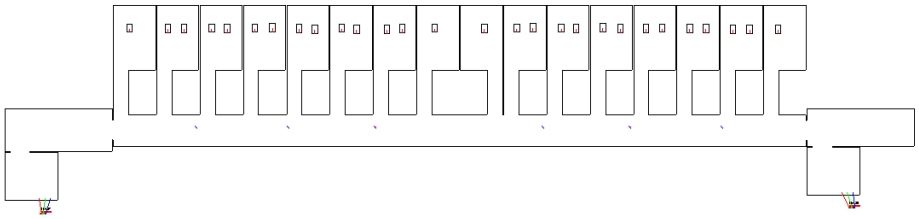
represented. In this instance, staff were assigned to patients and staff and then the newly developed model determined their performance – in accordance with the navigation of the device, geometrical issues, the terrain and the identity/number of the staff involved.



(i) One handling team of four operators, with 28 patients in stretchers



(ii) Three handling teams of two operators, with 28 patients in rescue sheets



(iii) Six handling teams of one operator, with 28 patients in evacuation chairs

Figure 7-15: Agent and device starting positions for functional demonstration

Expected Results: The (manually configured) numerical simulation presented in Chapter 5 determined evacuation times for each scenario in this test. It used the Ghent data averages; i.e. the average time taken to traverse the corridor including doors and the average time taken to traverse the stairwell including stoppages. The simulations conducted as part of this current test employ all of the components of the object model, *explicitly* representing the devices, their movement including specific door delays on the corridor and specific stoppage delays in the stairwells. As such, the user interaction with the model is radically reduced and the input parameters are different: for the numerical simulation the broad averages speeds were used, and for the explicit simulation the (predicted) modelled speeds were used. It is expected that these results will yield the same

outcome: that the model employed, with all of the sub-components combined, can replicate the overall average times. This will then demonstrate that the implemented explicit model has effectively characterized the scenario and performance in accordance with the earlier analysis that required a significant element of user configuration.

Test Results: As presented in Table 7-20, the results indicate that the evacuation duration for the explicit simulation in buildingEXODUS replicate the times recorded during the numerical simulation. This demonstrates that the implemented functionality performs as expected, and that the model is at least as effective as the numerical solution. It achieves this by explicitly representing the device, staff interaction with the device and the resultant performance based on the number and nature of the staff available and the device employed.

Table 7-20: Functional Demonstration Results

	Numerical Simulation Results				bEX Simulation Results			
Device	Male Teams		Female Teams		Male Teams		Female Teams	
	Day (Hrs)	Night (Hrs)	Day (Hrs)	Night (Hrs)	Day (Hrs)	Night (Hrs)	Day (Hrs)	Night (Hrs)
Stretcher	3.3	3.8	3.9	4.7	3.3	3.8	4.0	4.5
Evacuation Chair	0.5	0.9	0.6	1.1	0.5	0.9	0.6	1.0
Carry Chair	1.6	3.1	3.2	3.5	1.7	3.3	3.2	3.5
Rescue Sheet	1.1	1.6	1.5	2.1	1.2	1.5	1.6	2.0

Test Implication: This test satisfies the conditions set in that each case demonstrates that a credible evacuation time is predicted when explicitly simulating the repeated collection of patients in buildingEXODUS (with error: $\varepsilon \leq 6\%$). This implies that the explicit modelling of the process predicts the overall outcome indicated by the numerical simulation, without the user hard-wiring of staff performance. These tests are therefore indicative of the model's ability to simulate the horizontal and vertical hospital evacuation outlined in this scenario.

7.7.2 Stair ascent speeds and patient transfer at exit for repeated patient collection

A factor not currently quantified in the repeated collection of patients in hospital evacuation is the effort required to establish the handing and transportation of empty devices – the return legs after a patient has been deposited in a safe location. The devices considered in this thesis weighed between 7.3 kg and 13.1 kg. It therefore can be reasonably assumed that the burden of carrying evacuation equipment in order to collect another patient will reduce the stair ascent speed of the handlers; however, it is not known how significantly this may impact the time to evacuate. Furthermore, the time taken to transfer a patient out of a device at an exit is not known. However, the current functionality does allow the user to assess the potential impact of such performance reduction given presumed reduction in ascent speeds. This application is examined here. Although nominal staff speed reductions are allowed, this type of analysis would enable the user to assess overall impact on performance should specific speed reductions occur.

To simulate the effect of carrying empty devices up stairs, a demonstration is conducted where all-male and all-female teams evacuate 28 patients in the same set-up as the previous functional demonstration (section 7.7.1). A reduction in ascent speed is applied where all teams are allocated a nominal slower ascent speed (from 0.55 m/s to 0.3 m/s). Further to this, to simulate the effect of patient transfer at an exit, a delay time is specified when each patient exits the hospital. To represent this transfer time, the preparation delay times from the Ghent trials are applied to this exit transfer; however it is noted that the times taken to prepare a patient into a device and out of a device are likely different because of the different procedures employed. Using the rescue sheet, the most common device found in hospitals, this demonstration uses night staff availability: four staff members to evacuate 28 patients.

As presented in Table 7-21, both male and female teams take 10-20% longer to conduct the evacuation when there is a transfer delay at the exit. The reduction in stair ascent speed alone increases the evacuation time by 20-30%. The impact of both a transfer delay and a reduction in stair ascent speed increases the evacuation

time for male teams by 47% and for female teams by 40%. This indicates that these factors have a significant effect on evacuation outcomes; however more data are required to fully describe this impact. The results produced by the model during this test appear intuitively reasonable.

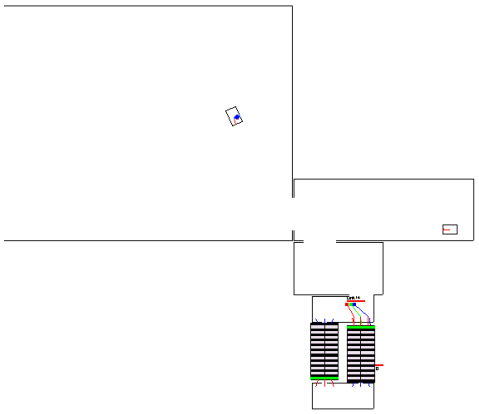
Table 7-21: The time taken to evacuate 28 patients with rescue sheets, including star ascending delays and exit transfer times.

Stair Ascent Speed (m/s)	Transfer delay at exit	Evacuation Times (hrs)	
		Male	Female
0.55	N	1.5	2.0
0.55	Y	1.8	2.3
0.30	N	2.0	2.5
0.30	Y	2.2	2.8

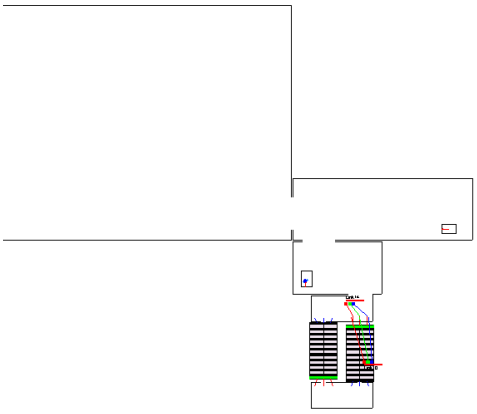
This test demonstrates that the explicit model representation allows a broader array of scenarios to be examined. The functionality of the model has been shown to interact appropriately and allow analysis to be extended to a wider array of scenarios than previously examined without undue user model configuration.

7.7.3 Evacuation of a wheelchair user with an evacuation chair

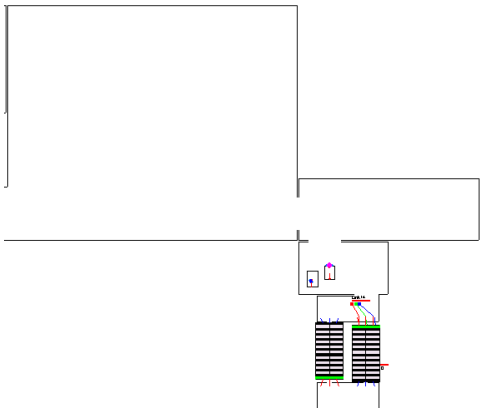
This scenario demonstrates the model's ability to represent other devices. A patient self-evacuates using a wheelchair horizontally to a refuge area in a stairwell. The patient is then transferred into an evacuation chair and evacuated through three flights of stairs. The wheelchair device is created in buildingEXODUS based on standard hospital wheelchair dimension: $l = 88cm, w = 60cm$ [257]; i.e. it and its basic movement characteristics are defined by the model and not the user. It is allocated an unassisted speed of 0.7 m/s [258, 259]. As depicted in Figure 7-16, the patient travels to the refuge area unassisted and waits to be collected. A nurse picks up an evacuation chair and when reaching the patient, takes 36 s to secure the patient into the device. The nurse then evacuates the patient down the stairs. This process with no other evacuating agents or devices takes 3 m 40 s.



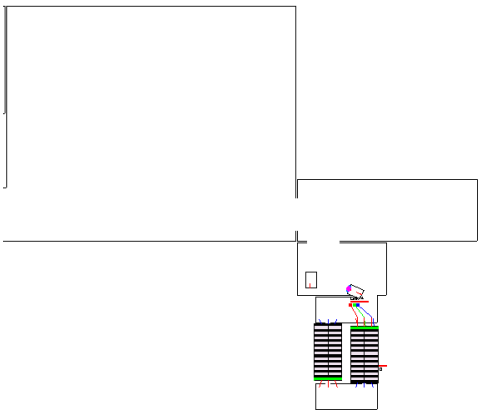
(i) Wheelchair user moves towards the staircase



(ii) Wheelchair user waits in the refuge area



(iii) A nurse picks up an evacuation chair transfers the patient into the device



(iv) The nurse evacuates the patient using the evacuation chair

Figure 7-16: Evacuation of a wheelchair user with an evacuation chair

During this test, the model is able to qualitatively simulate the path of the agent as expected, reflecting the expected travel speeds of the device given the terrain traversed, and then produces an overall (emergent) result that is intuitively reasonable and reflective of the conditions specified.

This test demonstrates a number of things: the model is able to represent multi-modal patient movement, staff intervention, device navigation, application of transfer delays and sensitivity of movement speeds to terrain. This is key is the representative explicit modelling of device movement during an hospital emergency procedure.

7.7.4 Progressive Horizontal Evacuation

This scenario examines the process of progressive horizontal evacuation which is integral to hospital evacuation procedures [2]. This scenario assumes that a fire has occurred the top (5th) floor of a mid-rise hospital. This represents a procedural response similar to the recent Royal Marsden and Great Ormond Street evacuations [59]: the scenario begins with horizontal evacuation, but as the situation develops, a full building evacuation is required. As per the layout presented in Figure 7-17, there are ten patients in beds in the East Ward and 12 patients in beds in the West Ward. The floor is divided into two separate fire-resistant compartments with an assumed 30 minute fire compartmentation time, i.e. the time in which a fire can be contained in the compartment. In this case, it is assumed that all 22 patients are bedridden and therefore require assistance. However, the staff availability is varied in two scenarios, representing expected night and day time staff availability, to determine the sensitivity of the outcome to the availability and performance of the staff present.

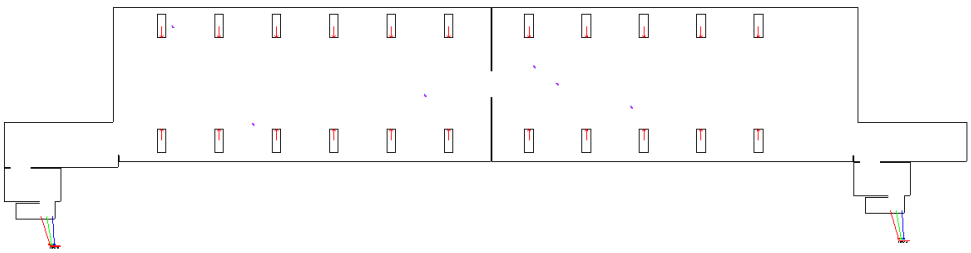


Figure 7-17: Progressive Horizontal Evacuation Demonstration Case

Again, it should be noted that once the patient / staff agents have been identified, scenario specific aspects represented (device presence, building configuration, ward layout, staff attributes, patient evacuation order, etc.), then subsequent evacuation performance is determined by the model given the explicit simulation of the evacuation progress.

In the first variant of this scenario, the East Ward has a 2:1 patient-staff ratio and the West Ward has a 4:1 patient-staff ratio. As such, there are five nurses assigned to the East Ward and three nurses assigned to the West Ward. However, two of the

nurses from the East Ward are initially positioned on the floor below, engaging in an administrative activity.

It is assumed that at time $t = 0$, the fire has just been discovered and a call made to horizontally evacuate the patients in immediate risk to the adjoining compartment. Therefore, the nurses from the East Ward are called back to their station to assist in the evacuation. The nurses from the fourth floor ascend one flight of stairs to return to their ward. One nurse from the West Ward also joins the staff in horizontal evacuation from the East Ward; however the remaining two West Ward nurses stay to tend to their patients.

Patients are horizontally transported in rescue sheets to the west compartment in the first stage of evacuation. It should be noted, as indicated in earlier tests, that subsequent vertical movement could have followed this horizontal component and that the whole process could also have included different types of devices and issues of reduced staff performance. This is excluded here to reduce redundancy. It is specified that at least one of each nurse handling team is female; therefore, the team moves as if it is all-female, at the speed of its slowest member. The model, given the collective attributes of the handling team, determines this automatically. Given this calibration, the patient population is moved into the adjacent compartment in 10 m 32 s.

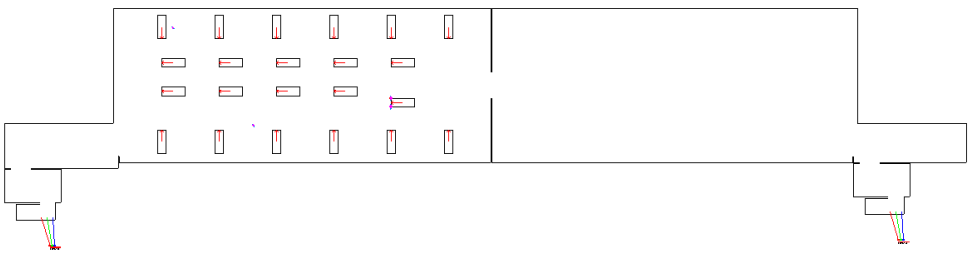


Figure 7-18: A completed progressive horizontal evacuation from one compartment

A second variant is examined where a night time scenario is then assumed. Patient-staff ratio is modified such that the East Ward has a 3:1 patient-staff ratio and the West Ward has a 6:1 patient-staff ratio. As such, there are four nurses assigned to the East Ward and two nurses assigned to the West Ward. As before,

two of the nurses from the East Ward are initially positioned on the floor below engaging in an administrative activity. It took 13 m 52 s to complete the horizontal evacuation process using night-time staff. The procedure takes 30% longer with the reduced staffing levels at night than it did with the staff available during the day shift.

This demonstrates that the model is able to represent the procedure employed, credible path adoption, specified device speeds (given the staff involved) and then forecast overall credible results, given the conditions present and the staff available. Again, the model functionality operates as expected and is able to interact to produce credible output for the scenario examined.

7.7.5 Summary

This section presented a number of tests to verify that the explicit representation of evacuation devices and associated procedural measures performs as expected, that the array of new functionality operates in conjunction with extant functionality, and that the outcomes produced are credible and representative. It is noted that the absence of relevant, detailed and comprehensive real incident data limits direct comparison. However, this does not preclude any baseline comparison and the examination of the model performance and the scenarios to which it might be applied.

The first case examined a scenario involving the repeated collection 28 patients requiring assistance. Two sets of results were examined: those produced when considerable user effort was required to configure the scenario, the patient/staff response, and the manual configuration of itineraries throughout; and those produced when the staff/patient/device performance was modelled explicitly and the results forecast. The results were evidently similar, suggesting that the updated model captures the previous attempt to hard-wire expected performance.

The second case demonstrated the model's ability to examine the potential impact of performance factors that have yet to be quantified: the reduction of speeds that

may incur when member of staff is carrying an empty device, and the time taken to transfer a patient on exit of a hospital. This demonstrated both the interaction of a number of explicit model functions, the generation of intuitively reasonable results and the readiness of the model for future data-collection; i.e. the impact of fatigue on performance. This builds on the first test case, where basic performance levels were confirmed, by explicitly including additional performance factors including the potential for deteriorating staff performance.

The third case examined the evacuation of a wheelchair user, combining non-assisted evacuation on the horizontal with assisted evacuation on the vertical. This demonstrated the model's ability to represent the impact of staff intervention on performance.

The fourth case demonstrated the process of progressive horizontal evacuation; forecasting the time it may take in which to move patients from one compartment to another. This represents the first time an established evacuation model has been applied to these scenarios, explicitly representing human operated objects in both horizontal and vertical evacuation. This is a significant advancement that allows the time to complete progressive horizontal evacuation to be compared with horizontal/vertical evacuation, as indicated in earlier test cases. Critically, this allows the comparison of the consequences of an evacuation should it proceed according to expectation (i.e. that progressive horizontal evacuation is sufficient) against a case where more drastic efforts are required (i.e. the fire is not contained and the entire hospital requires evacuation). As has become evident in recent incidents, this analysis is not purely academic.

It is acknowledged that the testing is limited – due to the benchmark cases available and the space available. Although not exhaustive, these cases have been deliberately selected to explore several key elements: the move from implicit to explicit, the impact of different devices, different staff, different procedures and individual attributes. In all instances, these cases clearly demonstrate the enhanced forecasting capability of the developed explicit model within buildingEXODUS. More so, it demonstrated the developed model represents

performance at low-levels (as specified), that this functionality produces qualitative and quantitative local conditions that are both intuitively acceptable and match existing data (albeit sparse), and is also able to produce high-level, emergent results that are credible given the scenarios examined. This chapter has then provided some basis (via both verification and validation testing) for the model's performance at different scales and according to different scenarios. It is proposed that this development represents a step-change in the simulation of hospital evacuation. It allows the user to configure the initial scenario to represent a range of different viable incidents, while then explicitly representing subsequent outcomes given the structural, procedural, population and behavioural variables present.

The omissions identified are suggestive of research required to better understand and quantify the behavioural factors that influence evacuation performance. The next section presents a discussion of the work undertaken in this thesis, addressing the research questions established in Chapter 1. The future work still required in the field to support further development are discussed as part of the concluding remarks.

8 DISCUSSION

This thesis has presented work undertaken to identify key factors that influence the outcomes of hospital evacuations, to review the functionality and limitations of current modelling approaches, and to implement advancements in data collection and model development. It has described the quantification of the performance of trained hospital staff in evacuating non-ambulant patients from hospitals using evacuation devices. It has presented the analysis of the devices tested, and compared their performance, and the development and implementation of mathematical algorithms to explicitly represent the dynamics of these devices within evacuation software. The following five key research questions were established in the introduction alongside the sections of this thesis that addresses them:

1) What influences the outcome of hospital evacuations? (Section 2.1)

2) What developments are required in order to improve hospital evacuation simulation? (Sections 2.2-2.4)

3) How do movement assist devices perform in the horizontal and vertical evacuation of people with reduced mobility? (Ch. 3 and 4)

4) How can these data be used to compare the performance of movement devices in evacuation? (Ch. 5)

5) How can movement devices be explicitly modelled? (Ch, 6 and 7)

In this chapter, these questions are discussed in turn, with key results highlighted.

8.1 What influences the outcome of hospital evacuations?

This century, there have been an average of approximately 1800 hospital fires each year in the United Kingdom [49, 48, 47, 46, 8]. In the planning for evacuations in the UK, locally and nationally commissioned services in the NHS must promote equal access and consideration for health and safety for disabled people and non-disabled people. Failure to provide a fit-for-purpose evacuation strategy for disabled people may be interpreted as indirect discrimination under the Equality Act [5]. Furthermore, the enforcement of the Regulatory Reform (Fire Safety)

Order in 2005 [33] means that it is no longer compulsory for hospital management to have fire certificates, but they are instead legally required to conduct and document comprehensive fire risk assessments. The onus is on hospital management to ensure the safety of all hospital occupants without reliance on the evacuation assistance of the fire services.

The progressive horizontal evacuation approach [2] is commonly specified in healthcare incident planning in which those that are in immediate danger are moved to a safer area and other occupants stay in place until the fire is successfully suppressed [69]. As determined in the case studies examined in this thesis, for example the full evacuation of Great Ormond Street and the Royal Marsden [59] in 2008, there is a need to prepare for vertical evacuation as well. It is also highlighted in the incidents explored, that developing emergency conditions may mean that critically ill patients are required to evacuate; therefore defend in place strategies alone are not sufficient. As is evident, healthcare management do not typically consider this a likely scenario in their incident planning. As a result of recent incidents, NHS London have highlighted that it is imperative to plan and test full site evacuation plans in every hospital [59].

Evaluating real hospital incidents found that the time available and the appropriateness of the response may not be as expected. There are many reasons for this. *Ad hoc* plans and equipment are used to compensate for shortfalls in dedicated resources to cope with the presence of those with movement impairments. Incidents can escalate quickly – requiring emergency procedures to adapt in order to ensure occupant safety. Given the need for vertical evacuation, movement assist devices are frequently required to evacuate PRM. Accurate information and communication (internal and external) of the incident is important. Inaccurate information can mean that the procedural response is quickly out of date with the evolving situation. Egress paths are not always in the required condition to allow emergency use. Emergency equipment is not always available. The performance of staff then varies significantly between incidents because of issues with training and availability. Moving patients therefore presents

numerous challenges. Staff training is important and not always sufficient, and staff levels fluctuate given the time of the scenario.

It is evident from the incidents presented in this thesis that the challenge of assisting the evacuation of a large number of people with reduced mobility is arguably the principal complication in hospital evacuation. Given the demographic shift approaching with the ageing population [73, 74], this is likely to be become a larger factor still, particularly in care homes for the elderly. Injury, death and property damage are more likely in buildings with elderly occupants than in those with a younger population [50]. In the UK more than half of the fatalities from fires in all buildings were people aged 65 years or older [1]. According to the most recent analysis, people who are 80 or older have more than four times the risk of dying in a fire than the average person [1]. In hospitals, planning for the evacuation of people with reduced mobility is particularly challenging. This is due to the large proportion of patients who are likely to require assistance to evacuate, and the need for multiple staff repeatedly assisting individual patients. A number of movement devices are used to assist evacuation of PRM, but little work has been undertaken to quantify their performance.

It is critical to understand how effective these devices are in hospital specific scenarios and quantify their impact on overall evacuation performance. It is proposed here that computer simulation may aid the calculation of required egress time, and the implications of imposing a number of different procedures. This would assist in hospital design, planning emergency procedures and risk assessment.

When only considering horizontal evacuation, the use of these devices and key elements, such as the size of the external exit, may be overlooked. In the case of the Royal Marsden evacuation [59], full evacuation drills, emergency equipment testing, or computer simulation would have highlighted the issue with the revolving exit doors. Risk assessments must include the egress for PRM in movement devices in order to identify these issues and to ensure compliance with fire codes [2].

Furthermore, these incidents reveal that currently the availability and training in the use of emergency equipment is not sufficient. In London hospitals, members of staff were using mattresses for evacuation for the first time in real incidents and have since recommended evacuation chairs at every floor [59]. However, there is no indication of how many chairs are required per patient population, nor the programme of training that will sufficiently prepare staff to use them for vertical evacuation.

8.2 What developments are required in order to improve hospital evacuation simulation?

A number of current egress models provide sufficient functionality to directly represent a simplified hospital evacuation or allow the user to manually configure agent performance to indirectly represent a simplified hospital evacuation. However, a key shortfall in current model functionality is the ability to explicitly represent the use of stair evacuation devices during hospital evacuations. Several models now include wheelchair devices [15, 18, 19, 20], using current data; i.e. the models represent the reduced travel speed adopted by someone using a wheelchair [17]. Although some models can represent the reduced travel speed associated with device use, they are not able to represent the shape and increased footprint of such a device, particularly in vertical movement, and the impact that it might have – on navigation, manoeuvrability, speed, and on the movement of the adjacent population. Understanding this impact has been shown to be critical in assessing the effectiveness of a procedure (or a device) in moving vulnerable populations to safety.

The synopsis of the current data for hospital evacuations demonstrates a significant gap in the current knowledge, particularly for the performance of emergency evacuation equipment. While a number of commercially available devices can be used to assist in evacuating PRM, there is minimal consistent data quantifying the performance of these devices. Recent studies [21, 22, 23, 213] found that the stair speeds of evacuation chairs varied considerably (0.17 m/s to

1.1 m/s) as did the effort required to operate the devices. Therefore, there is a need to further establish the factors that impact the devices, such as training and the performance of different handling teams: i.e. is there a difference between the speeds attained by male and female handlers, and does this indicate the physical demands of different devices? In addition to the speeds of the devices on the horizontal and vertical, these include the time taken to prepare the device, to traverse doors, impact of fatigue and the overtaking potential for other evacuees when a stair descent device is in operation.

8.3 How do movement assist devices perform in the horizontal and vertical evacuation of people with reduced mobility?

8.3.1 How long does it take to prepare a PRM for assisted evacuation?

During the Ghent trials, the time taken to prepare a PRM for evacuation by transferring them from a wheelchair to an evacuation device, ranged from 24 seconds to 120 seconds. Results indicate that the evacuation chair is the quickest device in which to prepare patients (on average 33 s), followed by the carry chair (on average 42 s), the rescue sheet (on average 65 s) and then the stretcher (78 s). The preparation times for devices where the patient was secured in a sitting position (the evacuation chair and carry chair) are considerably faster than the time taken with devices where the patient was secured in a lying position (the stretcher and the rescue sheet). However, more data are required to establish any difference incurred when PRM are secured into a device from a lying position. Many wards have non-ambulant patients permanently situated in beds [33], and this may have a significant impact on the time taken to prepare them. It is anticipated that the preparation time required could be less for the rescue sheet, as these are already positioned under the patient, however the manoeuvre from the bed to the ground may be cumbersome. It is also anticipated that the preparation time from bed to device may be greater for chair devices as the transition from a lying position to a seated position may incur delays. Furthermore, for some patients, the use of a chair device is unsuitable, for example those with neurological conditions that require specific head and neck support [260], and

those with chronic back pain that are diagnosed with a low sitting tolerance [261]. Therefore more data are required to investigate the performance of moving patients with varying physical requirements and from varying initial positions to securing them safely into movement devices. More data are also required to establish the times taken to secure patients' medical equipment into the devices.

8.3.2 What are the horizontal travel speeds for assisted evacuation?

The results derived from the Ghent trials indicate that in horizontal transportation the devices with wheels, i.e. the evacuation chair and carry chair, are the fastest, with average speeds of 1.5 m/s, comparable to the average pedestrian free walking speed derived by Fruin [235] of 1.4 m/s. This indicates that evacuation chair devices can achieve similar speeds to pedestrians on the horizontal, however is notable that these speeds are faster than the average horizontal speeds for wheelchairs in the literature (1.1 m/s [219, 218] and 1.3 m/s [17]. This may indicate that the increased weight of wheelchairs decreases travel speed: hospital transit wheelchairs weigh approximately 14.6 kg [257] and those for bariatric patients can weigh approximately 22 kg [262]; whereas the carry chair and evacuation chair used in these experiments weigh 7.3 kg and 10.6 kg respectively.

The stretcher has an average horizontal speed of 1.0 m/s, and the rescue sheet is the slowest device with an average speed of 0.9 m/s. On a 90° turn it is found that the chair devices are 9% slower on this turn than their average corridor speed, the stretcher is on average 16% slower, the rescue sheet 64% slower. It is expected that the nature of the floor covering will have an impact on horizontal travel speeds, in particular for the rescue sheet as it is dragged along the floor.

8.3.3 How long does it take to open and traverse doors during assisted evacuation?

A roaming video camera recorded the time taken to traverse doorways, from the time at which the first member of the handling team touched the door and the time at which the last part of the last handling team member's foot, or the last part of the device crossed the doorway. Comparable data were collected for two types of

doors: double doors that opened towards the device, and double doors that opened away from the device. As expected, it took longer for teams with devices to open doors that opened towards them than those that opened away from them. The data indicates that the evacuation chair has the fastest average door transition time for both “toward” and “away” doors (5.5 s and 4.5 s respectively), the stretcher took, on average 6.8 s and 4.7 s respectively, and the rescue sheet is the slowest with average traversal times of 9.9 s and 6.7 s respectively. As with the horizontal travel speeds, these times are likely affected by the floor covering, and are also likely to yield different results depending on the handle structure and weight of a door.

8.3.4 What are the vertical travel speeds for assisted evacuation?

From the Ghent trials, the average speed per floor indicates that, per floor, the evacuation chair is the fastest device (averaging 0.84 m/s) followed by the rescue sheet (averaging 0.67 m/s), the carry chair (averaging 0.60 m/s) and finally the stretcher (averaging 0.54 m/s). For the evacuation chair, the speed is comparable to the speeds derived by Lavender *et al*. [23]: approximately 0.86 m/s. However, other studies have recorded significantly different speeds: 0.21 m/s observed by Kuligowski *et al.* [22] and a range of approximately 0.26-1.11 m/s by Sano *et al.* [21]. This may indicate the importance of handler training, with the fastest times recorded by trained manual handlers and firefighters.

For the carry chair, the number of handlers affects the speeds attained, where three male handlers traversed the stairs at an average speed of 0.51 m/s, and four female handlers traversed the stairs at an average speed of 0.69 m/s. Lavender *et al.* [23] recorded a carry chair speed of approximately 0.34 m/s with two handlers. This indicates a successive increase in speed with more handlers, as expected, although more research is required to determine the full effect of this.

It is notable that the speeds attained by four female handlers carrying the stretcher (0.44 m/s) are slower than the same female teams carrying the carry chair (0.69 m/s), despite the carry chair load being only 1.7 kg lighter than the stretcher load. This indicates that weight alone does not determine the speed at which a device

can be carried: the device manoeuvrability and shape, and position of the PRM may also be factors.

8.3.5 Do handlers experience fatigue from assisted evacuation?

Fatigue does not appear to be an issue in the vertical descent speed of any of the devices when descending through 11 floors: no significant reduction of speed was recorded during the trials. However, the teams stopped frequently during the 11-floor stair descent: the stretcher teams stopped 2-5 times, for an average of 12 s; the carry chair teams stopped 2-7 times, for an average of 10 s; and the rescue sheet teams stopped 0-2 times, for an average of 6 s. When carrying the carry chair and the stretcher, teams primarily stopped to swap position and to wipe their hands or the handles of the device. The rescue sheet operators primarily stopped to readjust the strapping of the device, however they did not stop very often, and the evacuation chair was the only device that did not stop at any time during the descent.

While the results indicated that fatigue was not a determining factor for the speed of descending the stairwell, the number of stoppages perhaps indicates that the handling teams stopped due to fatigue, but somewhat recuperated when once they had swapped positions/rested. This does not mean, however, that fatigue would not be an important factor for a greater distance of stair descent, or for those who are not expertly trained. It is important to note that these trials did not explore the impact of repeated evacuation of patients: handling teams were given a break between trials: a minimum of one hour and 45 minutes. Therefore, more research is required to determine the effect of repeated evacuation on handler fatigue.

8.3.6 Can other people evacuate alongside vertical stair devices?

The Ghent video footage clearly demonstrated that people would overtake on the stairwell when there was a physical opportunity to do so. As the evacuation chair and the carry chair (male handlers) only occupied one lane, the other evacuees could easily overtake these devices. The rescue sheet occupied more than one

lane, and over evacuees took the opportunity to overtake in the instances when there was sufficient space. For the stretcher and the carry chair with a female handling team, it was impossible to overtake while concurrently descending the stairs; the group waited for the device to stop before passing. This may have influenced the handlers' decision to stop, although the questionnaire data were not rich enough to establish this as a motive. The evacuation chair allowed the most overtaking during the trials, which may have been due to its occupation of the least space on the stair of all of the devices as there was only one handler manoeuvring the device.

Studies have shown varying merging behaviour in staircases [263, 264], however, more research is required into the behaviours and impact of handlings teams in vertical evacuations, i.e. the circumstances under which they may stop in order to allow other evacuees to pass, as well as into the likelihood of evacuees travelling alongside and overtaking devices, as the Ghent trials only tested 24 young and physically fit evacuees.

8.3.7 What factors influence the performance of assisted evacuation?

For most of the performance indicators established in this work, the gender of the handling teams was a significant performance factor. In preparing a PRM for evacuation in a movement device, male teams are faster than female teams: on average the difference between male and female performance is smallest for the evacuation chair (22%), followed by the stretcher (30%), the carry chair (40%) and the rescue sheet, which has the greatest gender performance difference (48%). In horizontal movement, male teams are faster than female teams, with the carry chair having the smallest difference between male and female performance (5.2%), followed by the stretcher (9.4%), the evacuation chair (10.4%), and the rescue sheet having the greatest difference (37.9%). The results also indicate that female teams take longer than male teams to manoeuvre closed doors while using movement devices. When doors are bolted shut, the male teams take on average twice as long to negotiate the door while the female teams take on average 3.5 times as long. In vertical movement, the evacuation chair had the smallest difference in speeds attained (1.2%) between male and female teams. The female

stretcher team was significantly slower than the male team (30%) and the female rescue sheet team was significantly slower than the male team (37%). The results for the carry chair suggest that the female descent speed is greater than the male descent speed; however the female teams had an additional handler, so this is not directly comparable. Furthermore, the female handling teams did generally stop more than the male teams, and rested for longer during the stops possibly indicating higher levels of muscular fatigue.

Another factor identified is the effect of practice: handlers were on average 3.54% quicker the second time that they prepared a PRM. Although each participant was expertly trained in the preparation and operation of movement devices, this improvement may indicate the effect of recently repeating an action, or the effect of repeating an action with the same group of people. The literature indicates large differences between the performance of trained and untrained individuals, therefore a key area of further research is in the impact of training on the performance of those assisting PRM.

The number of operators required to utilise the device is also of great importance, especially in situations where there may be many PRM or in situations where there are few trained device handlers. The evacuation chair was the best device in this respect, only requiring a single handler for both horizontal and vertical movement, while the other devices required two, three, or four handlers.

8.4 How can these data be used to compare the performance of movement devices in evacuation?

In an attempt to provide a way of combining the performance factors of movement devices in a transparent, flexible and meaningful manner a simple metric was devised based on the weighted sum of each performance factor. The metric offers a simple approach to gauge the overall performance advantage of one device over another, allowing user-based priorities and user-specific performance factors to be considered. Ten performance factors were considered for each device: the preparation time; the number of essential operators for the preparation phase; the

straight horizontal speeds; the right angle turning speeds; the number of essential operators for the horizontal phase; the door transition times; the overall stair descent speed; the number of essential operators for the vertical phase; the number of lanes occupied in a two-lane staircase; and the operator safety ratings.

Assuming all the performance factors carry equal weight, the evacuation chair score indicates the best performance, scoring 25% better than the carry chair, 53% better than the rescue sheet and 92% better than the stretcher for male teams and, similarly, 30% better than the carry chair, 67% better than the rescue sheet and, 83% better than the stretcher for female teams. Different results can be established using weights to represent user priorities and specific scenarios; for example whether there are ample staff, or whether there is a significant horizontal or vertical portion in the scenario investigated. However, in using the performance results from the Ghent trials to compare devices, it must be emphasised that the factors presented in this metric assume the use of trained staff.

The collected data were also used in a demonstration numerical simulation to determine how long it would take to evacuate a ward of 28 non-ambulant patients through 11 floors, using only available night and day shift ward staff. The results show that, even using the fastest device (i.e. the evacuation chair), it would take at least 29 minutes to evacuate the ward using only the day staff and 55 minutes using only the night staff and that if the slowest device is used (i.e. stretcher) the evacuation times increase for both day and night staff, up to 228 minutes for male teams and 283 minutes for females.

An important finding from this numerical simulation is that it is not possible to evacuate 28 immobile patients through 11 floors only using available night shift staff and any of the four devices within a reasonable period of time. Using the day shift staff it may be possible to evacuate the ward within reasonable time only using the evacuation chair device. Furthermore, if a fatigue factor of 5% is employed for repeat ascent/descent incurred by ward staff, then evacuation times will increase by at least 20% and devices that require more than one handler

(stretcher, carry chair and drag mattress) will be more severely affected than devices that only require one handler (evacuation chair).

However, this software demonstration also highlights the limitations of numerical simulation. It was found that implicitly representing a device by using experimental data in this way does not physically represent the space it occupies, nor the associated behaviour of other occupants.

8.5 How can movement devices be explicitly modelled?

8.5.1 How can a hospital building be assessed for the accessibility of devices?

Methodology has been presented in this thesis to assess a hospital structure for the accessibility of movement devices on egress routes. The spaces available are decomposed to establish their Medial Axis (MA): the set of Voronoi [246] points that can be considered as the locus of centres of maximal circles within the geometry [247]. The MA and its Radius Function (RF) together constitute the Medial Axis Transform (MAT) [252], which estimates the geometric conditions for each possible route within structures. As such, hospital building plans are decomposed to establish whether movement devices will fit within their boundaries [254]. Viable routes are therefore pre-determined and are effectively delineated in bEX as a set of itineraries [240].

8.5.2 How can agent-device interactions be represented in an evacuation model?

The model developed in this work specified movement devices in terms of the parameters identified in the experimental data. Devices are specified using rectangular vertices. In general, the use of rectangular objects is considered appropriate for modelling within a hospital environment as the vast majority of transportable objects within hospitals can be approximated by a rectangular birds-eye shape, including wheelchairs, beds, stair movement devices, equipment trolleys, hoists, commodes and drip stands. Experimental data were also associated with the object to indicate the speed at which it travels, associated preparation times, as well as the size and space it occupies. Agent-device

interactions were modelled in terms of agent attachment points, i.e. the positions in which the devices were operated by the varying numbers of device handlers. A preparation delay was attributed to each device indicating the time taken to ready the patient for evacuation. The gender of the handling team was represented in the attributes of the team members, and in the speeds in which they could adopt. It was assumed that any team with a female member would travel at the female speeds identified; only all-male teams travel at the male speeds identified. To represent the tasks undertaken, including the repeated collection of patients, agents were given itineraries (a set of locations and time-dependant tasks) with which to specify their behaviour. As such, the model enables varying teams of handlers to prepare, pick up and drop off devices, travelling at the speeds assigned to them, and changing their attachment points according to their mode of travel: either horizontal or vertical.

8.5.3 How can the horizontal movement of devices be represented in an evacuation model?

Algorithms were developed to enable devices to move within a fine-node system, to navigate alongside other agents on a flat surface, and to manoeuvre corners and doorways during the simulation. The devices navigate based on the potential value of their surrounding nodes, i.e. selecting nodes that are closer to an exit or to their itinerary target for horizontal evacuation, and therefore progressing along their desired route. The algorithm considers nodes on a boundary (i.e. adjacent to a wall) as a less desirable option by assigning a larger potential value to these nodes, and therefore devices avoid the boundaries as required. Devices turn during their path according to an algorithm designed to assess the direction of the upcoming route choice, and take an average between two route choices if appropriate. In this way, the turning mechanism is smoothed and enables a realistic path. A further algorithm prescribes the movement of devices through doorways, ensuring an appropriate delay is imposed to represent the time taken to open a closed door and traverse the doorway at reduced speed as observed in the Ghent trials.

8.5.4 How can the vertical movement of devices be represented in an evacuation model?

Algorithms were developed to enable devices to descend stairs within buildingEXODUS, utilising its existing representation of stairs (as “transit nodes”) and landings to represent evacuation down stairs. Paths were determined according to the stairway lanes the devices travel within, as informed by the Ghent experiment, and elliptical paths calculated for the landing movement to ensure that devices turned in their respective lane as required. A stopping model was also developed, where devices stop periodically within their stairwell descent, as observed in the Ghent trials. Stopping data were applied (i.e. the distance between stops and the duration of stoppage), and the devices paused in the according to the parameters. Any empty lanes adjacent to the evacuating device on the stairs, or on the landing when the device were in their stopping positions, allow other evacuees to pass, as observed in the Ghent trials.

8.5.5 How can the functionality implemented be tested and verified?

In testing the route assessment methodology, it was found that the error incurred is proportional to the discretised grid used for the calculation. In the tests conducted using a mesh construct of 0.1m, the error is ≤ 0.071 metres, and is conservative by definition: points will always be considered too close to a boundary instead of too far away. Therefore, devices may be rejected for a route because their edges are within 7cm of a boundary, but may not be accepted for a route if they are too large. For the practicalities of this context, where it is being assessed whether a movement device will fit within geometric spaces, a 7cm error may have a negligible effect. Indeed, when considering objects that may be transporting people, a nominated space between them and potential boundaries may be a necessary assumption because of the agents attached. However, as the mesh size is a user-set parameter, this can be altered should a smaller error be required.

The functionality was tested for various configurations of 90° turns using realistic hospital dimensions that accord with UK codes [2]. In the 28 test cases, 24 detected all of the right-angled corners with errors as expected between 0.00m and 0.20m.

The four cases in which corners were not identified indicates that on paths where there are wider passageways connecting to smaller passageways, i.e. by a factor greater than two, then the wider turn is not recognised as a right angle. However, as the smaller turn is identified, it is found that the path has still been satisfactorily analysed.

Tests were conducted on the model to verify the physical representation of each device, and it was found that the model precisely represents the correct device dimensions with respect to the surrounding boundaries. The devices also occupied the correct area, as specified by their shape and successfully displaced the correct amount of agents (i.e. other agents do not overlap with the device). Agent-device interactions were tested and it was found that the specified preparation delay was incurred for all devices and teams of all genders. The attachment algorithm worked as prescribed as associated agents picked up, moved with, and dropped off the devices using the correct horizontal and vertical positioning.

The speed of each device was tested on the horizontal and it was found that all devices travelled at the prescribed speed within the model, with only minor errors noted: $\varepsilon \leq 0.8$ s. It was also found that paths were appropriately blocked by devices, where agents could not pass, and that agents only moved around the devices where there was room in the geometry i.e. vacant nodes adjacent to the device. Devices successfully navigated the corridor geometry, including corners and doorways. The test cases demonstrated that the correct time elapses when each of the devices are pushed and carried through doorways within the model with minor errors noted: $\varepsilon \leq 0.4$ s.

Similarly, the speed of each device in the model was tested in a stairwell geometry based on the emergency stairwell layout in the Ghent trials. It was found that all devices travelled at the prescribed speed per floor within the model, with only minor errors noted: $\varepsilon \leq 0.8$ s. Furthermore, the stopping algorithm indicated that the correct number and duration of stops incurred in the model. The ability for other agents to overtake each device was tested, and it was found that the devices that left a stair lane open (i.e. the evacuation chair and the carry chair with male

teams) successfully permitted other agents to pass on the stairs. For those devices that fully occupied the stairs, agents could only pass when the device had stopped on the landing.

These tests provided quantitative and qualitative verification of the model developed as part of this work, suggesting that the model is effective in reproducing the hospital evacuation behaviour observed in the Ghent trials.

8.5.6 How can the model implemented provide insight into hospital evacuations?

To verify the performance of the model functionality and validate against expectation where possible, an additional set of demonstrations were presented. Four target scenarios were applied within the model to demonstrate that the model can adequately forecast beyond the component test cases presented; i.e. that the model is not limited to the original experimental scenarios.

The first case demonstrated the evacuation of hospital wards with day and night staff, verifying that the combined functionality performs as expected, and that it produces credible output when compared with available benchmark data. The second case explored the impact of handling devices when they are not occupied by patients; i.e. the effort required to transport empty devices in repeated evacuation, and the process of transferring patients from devices at an external exit. This expanded upon the original functionality tested in the first case to demonstrate that the functionality is able to represent a richer set of factors and behaviours than basic implicit representation. The third case demonstrated the ability to extend the model to other devices; a wheelchair is included in a scenario that combines self-evacuating and assisted evacuating down stairs. As such, this demonstrated the capability to represent different procedural responses given populations with different types of impairments, and apply the model functionality to devices not intended for vertical evacuation. The fourth case demonstrated the ability to represent progressive horizontal evacuation, a key component of hospital evacuation procedures. This test further demonstrated the flexibility of the model

to represent the likely procedures in a hospital and thus compare responses; for example, the impact of staffing levels.

In all instances, the demonstrations clearly exhibited the enhanced forecasting capability of the developed explicit model within buildingEXODUS. More so, it demonstrated that the developed model represents performance at low-levels (as specified), that this functionality produces qualitative and quantitative local conditions that are both intuitively acceptable and match existing data (albeit sparse), and is also able to produce high-level, emergent results that are credible given the scenarios examined.

9 CONCLUSION AND FUTURE WORK

Hospital evacuations present a number of challenges. Hospitals are complex spatial environments and evacuations from them involve the movement of already vulnerable occupants to a place of safety. Recent incidents, regulatory developments and demographics suggest that the existing assumptions regarding the sufficiency of horizontal evacuation procedures may not always be sufficient, requiring vertical evacuations to be conducted. However, the vertical evacuation of those with severe movement impairments can be highly problematic – for the patients, for the staff and for the other evacuees. It is critical to understand the performance of vertical evacuation strategies, including the means by which people with reduced mobility can be assisted in stair descent.

The objective of this thesis has been to advance the understanding of the performance of evacuation devices used in vertical evacuation and to use this as a basis for model development - to allow hospital evacuations to be quantified more effectively. This thesis described the work undertaken to quantify the performance of trained hospital staff in evacuating non-ambulant patients from hospitals using evacuation devices, the analysis of the devices tested, and the development and implementation of mathematical algorithms to explicitly represent the dynamics of these devices within evacuation software.

Progressive horizontal evacuation is commonly employed in hospitals, although it may not always be sufficient. Vertical movement of those with impairments may be necessary in severe incidents. This requires significant staff involvement and the use of a variety of devices. The performance of such devices is sensitive to training levels and fatigue and will influence the clearance time of those directly involved and those evacuees sharing the stairwells where such devices are used. It is critical to understand how effective these devices are in the specific scenario and quantify their impact on overall evacuation performance – especially given the move towards risk assessment and performance-based design. Simulation tools have

been demonstrated to allow such quantification, although they require sufficient functionality and empirical support to do so.

Prior to this thesis, there were insufficient data on the performance of different evacuation devices and the underlying factors that influence this performance. Previous data focused on the average times taken for evacuation devices to traverse large horizontal and vertical areas. This precluded both the identification of the factors needed within a model and the means to quantify this representation. For example, the obstacles on an evacuation route (i.e. corners and doors); the effect of staff fatigue in assisted evacuation; the physical effort required in assisted evacuation as evidenced by the impact of handler gender on preparation times; and horizontal and vertical speeds. An experimental methodology was developed to better scrutinise experimental footage in order to identify the factors that influenced performance and to form an empirical basis for model development.

Existing evacuation models were examined to determine their suitability for use in simulating hospital evacuations. Considering the established influential performance factors and existing availability of data, the models were reviewed against those factors that influence hospital evacuation in real-world scenarios; key amongst which was the use of evacuation devices. Most models were unsuitable given innate limitations in the fundamental approach adopted. Others were able to simulate potential reductions in agent speed given the assumed use of a device, but were incapable of effectively representing the physical presence of the device or the associated staffing procedures.

The review of the data currently available and the current modelling capabilities highlighted a set of data and modelling omissions. These omissions formed the based for the data collection and modelling activities in this thesis: namely, the detailed analysis of trial footage in order to establish novel performance data and the explicit representation within evacuation software buildingEXODUS of four commonly used movement devices: a stretcher, an evacuation chair, a carry chair, and a rescue sheet.

The results from the data analysis indicate that the evacuation chair took the shortest time to prepare a patient for evacuation and that preparation times for devices where the patient was secured in a sitting position are considerably faster than the time taken with devices where the patient was secured in a lying position.

In horizontal evacuation the devices with wheels are the fastest, with average speeds comparable to typical pedestrian walking speeds. Stretcher and rescue sheet devices are significantly slower in horizontal movement. When traversing doors it took longer for teams transporting devices to open doors that opened towards them than those that opened away from them, as expected. The evacuation chair traversed doors quickly with one handler, however the stretcher and rescue sheet took significantly longer.

In vertical evacuation the evacuation chair is the fastest device, followed by the rescue sheet, the carry chair and finally the stretcher. Over ten floors, none of the devices exhibited significant successive decline in speed, however the decision to regularly stop may indicate occurrences of physical fatigue that are manageable by breaks over the distances tested. Significantly, it was found that the evacuation chair did not stop during stairway descent indicating that rest breaks were not required over ten floors. It was found that other evacuees overtake movement devices on the stairs when there is sufficient space to do so. Therefore, in a staircase that is wide enough for two lanes of pedestrians, devices that occupy more than one lane (i.e. the stretcher, rescue sheet and carry chair with four handlers) effectively block the stairs, unlike the carry chair with two handlers and the evacuation chair that only occupy one stairway lane.

The gender of the handling teams was found to be a significant performance factor, with men being faster than women in like-for-like tests. In vertical travel, female handling teams stop more often and stop for a longer duration than male teams. One important exception was the performance of male and female teams in vertical descent using the evacuation chair: with only 1% difference in speeds attained, indicating that there is near-equivalent gender performance over the stair distance tested. A further performance factor identified is the effect of

practice: on average teams are quicker the second time that they prepare a PRM. The number of operators required to utilise the device is also of great importance: the evacuation chair was the best device in this respect, only requiring a single handler for both horizontal and vertical movement, while the other devices required up to four handlers.

In order to quantitatively compare the performances of the evacuation devices investigated, a metric was devised to combine the results from the data analysis. In a direct comparison based on the findings of this work, and assuming all the performance factors carry equal weight, the evacuation chair score indicates the best performance, followed by the carry chair, rescue sheet and stretcher. This indicates that, given the experimental scenario presented, the devices with wheels and where the PRM is in a sitting position, generally outperform the other devices in experimental conditions with highly trained staff.

Numerical simulations compared the performance of devices in a scenario where a hypothetical hospital ward is evacuated using day and shift staff. The results indicate that it is not possible to evacuate 28 immobile patients through 11 floors only using available night shift staff and any of the four devices within a reasonable period of time. Using the day shift staff it may be possible to evacuate the ward within a reasonable time only using the highest performing device. This exercise also highlighted limitations in this numerical simulation; it was found that implicitly representing a device by using experimental data to reduce agents' speeds does not physically represent the space it occupies, nor the associated behaviour of other occupants.

The model developed in this work specified movement devices in terms of the parameters identified in the experimental data. Devices are specified using rectangular vertices, sufficient for approximating wheelchairs, beds, stair movement devices, and other medical equipment. Experimental data were also associated with the object to indicate the speed at which it travels, associated preparation times, as well as the size and space it occupies and the number of handlers required. Algorithms were presented that enable devices to move within

a fine-node system, to navigate alongside other agents on a flat surface and on stairs, and to manoeuvre corners and doorways during the simulation in accordance with the data collected. The gender of the handlers informed the speeds applied. A stopping model is also presented, to represent the devices stopping periodically within the stairwell, as indicated by the experimental results. Numerous quantitative and qualitative testing was conducted. This demonstrated that the model developed as part of this work is effective in reproducing the hospital evacuation behaviour observed in the data collected during this work (e.g. during the Ghent trials) and that it is suitable for application within broader hospital scenarios.

Prior to the work discussed here, there were insufficient data to understand and quantify the performance of evacuation devices. Although further work is still required, the data collected has significantly enhanced understanding and capacity to quantify the performance of a number of different devices. Importantly, it also enabled the explicit simulation of this performance within an evacuation model. This is a significant and novel development, given the functionality that had to be introduced to cope with the procedural, navigational and geometric aspects of the use of the device. This has now been achieved and demonstrated to adequately represent the real-world behaviour being simulated. This representation is much more effective and credible than had previously been achieved.

This enhancement now allows practitioners and interested parties to test the use of evacuation devices as part of different hospital evacuation procedures and their impact (positive or negative) on overall performance – and to quantify the factors that influence this performance. This significantly enhances planning and diagnostic capabilities of the model within hospital and other healthcare facilities. This forecasting capacity enables insight to be gained prior to the implementation of a new procedure, a new building design or the use of new devices. As such, it should help ensure that the adoption of new designs are better informed and that risk assessments and evidence-based analyses are better supported in the future.

9.1 FUTURE WORK

This section looks at each component of the work undertaken and specifies further development identified to address the limitations identified. The following sections align with the relevant thesis chapters: Data Collection and Experimental Results; Performance Evaluation; and Theoretical Model.

9.1.1 Data Collection and Experimental Results

The following future data requirements were identified in the discussion chapter (8.3):

- to investigate the time taken to prepare patients from varying initial positions to securing them safely into movement devices;
- to establish the times taken to secure patients' medical equipment into the devices;
- to identify the impact of floor covering on speeds attained by movement devices in corridors;
- to identify factors that may impact the time taken to traverse a doorway, for example the handle structure and weight of the door;
- to determine the extent to which the number of handlers and the devices' weight informs speed at which a device can be carried and whether the device manoeuvrability, shape, and position of the PRM are also factors,
- to investigate the effect of repeated evacuation on handler fatigue and the associated behaviours of handling teams, i.e. the circumstances under which they may stop in order to allow other evacuees to pass;
- to establish the likelihood of evacuees travelling alongside and overtaking devices in a dense flow of evacuees; and
- to investigate the differences between the performance of trained and untrained individuals, and the effectiveness of different types and frequency of training.

Further to this, more research is required into the validity of the assumption that if any one member of the handling team is female, the team will operate at the speed

of an all-female team. While it has been found that many performance parameters are dependent on the gender of the handling team, this was derived from all-male and all-female performance. While it is sensible to assume that the speeds attained by the faster male teams approaches optimal device performance under the experimental conditions due to their level of training, it is uncertain how a team comprising male and female operators will perform. Further experimental/empirical data are required to investigate the performance of mixed gendered teams. Interpolating the data between all-male and all-female teams may not give an accurate representation.

Future data collection efforts are required to establish the handling and transportation of empty devices. In the Ghent trials, the device was ready to be used, however in reality the device may be stored elsewhere and therefore a delay may be incurred in retrieving and preparing the device itself. In repeated evacuation, the time taken to move the patient out of the device at an exit is also not known. Furthermore, empty devices may need to be carried up the stair in order to collect another patient. Therefore, it is important to study the reduction in speed incurred by carrying an empty device up stairs, as it may significantly affect the evacuation time.

The effect on evacuation time when multiple devices are directed along the same route is worthy of investigation. Similarly, more research is required to assess how closely people evacuate alongside a device in a corridor as this was only investigated in the stairwell during the Ghent trials. It has not been established whether occupants may slow their speed in anticipation of a device, or whether there are behavioural differences between peoples' reaction to a device in evacuation flow; for example groups and family may evacuate closely with one of their members in a device, whereas others may leave more room. Furthermore, the device dynamics in counter-flow is unknown.

9.1.2 Performance Evaluation

Further analysis of the performance of varying devices would be beneficial to provide further insight into real life evacuation scenarios. A cost-benefit approach to performance comparison may prove illuminating for hospital and other building management to assess the implications of selecting a number of varying devices, particularly to compare their evacuation performance against the costing constraints of fire safety provision, and the impact of training when more data are available. To extend the performance metric, additional factors can be included to incorporate other considerations as data and need arises. For example, the effect of physical effort on the handlers could be included in the comparison, as more analyses of the ergonomics of devices are published. Performance could also be considered regarding the individual progress per operator i.e. the number of metres travelled per operator per second, as well as the impact and costs of various training programmes could be explored.

9.1.3 Theoretical Model

The work presented in this thesis represents the first attempt to model hospital evacuation within an established egress model using explicit representation of movement devices. There are many other model developments that may be considered to further enhance the functionality: the representation of patient preparation from varying initial positions (e.g. lying down) and the attachment of medical equipment; the adjustment of speeds in light of new performance factors such as levels of training, device weight, handler fatigue, and the different genders and physical capabilities within a handling team; and the behaviours of evacuees travelling alongside and overtaking devices in a dense flow. Better information about device acceleration, momentum and braking would also support an improved model of device movement.

A worthwhile development would be adaptable agent itineraries to enable the simulation of agents who are not staff (e.g. visitors and other hospital staff) to aid in the assistance of PRM. Furthermore, itineraries that are conditional on a developing situation, or based on communication between agents would greater

represent the reality of hospital procedures, particularly the communication and interaction between hospital staff and emergency responders.

The movement model described herein only explicitly considers rectangular shapes but the general methodology could be extended to account for non-rectangular human manoeuvred shaped obstacles. This could enable the simulation of objects such as prams, trolleys and luggage, and also be applied to larger transport structures, such as systems of cars and buses, emergency fire and medical vehicles, and moving barriers in crowds, such as police horses. Indeed the model could be developed to tie in with existing transport models relating to hospital resource allocation [168, 203].

REFERENCES

[1] Department for Communities and Local Government, “Fire Statistics: Great Britain, April 2013 to March 2014,” Department for Communities and Local Government, London, 2015.

[2] Department of Health, “Health Technical Memorandum 05-02: Firecode Guidance in support of functional provisions (Fire safety in the design of healthcare premises) 2014 Edition,” 8 May 2014. [Online]. Available: https://www.gov.uk/government/publications/guidance-in-support-of-functional-provisions-for-healthcare-premises. [Accessed 24 June 2014].

[3] British Standards Institution, *BS 9999:2008 Code of Practice for Fire Safety in the design, management and use of buildings,* London: British Standards Institution, 2008.

[4] A. Childers and K. Taaffe, “Healthcare Facility Evacuations: Lessons Learned, Research Activity, and the Need for Engineering Contributions,” *Journal of Healthcare Engineering,* no. 1, pp. 125-140, 2010.

[5] *Equality Act 2010 (c.15).*

[6] BBC News, “Hospital Fire was a 'Wake up call',” BBC, 28 January 2008. [Online]. Available: http://news.bbc.co.uk/1/hi/programmes/file_on_4/7213205.stm. [Accessed 24 July 2013].

[7] HMG, “Fire Safety Risk Assessment, Means of Escape for Disabled People,” Reference number 06 FRSD 03913(a), UK, 2007.

[8] Department for Communities and Local Government, *National Statistics: Fire Statistics 2008, United Kingdom,* London: Department for Communities and Local Government, 2008.

[9] Office for Disability Issues, Department for Work and Pensions, “Disability Facts and Figures,” 16 January 2014. [Online]. Available: https://www.gov.uk/government/publications/disability-facts-and-figures/disability-facts-and-figures. [Accessed 3 July 2014].

[10] United Nations, *Convention on the Rights of Persons with Disabilities,* 2006.

[11] Government of Canada, “National Model Construction Code Documents: Objective-based Codes,” 22 11 2013. [Online]. Available: http://www.nationalcodes.nrc.gc.ca/eng/faq/objective_based_codes.html. [Accessed 25 June 2014].

[12] The Australia Building Codes Board, "The National Constructive Code - A Performance-Based Code," 20 June 2013. [Online]. Available: http://www.abcb.gov.au/en/about-the-national-construction-code/the-ncc-performance-based-code. [Accessed 25 June 2014].

[13] D. A. Purser, "ASET and RSET: Addressing Some Issues In Relation To Occupant Behaviour and Tenability," *Fire Safety Science,* vol. 7, pp. 91-102, 2003.

[14] E. D. Kuligowski and R. D. Peacock, "Review of Building Evacuation Models, 2nd Edition (Report No. NIST TN 1680)," National Institute of Standards and Technology, Gaithersburg, MD, 2010.

[15] STEPS - Simulation Group, "STEPS (Simulation of Transient Evacuation and Pedestrian movements) User Manual," Mott MacDonald, Croydon, UK, 2011.

[16] E. R. Galea, P. J. Lawrence, S. Gwynne, L. Filippidis, D. Blackshields and D. Cooney, "buildingEXODUS v5.1 User Guide and Technical Manual," Fire Safety Engineering Group, University of Greenwich, London, 2013.

[17] K. E. Boyce, T. J. Shields and G. W. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline," *Fire Technology,* vol. 35, no. 1, pp. 51-67, 1999.

[18] K. Christensen and Y. Sasaki, "Agent-Based Emergency Evacuation Simulation with Individuals with Disabilities in the Population," *Journal of Artificial Societies and Social Simulation 11,* vol. 3, no. 9, 2008.

[19] SimWalk, "SimWalk V4.0 User Guide," [Online]. Available: www.simwalk.com/downloads/UserGuide40.pdf. [Accessed 2 February 2015].

[20] J. Wall and N. Waterson, "Predicting evacuation times – a comparison of the STEPS simulation approach with NFPA 130," *Fire Command Studies,* vol. 1, no. 1, 2002.

[21] T. Sano, Y. Omiya and I. Hagiwara, "Evacuation from High-Rise Buildings by Using an Evacuation Chair," in *6th Asia Oceania symposium on Fire Science and Technology, International Association Fire Safety Science*, Hefei, China, 17-20 March, 2004.

[22] E. Kuligowski, B. Hoskins and R. Peacock, "Evacuation of People with Disabilities on Stairs," in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September 2012.

[23] S. A. Lavender, G. Hedman, P. A. Reichelt, J. Mahta, K. M. Conrad and S. Park, "Ergonomic Evaluation of Manually Carried and Track-Type Stair Descent Devices used for the Evacuation of High Rise Buildings," in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September 2012.

[24] Office for National Statistics (ONS), "Statistical Bulletin: National Population Projections, 2010-based Statistical Bulletin," Office for National Statistics, London, 2011.

[25] A. Hunt, E. R. Galea and P. J. Lawrence, "An analysis and numerical simulation of the performance of trained hospital staff using movement assist devices to evacuate people with reduced mobility," *Fire Mater.,* no. doi: 10.1002/fam.2215, 2013.

[26] J. Parke, S. Gwynne, E. Galea and P. Lawrence, "Validating the buildingEXODUS evacuation model using data from an unannounced trial evacuation," in *Procedings of 2nd International Pedestrian and Evacuation Dynamics Conference*, London, UK, 2003.

[27] HMG, "The Building Regulations 2010. Approved Document B (Fire safety) – Volume 2 - Buildings other than dwellinghouses (2006 edition incorporating 2010 and 2013 amendments)," January 2013. [Online]. Available: http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partb/bcapproveddocumentsb/bcapproveddocbvol2/#Download. [Accessed 9 March 2014].

[28] British Standards Institute, *PD 7974-6:2004 The application of fire safety engineering principals to fire safety design of buildings,* London: British Standards Institute, 2004.

[29] The Royal Institution of Naval Architects, "MSC Circ 1033 and 1283," [Online]. Available: http://www.rina.org.uk/msc-circ-1033-1238.html. [Accessed 25 June 2014].

[30] UN General Assembly, *Universal Declaration of Human Rights,* 10 December 1948, 217 A (III).

[31] United Nations (UN), "Convention on the Rights of Persons with Disabilities," 13 September 2006. [Online]. Available: http://www.un.org/disabilities/convention/conventionfull.shtml. [Accessed 4 March 2014].

[32] *Disability Discrimination Act 1995 (c.50).*

[33] HMG, *The Regulatory Reform (Fire Safety) Order,* 2005.

[34] HMG, *Guidance: Fire Safety Risk Assessment, Offices and Shops. HMG, Reference number 05 FRSD 03338(a).,* 2006.

[35] Department of Finance and Personnel, "Building Regulations (Northern Ireland)," Norther Ireland Civil Service, Belfast, UK, 2012.

[36] *Disability Discrimination Act 2005 (c.13).*

[37] Commission for Equality and Human Rights (CEHR), "Health and safety in the workplace," 30 June 2009. [Online]. Available: http://www.equalityhumanrights.com/your-rights/equal-rights/disability/disability-in-employment/health-and-safety-in-the-workplace. [Accessed 3 March 2014].

[38] N. C. McConnell and K. E. Boyce, "Refuge areas and vertical evacuation of multistorey buildings: the end users' perspectives," *Fire and Materials. Special Issue: Human Behaviour in Fire,* vol. 39, no. 4, pp. 396-406, 2013.

[39] G. Proulx and J. Pineau, "Review of Evacuation Strategies for Occupants with Disabilities: Internal Report No. 712. National Fire Laboratory," Insititute for Research in Construction, National Research Council, Ottawa, 1996.

[40] S. R. Hart, A. Yajnik, J. Ashford, R. Springer and S. Harvey, "Operating Room Fire Safety," *The Ochsner Journal,* vol. 11, no. 1, pp. 37-42, 2011.

[41] *Mental Health Act 1983 (c.20).*

[42] New York Centers for Terrorism Preparedness and Planning (NYCTP), "Hospital Evacuation Protocol," Bioterrorism Hospital Preparedness Program: NYC Department of Health and Mental Hygiene, NYC, USA, 2006.

[43] C. S. Cocanour, S. J. Allen, J. Mazabob, J. W. Sparks, C. Fischer, J. Romans and K. P. Lally, "Lessons Learned from the Evacuation of an Urban Teaching Hospital," *Arch Surg,* vol. 137, no. 10, pp. 1141-1145, 2002.

[44] Committee on Homeland Security and Governmental Affairs, "Hurricane Katrina: A Nation Still Unprepared," 2006. [Online]. Available: http://www.gpo.gov/fdsys/pkg/CRPT-109srpt322/pdf/CRPT-109srpt322.pdf. [Accessed 7 August 2013].

[45] C. H. Schultz, K. L. Koenig and R. J. Lewis, "Implications of hospital evacuation after the Northridge, California, earthquake," *New Engl J Med,* vol. 348, no. 14, pp. 349-355, 2003.

[46] Department for Communities and Local Government, "National Statistics: Fire Statistics 2010 to 2011, Great Britain," Department for Communities and Local Government, London, 2011.

[47] Department for Communities and Local Government, "National Statistics: Fire Statistics 2011 to 2012, Great Britain," Department for Communities and Local Government, London, 2012.

[48] Department for Communities and Local Government , "National Statistics: Fire Statistics 2012 to 2013, Great Britain," Department for Communities and Local Governmen, London, 2013.

[49] Department for Communities and Local Government, “National Statistics: Fire Statistics 2013 to 2014, Great Britain,” Department for Communities and Local Government, London, 2014.

[50] M. Ahrens, “Fires In Health Care Facilities,” National Fire Protection Association : Fire Analysis and Research Division, Quincy, MA, 2012.

[51] U.S. Fire Administration, “Residential and nonresidential building fire and fire loss estimates by property use and cause (2003-2012),” U.S. Fire Administration, Emmitsburg, MD, 2014.

[52] New Zealand Fire Service, “New Zealand Fire Service Emergency Incidents Statistics,” New Zealand Fire Service, Wellington, NZ, 2011.

[53] National Fire Protection Association (NFPA), “Deadliest hospital fires in the United States,” December 2008. [Online]. Available: http://www.nfpa.org/research/reports-and-statistics/fires-by-property-type/health-care-facilities/deadliest-hospital-fires. [Accessed 23 March 2015].

[54] The Guardian, “Dozens killed in Chinese hospital fire,” Guardian News and Media Limited, 16 December 2005. [Online]. Available: http://www.theguardian.com/world/2005/dec/16/china. [Accessed 5 May 2015].

[55] BBC News, “China fire in care home kills 38,” BBC, 26 May 2015. [Online]. Available: http://www.bbc.co.uk/news/world-asia-china-32879841. [Accessed 27 May 2015].

[56] BBC News, “Henan nursing home fire due to 'poor construction',” BBC, 28 May 2015. [Online]. Available: http://www.bbc.co.uk/news/world-asia-china-32911115. [Accessed 28 May 2015].

[57] A. Humphreys, “Another inquest probes need for sprinkler systems in retirement homes in light of 2009 blaze that killed four.,” National Post, 16 April 2012. [Online]. Available: http://news.nationalpost.com/news/canada/another-inquest-probes-need-for-sprinkler-systems-in-retirement-homes-in-light-of-2009-blaze-that-killed-four. [Accessed 1 May 2015].

[58] A. P. Harpur, K. E. Boyce and N. C. McConnell, “An Investigation into the Circumstances Surrounding Fatal Dwelling Fires Involving the Elderly during 1999 - 2009,” in *Interflam 2013: 13th International Conference and Exhibition on Fire Science and Engineering* , Windsor, UK, 2014.

[59] A. Wapling, C. Heggie, V. Murray, J. Bagaria and C. Philpott, “Review of five London Hospital Fires and their Management,” NHS London, London, 2009.

[60] C. Schultz, K. Koenig, E. Auf der Heide and R. Olson, “Benchmarking for hospital evacuation: a critical data collection tool,” *Prehosp Disaster Med.,* vol. 5, no. 20, pp. 331-342, 2005.

[61] EMERCOM of Russia, “Fire at psychoneurological hospital in Moscow region,” 26 April 2013. [Online]. Available: http://en.mchs.ru/articles/digest/item/408644/. [Accessed 7 August 2013].

[62] D. Purser, “Fire Safety and evacuation implications from behaviours and hazard development in two fatal care home incidents,” *Fire Mater,* vol. 39, no. 4, pp. 430-452, 2014.

[63] EMERCOM of Russia, “EMERCOM of Russia,” 26 April 2013. [Online]. Available: http://en.mchs.ru/articles/digest/item/408644/. [Accessed 7 August 2013].

[64] M. Elder, “Moscow Hospital Fire Turns Spotlight on Russia's Terrible Safety Record,” 26 April 2013. [Online]. Available: http://www.theguardian.com/world/2013/apr/26/moscow-hospital-fire. [Accessed 7 August 2013].

[65] Tanaka, H, A. Iwai, J. Oda, Y. Kuwagata and T. Matsuoka, “Overview of evacuation and transport of patients following the 1995 Hanshin-Awaji earthquake,” *J Emerg Med,* vol. 16, pp. 439-444, 1998.

[66] R. Powers and E. Daily, International Disaster Nursing, New York: Cambridge University Press, 2010.

[67] The Associated Press, “Two Troubled New Orleans Hospitals Evacuated,” 3 September 2005. [Online]. Available: http://www.nbcnews.com/id/9159926/ns/health-health_care/t/two-troubled-new-orleans-hospitals-evacuated/#.UgOMx421GSp. [Accessed 7 August 2013].

[68] B. H. Gray and K. Hebert, “After Katrina: Hospitals in Hurrican Katrina,” July 2006. [Online]. Available: http://www.urban.org/UploadedPDF/411348_katrinahospitals.pdf. [Accessed 7 August 2013].

[69] magazine.sfpe.org, “SIP & DIP - Stay In Place & Defend In Place,” Society of Fire Protection Engineers, 1 January 2007. [Online]. Available: http://magazine.sfpe.org/occupants-and-egress/sip-dip-stay-place-defend-place. [Accessed 6 May 2015].

[70] B. Heffernan and S. Maguire, “Hospital evacuated after storms cause flood chaos,” 27 July 2013. [Online]. Available: http://www.independent.ie/irish-news/hospital-evacuated-after-storms-cause-flood-chaos-29452625.html. [Accessed 7 August 2013].

[71] S. Gwynne, E. Galea, P. Lawrence and J. Hickson, “The Collection and Analysis of Pre-Evacuation Times Derived from Evacuation Trials and their Application to Evacuation Modelling,” *Fire Technology,* vol. 39, no. 2, pp. 179-195, 2003.

[72] D. Purser and M. Kuipers, “Interactions between buildings, fire and occupant behaviour using a relational database created from incident investigations and interviews,” in *3rd International Symposium on Human Behaviour in Fire, Belfast, UK 1-3rd September 2004*, London, UK, 2004.

[73] United Nations, “World Population Prospects: The 2012 Revision ,” Population Division, Dept. of Economic and Social Affairs, United Nations; New York, NY, 2013.

[74] W. Lutz, W. Sanderson and S. Scherbov, “The coming acceleration of global population ageing,” *Nature,* no. 451, pp. 716-719, 2008.

[75] The Scottish Government, “Scottish Building Standards Technical Handbook: Non-Domestic, Annex 2.B Additional guidance for hospitals,” The Scottish Government, Livingston, Scotland, 2013.

[76] J. Saffle, “The 1942 fire at Boston's Cocoanut Grove nightclub,” *The American Journal of Surgery,* vol. 166, no. 6, p. 581–591, 1993.

[77] H. Klüpfel, M. Schreckenberg and T. Meyer-König, “Models for Crowd Movement and Egress Simulation,” *Traffic and Granular Flow ’03,* pp. 357-372, 2005.

[78] S. Gwynne, “Representing egress data,” *Fire Mater. ,* no. 36, p. 441–457, 2012.

[79] S. Gwynne and E. Galea, A Review of the Methodologies and Critical Appraisal of Computer models used in the Simulation of Evacuation from the Built Environment, London: University of Greenwich CMS Press, No. 97/IM/21, 1997.

[80] BBC News, “Germany WW2 bomb find prompts Cologne's biggest evacuation,” BBC, 27 May 2015. [Online]. Available: http://www.bbc.co.uk/news/world-europe-32897388. [Accessed 2015 May 2015].

[81] E. Hunt, *Discussion on patient evacuation capabilities with Community Nurse Case Manager [meeting] (Personal communication, 18 December 2014),* London, 2014.

[82] J. G. Sørensen and A. Dederichs, “Evacuation Characteristics of Blind and Visually Impaired People: Walking Speeds on Horizontal Planes and Descending Stairs,” in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September 2012.

[83] W. Myles and P. Saunders, “The physiological cost of carrying light and heavy loads,” *European Journal of Applied Physiology and Occupational Physiology,* vol. 42, no. 2, pp. 125-131, 1979.

[84] J. Augustine and J. T. Schoettmer, “Evacuation of a Rural Community Hospital: Lessons Learned from an Unplanned Event,” *Disaster Management Response,* vol. 3, no. 3, pp. 68-72, 2005.

[85] E. Ronchi and D. Nilsson, “Fire evacuation in high-rise buildings: a review of human behaviour and modelling research,” *Fire Science Reviews,* vol. 2, no. 7, 2013.

[86] G. Proulx, “Highrise Evacuation: a Questionable Concept,” in *2nd International Symposuim on Human Behaviour in Fire*, Boston, MA, 2001.

[87] G. Proulx and J. Pineau, “The Impact of Age on Occupants' Behaviour during a Residential Fire,” in *Human Factors and Ergonomics Society 40th Anuual Meeting, September 2-6 1996*, Philadelphia, Pennsylvania, 1996.

[88] World Health Organization, “Hospital emergency response checklist: An all-hazards tool for hospital administrators,” World Health Organization, Copenhagen, Denmark, 2011.

[89] World Health Organization, “A practical tool for the preparation of a hospital crisis preparedness plan, with special focus on pandemic influenza. 2nd edition,” World Health Organization Regional Office for Europe, Copenhagen, Denmark, 2007.

[90] R. Zane, P. Biddinger, A. Hassol, T. Rich, J. Gerber and J. DeAngelis, “Hospital Evacuation Decision Guide: Prepared for Agency for Healthcare Research and Quality, (Prepared under Contract No. 290-20-0600-011.) AHRQ Publication No. 10-0009,” Agency for Healthcare Research and Quality, Rockville, MD, 2010.

[91] K. H. Sexton, L. M. Alperin and J. D. Stobo, “Lessons from Hurricane Rita: the University of Texas Medical Branch Hospital's evacuation,” *Acad Med,* vol. 82, no. 8, pp. 792-6, 2007.

[92] K. V. Iserson, “Vertical Hospital Evacuations: A New Method,” *Southern Medical Journal,* vol. 106, no. 1, pp. 37-42, January 2013.

[93] G. Hedman, “Travel Along Stairs by Individuals with Disabilities: A Summary of Devices Used During Routine Travel and Travel During Emergencies,” in *Fifth International Conference on Pedestrian and Evacuation Dynamics*, Gaitherburg, MD, 2010.

[94] G. Hedman, “Travel Along Stairs by Individuals with Disabilities: A Summary of Devices Used During Routine Travel and Travel During Emergencies,” *Pedestrian and Evacuation Dynamics 2011,* pp. 109-119, 2011.

[95] Evacusafe UK, “Evacuslider Rescue-sheets,” [Online]. Available: http://www.evacusafe.net/store/product-group-evacusliders.asp. [Accessed 2 December 2014].

[96] LifeSlider, “LifeSlider is an emergency evacuation device,” [Online]. Available: http://www.lifeslider.com/frontpage. [Accessed 2 December 2014].

[97] Spectrum Healthcare, “Albacmat: Portable Evacuation Stretcher,” 2014. [Online]. Available: http://www.spectrumhealthcare.co.uk/products/albacmat/. [Accessed 4 July 2014].

[98] Evac+Chair International Limited, “Evac+Chair Model Range,” [Online]. Available: http://www.evac-chair.co.uk/Evac-Chair-Model-Range.aspx. [Accessed 2 December 2014].

[99] Garaventa Lift, “Evac-Trac - how to operate the evacuation chair,” [Online]. Available: http://www.evacutrac.com/operation.html. [Accessed 2 December 2014].

[100] Baronmead International Ltd, “CD7 Evacuation Chair,” [Online]. Available: http://www.baronmead.com/portfolio/cd7-evacuation-chair/. [Accessed 2 December 2014].

[101] Safety Chairs, “Emergency Chair Model 400,” [Online]. Available: http://safetychairs.net/emergencychair.htm. [Accessed 2 December 2014].

[102] Junkin Safety Appliance Company, “Junkin: Rescue Chairs,” [Online]. Available: http://www.junkinsafety.com/RescueChairs. [Accessed 2 December 2014].

[103] Ferno (UK) Limited, “Rescue and Evacuation Equipment: Rescue Stretchers,” [Online]. Available: http://www.ferno.co.uk/rescue-and-evacuation/rescue-stretchers. [Accessed 2 December 2014].

[104] Spectrum Healthcare (UK) Limited, “Foldable Stretcher: Light weight, collapsible stretcher,” [Online]. Available: http://www.spectrumhealthcare.co.uk/products/foldable-stretcher/. [Accessed 2 December 2014].

[105] R. Cooper, “Wheelchair Standards: It's All About Quality Assurance and Evidence-based Practice,” *J Spinal Cord Med,* vol. 29, no. 2, pp. 93-93, 2006.

[106] G. Hedman, “Stair Descent Devices: An Overview of Current Devices and Proposed Framework for Standards and Testing,” in *Human Behaviour in Fire Symposium*, Cambridge, UK, 13-15 July, 2009.

[107] G. Hedman, “Status Report on the Development of the RESNA Performance Standard for Emergency Stair Travel Devices,” in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September, 2012.

[108] E. D. Kuligowski, “Guidance on Fire Emergency Procedures for Emergency Stair Travel Devices: National Institute of Standards and Technology Technical Note 1824,” National Institute of Standards and Technology, Gaithersburg, MD, 2013.

[109] S. Gwynne, D. Purser and D. Boswell, "Pre-warning staff delay: a forgotten component in ASET/RSET calculations," in *Proceedings of the 5th Pedestrian and Evacuation Dynamics Conference, National Institute of Standards and Technology*, Maryland, 2010.

[110] Z. Zamanian, M. Evazian, I. Hazeghi and H. Daneshmandi, "Fire Safety Status in the Hospitals of Shiraz," *International Journal of Occupational Hygiene ,* no. 5, pp. 96-100, 2013.

[111] E. R. Galea, J. Shields, D. Canter, K. Boyce, R. Day, L. Hulse, A. Siddiqui, L. Summerfield, M. Marselle and P. Greenall, "Methodologies employed in the Collection, Retrieval and Storage of Human Factors Information Derived from First Hand Accounts of Survivors of the WTC Disaster of 11 September 2001," *Journal of Applied Fire Science,* vol. 15, no. 4, pp. 253-276, 2006.

[112] C. D. Burt, N. Henningsen and N. Consedine, "Prompting correct lifting posture using signs," *Applied ergonomics,* vol. 30, no. 4, pp. 353-359, 1999.

[113] B. Lange, P. Requejo, S. Flynn, A. Rizzo, F. Valero-Cuevas and L. Baker, "The potential of virtual reality and gaming to assist successful aging with disability," *Phys Med Rehabil Clin N Am.,* vol. 21, no. 2, pp. 339-356, 2010.

[114] S. T. Diekman, T. A. Stewart, S. L. Teh and M. F. Ballesteros, "A qualitative evaluation of fire safety education programs for older adults," *Health promotion practice,* vol. 28, no. 2, 19 May 2008.

[115] S. S. Harrington, "The effects of computer-based training on immediate and residual learning of nursing facility staff," *The Journal of Continuing Education in Nursing,* vol. 35, no. 4, p. 154, 2004.

[116] M. Kinateder, E. Ronchi, D. Nilsson, M. Kobes, M. Muller, P. Pauli and A. Muhlberger, "Virtual reality for fire evacuation research," in *2014 Federated Conference on Computer Science and Information Systems (FedCSIS)*, Warsaw, Poland, 2014.

[117] E. Currie and R. A. Carr Hill, " What are the reasons for high turnover in nursing? A discussion of presumed causal factors and remedies," *International Journal of Nursing Studies,* vol. 49, no. 9, pp. 1180-1189, 2012.

[118] ABT Associates, "Hospital Evacuation Decision Guide: Pre-disaster self assessment," May 2010. [Online]. Available: http://archive.ahrq.gov/prep/hospevacguide/hospevac2.htm. [Accessed 7 August 2013].

[119] F. Olsson, *Thesis entitled: Tolerable Fire Risk Criteria for Hospitals,* Lund: Department of Fire Safety Engineering, Lund University, 1999.

[120] H. Weckman, "Evacuation of a theatre: exercise vs calculations," *Fire Mater.,* vol. 23, no. 6, pp. 1099-1018, 1999.

[121] D. Nilsson and A. Johansson, "Social influence during the initial phase of a fire evacuation—Analysis of evacuation experiments in a cinema theatre," *Fire Safety Journal,* vol. 44, no. 1, pp. 71-79, 2009.

[122] S. Gwynne, E. Galea, P. Lawrence and M. Owen, "An Investigation of the Aspects of Occupant Behaviour Required for Evacuation Modelling," *Journal of Applied Fire Science,* vol. 8, no. 1, pp. 19-59, 1998–1999.

[123] J. Bryan, "Chapter 12: Behavioral Response to Fire and Smoke," in *SFPE Handbook of Fire Protection Engineering Section*, 4th Edition ed., P. J. Dinenno, D. Drysdale, C. L. Beyler and D. W. Walton, Eds., National Fire Protection Association (NFPA), 2008, pp. 3-315.

[124] E. D. Kuligowski, "NIST Technical Note 1632: The Process of Human Behavior in Fires," National Institute of Standards and Technology, Gaithersburg, MD, 2009.

[125] E. D. Kuligowski and S. M. V. Gwynne, "The Need for Behavioral Theory in Evacuation Modelling," *Pedestrian and Evacuation Dynamics 2008,* pp. 721-732, 2010.

[126] M. Kobes, I. Helsloot, B. Vries and J. Post, "Building safety and human behaviour in fire: A literature review," *Fire Safety Journal,* vol. 45, pp. 1-11, 2010.

[127] J. M. Chertkoff and R. H. Kushigian, Don't panic: The psychology of emergency egress and ingress, New York: Praeger Publishers, 1999.

[128] N. W. F. Bode, A. U. K. Wagoum and E. A. Codling, "Information use by humans during dynamic route choice in virtual crowd evacuations," *Royal Society Open Science,* vol. 2, no. 140410, 2015.

[129] T. Shields and K. E. Boyce, "A study of evacuation from large retail stores.," *Fire Safety Journal,* vol. 35, no. 1, pp. 25-49, 2000.

[130] S. Bengtson, L. Kecklund, E. Siré, K. Andrée and S. Willander, "How Do People With Disabilities Consider Fire Safety and Evacuation Possibilities in Historical Buildings?," in *Fifth International Conference on Pedestrian and Evacuation Dynamics*, Gaithersburg, MD, 2010.

[131] T. J. Shields, B. Smyth, K. E. Boyce and G. W. H. Silcock, "Evacuation behaviours of occupants with learning difficulties in residential homes," *Disability and Rehabilitation,* vol. 21, no. 1, pp. 39-48, 1999.

[132] M. Almejmaj and B. Meacham, "The Effects of Cultural and Social Differences Between the West and Saudi Arabia on Emergency Evacuation - Preliminary Findings," in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September, 2012.

[133] J. H. Sørensen, "When shall we leave? Factors affecting the timing of evacuation departures," *International Journal of Mass Emergencies and Disasters,* vol. 9, no. 2, pp. 153-165, 1991.

[134] J. Edworthy and E. Hellier, "Fewer but better auditory alarms will improve patient safety," *Quality and Safety in Health Care,* vol. 14, no. 3, pp. 212-215, 2005.

[135] J. Capote, D. Alvear, O. Abreu, A. Cuesta and J. Hernando, "Children Evacuation: Empirical Data and Egress Modelling," in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, London, UK, 19-21 September, 2012.

[136] L. Ulriksen and A. Dederichs, "Simulex simulations on the evacuation of day-care centres for children 0-6 years," in *6th International Conference on Pedestrian and Evacuation Dynamics - PED 2012*, Delft, The Netherlands, 2012.

[137] C. W. Johnson, "Using computer simulations to support a risk-based approach for hospital evacuation. A Department of Computing Science Briefing," Glasgow Accident Analysis Group, University of Glasgow, Glasgow, 2006.

[138] Fire Protection Research Fouccation, "White Paper," in *Fire Protection and Safety: The Next 25 Years, November 17 & 18, 2008*, Ronald Reagan Building, Washington, DC, 2008.

[139] R. D'Aliesio, "How an Ontario seniors'-home fire changed the rules on sprinkler safety," The Globe and Mail, 24 January 2014. [Online]. Available: http://www.theglobeandmail.com/news/national/how-an-ontario-seniors-home-fire-changed-the-rules-on-sprinkler-safety/article16480384/. [Accessed 1 May 2015].

[140] BBC News, "Peru: 26 die in blaze at Lima drug rehab centre," BBC News, 28 January 2012. [Online]. Available: http://www.bbc.co.uk/news/world-latin-america-16775181. [Accessed 11 December 2014].

[141] M.-J. Siikonen and K. Suikonen, "People Flow and Automated Transportation with Hospital Elevators," *Business Briefing: Hospital Engineering & Facilities Managements,* vol. 2, pp. 41-44, 2005.

[142] E. Kuligowski and B. Hoskins, "Elevator Messaging Strategies," The Fire Protection Research Foundation, 2011.

[143] J. Starke, K. B. Thomsen, A. Sørensen, C. Marschler, F. Schilder, A. Dederichs and P. Hjorth, "Nonlinear effects in examples of crowd evacuation scenarios," in *17th International Conference on Intelligent Transportation Systems (ITSC)*, Qingdao, China, 2014.

[144] S. Gwynne, E. Galea, M. Owen, P. Lawrence and L. Filippidis, "A Review of the Methodologies Used in Evacuation Modelling," *Fire Mater,* vol. 23, pp. 383-388, 1999.

[145] L. Yang, W. Fang, R. Huang and Z. Deng, "Occupant evacuation model based on cellular automata in fire," *Chinese Science Bulletin,* vol. 47, no. 17, pp. 1484-1488, 2002.

[146] P. Thompson, J. Wu and E. Marchant, "Simulex 3.0: modelling evacuation in multi-storey buildings," in *5th International Symposium on Fire Safety Science*, Melbourne, 1997.

[147] M. Cisek and M. Kapalka, "The Use of Fine – Coarse Network Model for Simulating Building Evacuation with Information System," in *Pedestrian and Evacuation Dynamics 2011*, 2011.

[148] A. Grandison, Y. Muthu, P. Lawrence and E. Galea, "Simulating the evacuation of very large populations in large domains using a parallel implementation of the buildingEXODUS evacuation model," in *Interflam 2007 11th International Fire Science and Engineering Conference*, London, 2007.

[149] C. Rogsch, W. Klingsch, A. Seyfried and H. Weigel, "How reliable are commercial software-tools for evacuation calculation?," in *Interflam 2007*, London, UK, 2007.

[150] B. Forell, H. Klüpfel, S. Schelter and V. Schneider, "Comparison of Evacuation Simulation Models," in *Pedestrian and Evacuation Dynamics 2012*, 2014.

[151] E. Kuligowski, The evaluation of Performance-Based Design Process for a Hotel Building: The Comparison of two Egress Models. Master of Science Thesis. Department of Fire Protection Engineering, MD: Department of Fire Protection Engineering. University of Maryland, 2003.

[152] J. Lord, B. Meacham, A. Moore, R. F. Fahy and G. Proulx, "Guide for Evaluating the Predictive Capabilities of Computer Egress Models," NIST, Maryland, USA, 2005.

[153] B. Hoskins and J. Milke, "Differences in Measurement Methods for Travel Distance and Area for Estimates of Occupant Speed on Stairs," *Fire Safety Journal,* vol. 48, pp. 49-57, 2012.

[154] S. Gwynne and E. Kuligowski, "The faults with default," in *Interflam 2010*, Nottingham, UK, 2010.

[155] E. Ronchi and M. Kinsey, "Evacuation models of the future: Insights from an online survey on user's experiences and needs," in *Proceedings of the Advanced Research Workshop: "Evacuation and Human Behaviour in Emergency Situations"*, Cantabria, Spain, 2011.

[156] S. Gwynne, E. Galea, M. Owen, P. Lawrence and L. Filippidis, "Review of modelling methodologies used in the simulation of evacuation," *Journal of Building and the Environment,* vol. 34, pp. 441-749, 1999.

[157] G. Santos and B. Aguirre, "A Critical Review of Emergency Evacuation Simulation Models: Preliminary Paper #339," Disaster Research Center, University of Delaware, Newark, DE, 2004.

[158] M. Owen, E. Galea and P. Lawrence, "Advanced Occupant Behavioural Features Of The Building-exodus Evacuation Model," *Fire Safety Science,* vol. 5, pp. 795-806, 1997.

[159] J. E. Castle, "Working Paper Series, Paper 115: Guidelines for Assessing Pedestrian Evacuation Software," Centre for Advanced Spatial Analysis: University College London, London, 2007.

[160] E. Kuligowski and S. Gwynne, "What a Users Should Know When Selecting an Evacuation Model," *Fire Protection Engineering,* vol. 3, no. Fall , pp. 30-40, 2005.

[161] E. Galea, S. Deere, R. Brown, I. Nicholls, Y. Hifi and N. Bresnard, "The SAFEGUARD validation data-set and recommendations to IMO to update MSC Circ 1238," in *SAFEGUARD Passenger Evacuation Seminar, The Royal Institution of Naval Architects*, London, UK, 2012.

[162] ISO, *Fire safety engineering -- Assessment, verification and validation of calculation methods - Part 5: Example of an Egress model (ISO/TR 16730-5:2013),* Geneva, Swizerland: International Organization for Standardization, 2013.

[163] E. Ronchi, E. Kuligowski, P. Reneke, P. Peacock and D. Nilsson, "NIST Technical Note 1822: The Process of Verification and Validation of Building Fire Evacuation Models," National Institute of Standards and Technology, Gaithersburg MD, 2013.

[164] R. Lubaś, M. Mycek, J. Porzycki and J. Wąs, "Verification and Validation of Evacuation Models – Methodology Expansion Proposition," in *The Conference on Pedestrian and Evacuation Dynamics 2014 (PED 2014)*, Delft, The Netherlands, 2014.

[165] M. Spearpoint, "Comparitive Verification Exercise on a Probabilistic Network Model for Building Evacuation," *Journal of Fire Sciences,* vol. 27, no. 5, pp. 409-430, 2009.

[166] N. Dimakis, A. Filippoupolitis and E. Gelenbe, "Distributed Building Evacuation Simulator for Smart Emergency Management," *The Computer Journal,* vol. 53, no. 9, pp. 1384-1400, 2010.

[167] M. Brunnhuber, H. Schrom-Feiertag, G. Hesina, D. Bauer and W. Purgathofer, "Simulation and Visualization of the Behavior of Handicapped People in Virtually Reconstructed Public Buildings," in *REAL CORP 2010 Proceedings/Tagungsband*, Vienna, 2010.

[168] K. Taaffe, M. Johnson and D. Steinmann, "Improving Hospital Evacuation Planning using Simulation," in *Proceedings of the 2006 Winter Simulation Conference*, Monterey CA, 2006.

[169] S. Uehara and K. Tomomatsu, “Evacuation Simulation System Considering Evacuee Profiles and Spatial Characteristics,” *Fire Safety Science* , vol. 7, pp. 963-974, 2001.

[170] H. Notake, Y. Sugiyama, M. MHirota, K. Machida, S. Nakano, Y. Hasemi, S. Tsuchiya, S. Kawasaki and M. Iida, “Application of Evacuation Safety System for High-rise Hospital,” in *SFPE Europe Conference on Fire Safety Engineering (Presentation)* , Copenhagen, Denmark, 2015.

[171] G. Santos and B. Aguirre, “Preliminary Paper #339 A Critical Review of Emergency Evacuation Simulation Models,” University of Delaware Disaster Research Center, Newark, DE, 2004.

[172] V. Schneider, “Modelling of human response and behaviour in complex surroundings,” in *3rd International Symposium on Human Behaviour in Fire*, Belfast, 2004.

[173] M. Harmon and J. Joseph, “Evacuation Planning Tool (EPT) for Emergency, Event and Space Planning,” in *Pedestrian and Evacuation Dynamics 2011*, 2001.

[174] K. Boyce, J. Fraser-Mitchell and J. Shields, “Survey analysis and modelling of office evacuation using the CRISP model,” in *Human Behaviour in Fire - Proceedings of the 1st International Symposium*, Belfast, UK, 1998.

[175] J. Fraser-Mitchell, “Simulated evacuations of an airport terminal building, using the CRISP model,” in *2nd International Symposium in Human Behavior in Fire*, Boston, MA, 2001.

[176] N. Ketchell, S. Cole and D. Webber, “The EGRESS code for human movement and behaviour in emergency evacuation,” *Engineering for Crowd Safety,* pp. 361-370, 1994.

[177] S. Ko, “Comparison of evacuation times using Simulex and EvacuatioNZ based on trial evacuations,” Engineering Research Report 2003/9 University of Canterbury, New Zealand, 2003.

[178] R. Fahy, “Verifying the predictive capability of EXIT89,” in *2nd International ymposium on Human Behaviour in Fire*, Boston, MA, 2001.

[179] T. Korhonen, S. Hostikka, Heliövaara, H. S Ehtamo and K. Matikainen, “FDS+Evac: evacuation module for fire dynamics simulator,” in *Interflam2007: 11th International Conference on Fire Science and Engineering*, London, UK, 2007.

[180] M. Bensilum and D. Purser, “ Gridflow: an object-oriented building evacuation model combining pre-movement and movement behaviours for performance-based design,” in *7th International Symposium on Fire Safety Science*, Worcester, MA, 2002.

[181] J. Berrou, J. Beecham, P. Quaglia, M. Kagarlis and A. Gerodimos, "Calibration and validation of the Legion simulation model using empirical data," in *Pedestrian and Evacuation Dynamics 2005*.

[182] X. Pan, C. Han, K. Dauber and K. Law, " Human and social behavior in computation modeling and analysis of egress," *Automation in Construction,* vol. 15, pp. 448-461, 2006.

[183] E. Morrow, "MassMotion: simulating human behaviour to inform design for optimal performance," *The Arup Journal,* pp. 38-40, 2010.

[184] J. Cappuccio, "Pathfinder: A computer-based timed egress simulation," *Fire Protection Engineering,* vol. 1, no. 8, pp. 11-12, 2000.

[185] H. Klupfel and T. Meyer-Konig, "Characteristics of the PedGo software for crowd movement and egress simulation," in *2nd International Conference in Pedestrian and Evacuation Dynamics (PED)*, London, UK, 2003.

[186] R. Kukla, J. Kerridge, A. Willis and J. Hine, "PEDFLOW: Development of an Autonomous Agent Model of Pedestrian Flow," *Transportation Research Record,* no. 1774, pp. 11-17, 2001.

[187] L. Buckmann and J. Leather, "Modelling station congestion the PEDROUTE way," *Traffic Engineering and Control,* vol. 35, pp. 373-377, 1994.

[188] V. Shestopal and S. Grubits, "Evacuation model for merging traffic flows in multi-room and multistory buildings," in *Fire Safety Science - Proceedings of the 4th International Symposium*, Ottawa, Canada, 1994.

[189] S. Lo, Z. Fang and G. Zhi, "An evacuation model: the SGEM package," *Fire Safety Journal,* vol. 39, no. 3, pp. 169-190, 2004.

[190] A. Steiner, M. Philipp and A. Schmid, " Parameter estimation for a pedestrian simulation model," in *7th Swiss Transport Research Conference* , Monte Verità, 2007.

[191] C. Sun, B. de Vries and Q. Zhao, "Architectural cue model in evacuation simulation for underground space," in *Pedestrian and Evacuation Dynamics 2008*, 2008.

[192] J. D. Sime, "Movement towards the familar: Person and place affilliation in a fire entrapment setting," *Environmental Behaviour,* vol. 17, no. 6, pp. 697-724, 1985.

[193] E. Ronchi, "Evacuation Modelling and Human Behaviour using FDS Evac in Urban Tunnel Fires," in *First International Conference on Evacuation Modelling and Management 23-25 September 2009*, Delft, The Netherlands, 2009.

[194] E. Galea, P. Lawrence, M. Owen and L. Fillipidis, “Adapting the buildingEXODUS Evacuation Model for Hospital Specific Evacuation Scenarios,” in *Proceedings of the 8th International Fire Science and Engineering Conference: Interflam'99*, London, UK, 1999.

[195] N. Waterson, A. Mecca and J. Wall, “Evacuation of a multilevel office building: comparison of predicted results using an agent-based model with measured data, in,” in *Interflam 2004: 10th International Fire Science and Engineering Conference*, Edinburgh, UK, 2004.

[196] D. Newman, N. Rhodes and H. Locke, “Simulation versus code methods for predicting airport evacuation,” in *1st International Symposium on Human Behaviour in Fire*, Ulster, UK, 1998.

[197] H. D and P. Molnár, “Social force model for pedestrian dynamics,” *Phys. Rev. E ,* vol. 51, no. 5, pp. 4282-4286, 1995.

[198] R. Löhner, “ On the modelling of pedestrian motion,” *Applied Mathematical Modelling,* vol. 34, pp. 366-382, 2010.

[199] F. Zanlungo, D. Brščić and T. Kanda, “Pedestrian group behaviour analysis under different density conditions,” in *The Conference on Pedestrian and Evacuation Dynamics (PED 2014)*, Delft, The Netherlands, 2014.

[200] V. Schneider and R. Könnecke, “Microscopic Modelling of Agents with Mobility Restrictions and Small-Size Social Groups,” in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September 2012.

[201] M. T. Manley, *Exitus: An Agent-Based Evacuation Simulation Model For Heterogeneous Populations [Thesis],* Utah: Utah State University , 2012.

[202] M. Manley and Y. S. Kim, “Modeling emergency evacuation of individuals with disabilities (exitus): An agent-based public decision support system,” *Expert Systems with Applications,* vol. 39, no. 9, pp. 8300-8311, 2012.

[203] E. Tayfur and K. Taaffe, “Allocation of Resources for Hospital Evacuation Simulation,” in *Proceedings of the 2007 Winter Simulation Conference*, Washington, DC, 2007.

[204] J. Duanmu, K. Taaffe and M. Chowdhury, “Minimizing patient transport times during mass population evacuations,” *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2196, pp. 150-158, 2010.

[205] K. Taaffe and E. Tayfur, “Evaluating the Robustness of Hospital Evacuation Plans,” in *Proceedings of the 2006 Industrial Engineering Research Conference*, Orlando, FL, 2006.

[206] V. M. Predtechenskii and A. L. Milinskii, Planning for Foot Traffic Flow in Buildings, New Delhi: Amerind Publishing Company Inc, 1987.

[207] J. Pauls, "Movement of People," in *SFPE Handbook of Fire Protection Engineering*, Bethesda, MD, Society of Fire Protection Engineers, 1995, pp. 3-263 - 3-285.

[208] S. Gwynne and E. Kuligowski, "The Faults with Default," in *Proceedings of the 2010 Interflam Conference, July 5-7 2010*, Nottingham, 2010.

[209] S. Gwynne and E. Rosenbaum, "Emergency Movement," in *The SFPE Handbook of FIre Protection Engineering*, Fourth Edition ed., Bethesda, MD, Society of Fire Protection Engineers, pp. 3-373.

[210] E. R. Galea, M. Sauter, S. Deere and F. L, "Investigating the Impact of Culture on Evacuation Behaviour - a Turkish Data-Set," in *IAFSS 10th International Symposium on Fire Safety Science, 19-24 June 2011*, College Park, MD, 2011.

[211] R. Ono, M. Valentin and F. Vittorino, "Walking Speed Data of Fire Drills at an Elementary School," in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September , 2012.

[212] A. Larusdottir and A. Dederichs, "Behavioural Apects of Movement Down Stairs During Elementary School Fire Drills," in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September, 2012.

[213] A. P. Adams and E. R. Galea, "An Experimental Evaluation of Movement Devices used to assist People with Reduced Mobility in High-Rise Building Evacuations," in *Proceedings of Pedestrian and Evacuation Dynamics: 5th International Conference*, Gaithersburg, MD, 8-10 March 2010.

[214] A. Brand, M. Sörqvist, P. Håkansson and J. E. Johansson, "Evacuation Safety for Locomotion Disabled People," in *Proceedings of 2nd International Symposium Human Behaviour in Fire, 26-28 March 2001*, Massachusetts Institute of Technology, USA, 2001.

[215] T. Fujiyama and N. Tyler, "An Explicit Study on Walking Speeds of Pedestrians on Stairs," in *Proceedings 10th International Conference on Mobility and Transport for Elderly and Disabled People, 23-26 May 2004*, Hamamatsu, Japan, 2004.

[216] C. S. Jiang, S. Z. Zheng, F. Yuan, H. J. Jia, Z. N. Zhan and J. J. Wang, "Experimental Assessment on the Moving Capabilities of Mobility-Impaired Disabled," *Safety Science,* vol. 50, no. 4, pp. 974-985, 2012.

[217] P. Proulx, J. C. Latour, J. W. McLaurin, J. Pineau, L. E. Hoffman and C. Laroche, "Housing Evacuation of Mixed Abilities Occupants in Highrise Buildings, Internal Report No. 706," National Research Council of Canada, Ottawa, ON, 1995.

[218] T. J. Shields, Fire and Disabled People in Buildings, Building Research Establishment Report BR231, vol. ISBN 0 85125 546 9., 1993.

[219] T. J. Shields, K. E. Boyce, G. W. H. Silcock and B. Dunne, "The Impact of a Wheelchair Bound Evacuee on the Speed and Flow of Evacuees in a Stairway During and Uncontrolled Unannounced Evacuation," *Journal of Applied Fire Science,* vol. 7, no. 1, 1997.

[220] J. Fruin, Pedestrian Planning and Design, Mobile, AL: Elevator World Inc, 1987.

[221] J. Pauls and D. Cantor, "Building Evacuation: Research Findings and Recommendations," in *Fires and Human Behavior*, New York, John Wiley & Sons, 1980, pp. 251-275.

[222] R. D. Peacock, B. L. Hoskins and E. D. Kuligowski, "Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories.," *Safety Science,* vol. 50, no. 8, pp. 1655-1664, 2012.

[223] V. M. Predtechenskii and A. I. Milinskiĭ, "Planning for foot traffic flow in buildings," National Bureau of Standards, US Department of Commerce, and the National Science Foundation, Washington, DC, 1978.

[224] H. Hyun-seung, C. Jun-ho and H. Won-hwa, "Calculating and verifying the staircase-length for evacuation analysis," in *Pedestrian and Evacuation Dynamics*, Springer US, 2011.

[225] G. Proulx, B. Kyle and J. Creak, "Effectiveness of a photoluminescent wayguidance system," *Fire Technology,* vol. 36, no. 4, pp. 236-238, 2000.

[226] J. G. Sørensen and A. S. Dederichs, "Evacuation from a Complex Structure – The Effect of Neglecting Heterogeneous Populations," in *The Conference on Pedestrian and Evacuation Dynamics 2014* , Delft, The Netherlands, 2014.

[227] S. A. Lavender, K. M. Conrad, P. A. Reichelt, P. W. Johnson and F. T. Meyer, "Biomechanical Analyses of Paramedics Simulating Frequently Performed Strenuous Work Tasks," *Applied Ergonomics,* vol. 31, pp. 167-177, 2000.

[228] T. Shimada and H. Naoi, "An experimental study on the evacuation flow of crowd including wheelchair users," *Fire Science and Technology,* vol. 25, no. 1, pp. 1-14, 2006.

[229] E. Galea, P. Lawrence and L. Fillipidis, "Extending the Capabilities of the buildingEXODUS Evacuation Model to Cater for Hospital Evacuations," in *Third International Conference on Fire Research and Engineering*, pp 39-50, 1999.

[230] R. F. Fahy and G. Proulx, "Towards creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling," in *Proceedings for the 2nd International Symposium on Human Behavior in Fire, 26/28 March 2001,*, Massachusetts Institute of Technology, Boston, MA,, 2001.

[231] A. Hunt, E. R. Galea and P. J. Lawrence, "An Analysis of the Performance of Trained Staff using Movement Assist Devices to Evacuate the Non-Ambulant," in *Proceedings of 5th International Symposium: Human Behaviour in Fire*, Cambridge, UK, 19-21 September 2012.

[232] UZ-Gent, "Practical Guide for Emergency Teams," in *Rugklacht preventie voor urgentie teams, 3rd edition, ISBN 90 382 0370 5*, Ghent, Manutentieteam Universitair Ziekenhuis Gent, 2002, pp. pp100-146.

[233] Evacupod, "EVACUPOD: Emergency Evacuation Devices," 2014. [Online]. Available: http://evacupod.com/products/. [Accessed 4 July 2014].

[234] E. R. Galea, G. Sharp and P. J. Lawrence, "Investigating the Representation of Merging Behaviour at the Floor-Stair Interface in Computer Simulations of Multi-Floor Building Evacuations," *Journal of Fire Protection Engineering,* vol. 18, no. 4, pp. 291-316, 2008.

[235] J. J. Fruin, Service Pedestrian Planning and Design, (reprint 1987) ed., Mobile, AL: Metropolitan Association of Urban Designers and Environmental Planners, Elevator World Educational Services Division, 1971 .

[236] J. Choi, E. R. Galea and W. H. Hong, "Individual Stair Ascent and Descent Walk Speeds Measured in a Korean High-rise Building," *Journal of Fire Protection Engineering,* p. doi:10.1177/1042391513492738, 2013.

[237] E. Ronchi, P. A. Reneke and R. D. Peacock, "A method for the analysis of behavioural uncertainty in evacuation modelling," *Fire Technology,* vol. 50, no. 6, pp. 1545-1571., 2014.

[238] E. Ronchi, D. Alvear, N. Berloco, J. Capote, P. Colonna and A. Cuesta, "Human behaviour in road tunnel fires: Comparison between egress models (FDS+ Evac, STEPS, Pathfinder)," in *Interflam 2010: 12th International Fire Science and Engineering Conference* , Nottingham, UK, 2010.

[239] I. Frost, M. K. Patel, E. R. Galea, P. Rymacrzyk and R. N. Mawhinney, "A Semi-Automated Approach to CAD Input into Field Based Fire Modelling Tools," in *Proceedings of the 9th International Fire Science and Engineering Conference: Interflam '01*, published by Interscience Communications Ltd, London, UK, 17-19 September 2001.

[240] E. R. Galea, P. J. Lawrence and L. Filippidis, "Extending the Capabilities of the buildingEXODUS Evacuation Model to Cater for Hospital Evacuations," in *Proceedings of the Third International Conference on Fire Research and Engineering*, Chicago, 4-8 October 1999.

[241] H. Xie, L. Filippidis, E. R. Galea, D. Blackshields and P. J. Lawrence, "Experimental analysis of the effectiveness of emergency signage and its implementation in evacuation simulation," *Fire Mater.,* vol. 36, no. 5-6, pp. 367-382, 2012.

[242] E. Galea, Z. Wang, A. Veeraswamy, F. Jia and P. J. Lawrence, "Coupled Fire/Evacuation Analysis of the Station Nightclub Fire," in *Fire Safety Science; Proceedings of the ninth international symposium*, Karlsruhe, Germany, 2008.

[243] S. Gwynne, E. R. Galea, P. J. Lawrence, M. Owen and L. Filippidis, "Adaptive Decision-Making in BuildingEXODUS in Response to Exit Congestion," in *Fire Safety Science: Proceedings of the sixth international symposium*, Poitier, France, 1999.

[244] M. Foskey, M. Garber, M. C. Lin and D. Manocha, "A Voronoi-Based Framework for Motion Planning and Maintainability Applications," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2001*, Maui, HI, USA, 29 October - 3 November 2001.

[245] A. Okabe, B. Boots, K. Sugihara and S. N. Chui, Spatial Tessellations - Concepts and Applications of Voronoi Diagrams. 2nd edition, ISBN 0471-98635-6: John Wiley, 2000.

[246] F. Aurenhammer and R. Klein, "Voronoi Diagrams," in *Handbook of Computational Geometry, Chapter V*, Graz, Austria, Elsevier Science Publishing, 2000, pp. 201-290.

[247] H. I. Choi, S. W. Choi and H. P. Moon, "Mathematical theory of medial axis transform," *Pacific Journal of Mathematics,* vol. 181, no. 1, pp. 57-88, 1997.

[248] J. Bruck, J. Gao and A. Jiang, " MAP: Medial axis based geometric routing in sensor networks," *Wireless Networks,* vol. 13, no. 6, pp. 835-853, 2007.

[249] D. Sheehy, C. Armstrong and D. Robinson, "Shape description by Medial Surface Construction.," *IEEE Trans Visualization & Computer Graphics,* vol. 2, pp. 62-72, 1996.

[250] J. Reddy and G. Turkiyyah, "Computation of 3-D skeletons by a generalized Delaunay triangulation technique," *Computer-Aided Design,* vol. 27, no. 9, pp. 677-694, 1995.

[251] V. Srinivasan and L. Nackman, "Voronai Diagram of multiply connected polygonal domains," *IBM Journal of Research and Development,* vol. 31, pp. 373-381, 1987.

[252] H. N. Gürsoy and N. M. Patrikalakis, "Automated interrogation and adaptive subdivision of shape using medial axis transform," *Advances in Engineering Software and Workstations,* vol. 13, no. 5-6, pp. 287-302, 1991.

[253] P. Y. Ang and C. G. Armstrong, “Adaptive shape-sensitive meshing of the medial axis,” *Engineering with computers,* vol. 18, no. 3, pp. 253-264, 2002.

[254] R. T. Boute, “Moving a Rectangle around a Corner: Geometrically,” *The American Mathematical Monthly,* vol. 111, no. 5, pp. 435-437, 2004.

[255] International Maritime Organization (IMO), “MSC Circ 1238; Guidelines for Evacuation Analysis,” 2007.

[256] E. Ronchi, D. Nilsson, O. Zechlin, W. Klein and M. H. , “Employing validation and verification tests as an integral part of evacuation model development,” in *Interflam 2013*, Windsor, UK, Interscience Communication Limited, 2013, pp. 979-990.

[257] UK Wheelchairs, “Transit Wheelchairs,” UGO Healthcare, [Online]. Available: http://www.uk-wheelchairs.co.uk/transit-wheelchairs. [Accessed 2014 December 2].

[258] A. Brand, M. Sörqvist, P. Håkansson and J. E. Johansson, “Evacuation Safety for Locomotion Disabled People,” in *Proceedings of 2nd International Symposium Human Behaviour in Fire, 26-28 March 2001*, Massachusettes Instituite of Technology, USA, 2001.

[259] T. J. Shields, K. E. Boyce, G. W. H. Silcock and B. Dunne, “The Impact of a Wheelchair Bound Evacuee on the Speed and Flow of Evacuees in a Stairway During and Uncontrolled Unannounced Evacuation,” *Journal of Applied FIre Science,* vol. 7, no. 1, 1997.

[260] S. M. Michael, D. Porter and T. E. Pountney, “Tilted seat position for non-ambulant individuals with neurological and neuromuscular impairment: a systematic review,” *Clin Rehabil,* vol. 21, no. 12, p. 1063–1074, 2008.

[261] J. P. Brokaw, W. C. Walker, D. X. Cifu and M. Gardner, “Sitting and Standing Tolerance in Patients with Chronic Back Pain: Comparison between Physician Prediction and Covert Observation,” *Arch Phys Med Rehabil,* vol. 85, no. 5, pp. 837-9, 2004.

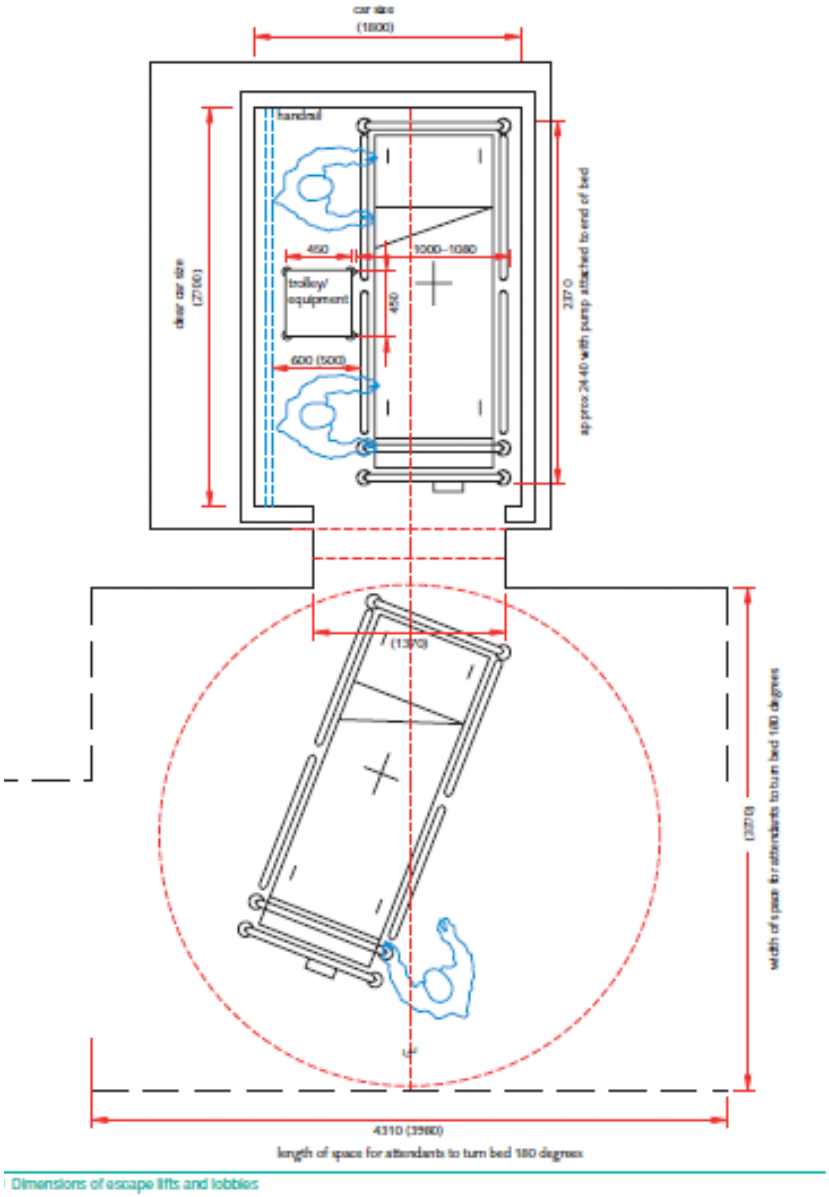
[262] East of England NHS Collaborative Procurement Hub, “Bariatric Furniture and Equipment Framework Catalogue: Wheelchairs,” East of England NHS Collaborative Procurement Hub, Fulbourn, UK, 2012.

[263] K. E. Boyce, D. A. Purser and T. J. Shields, “Experimental studies to investigate merging behaviour in a staircase,” *Fire and Materials,* vol. 36, no. 5-6, pp. 383-398., 2012.

[264] D. Purser and K. E. Boyce, “Implications of Modelling and Experimental Studies of Evacuation Behaviour on Stairs for Multi-storey Building Design,” in *4th International Symposium: Human Behaviour in Fire 2009*, Cambridge, UK, 2009.

APPENDICES

A. Dimensions of Escape Lifts and Trolleys - DH [2]



Picture credit: Department of Health, "Health Technical Memorandum 05-02: Firecode Guidance in support of functional provisions (Fire safety in the design of healthcare premises) 2014 Edition," 8 May 2014. [Online]. Available: https://www.gov.uk/government/publications/guidance-in-support-of-functional-provisions-for-healthcare-premises. [Accessed 24 June 2014].

B. Assisted Patient Evacuation Down a Stairway - DH [2]

A Minimum clear landing width (mm)	B Minimum clear stair width (mm)	C Minimum clear landing depth (mm)	
2800	1100	1950	allows assisted patient evacuation only
2800	1200	1925	
2800	1300	1850	allows assisted patient evacuation and restricted ambulant passing
3000	1400	1750	
3200	1500	1550	
3400	1600	1600*	allows assisted patient evacuation plus ambulant passing
3800	1800	1800*	

* Stair width is not determined by the number of people expected to use the stairs in a fire emergency, but principally by the requirements of assisted patient evacuation.

The evacuation strategy and the notes below will determine the optimum requirements for stair widths and landing depths.

For a clear landing width of 3400 mm, the minimum clear landing depth for assisted patient evacuation is 1450 mm. 1600 mm is the recommended depth to enable ambulant passing and to equal the stair clear width. See BS 8300.

For a clear landing width of 3800 mm, the minimum clear landing depth for assisted patient evacuation is 1750 mm. 1800 mm is recommended to equal the stair width. See BS 8300.

Table 3 Alternative stair and landing dimensions to facilitate assisted patient evacuation

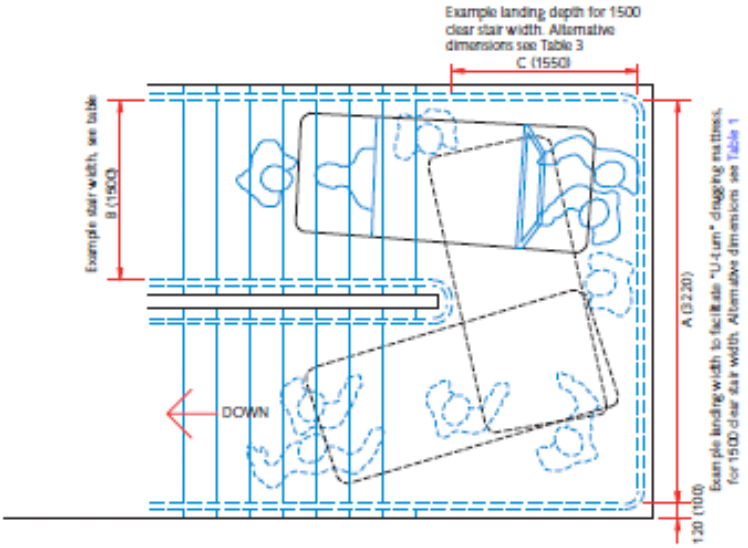


Figure 10 Assisted patient evacuation down a stairway

Picture credit: Department of Health, "Health Technical Memorandum 05-02: Firecode Guidance in support of functional provisions (Fire safety in the design of healthcare premises) 2014 Edition," 8 May 2014. [Online]. Available: https://www.gov.uk/government/publications/guidance-in-support-of-functional-provisions-for-healthcare-premises. [Accessed 24 June 2014].

C. Unassisted and assisted stair descent for PRM

Author	Place, Year	No. Participants (%M. %F) [Age range]	PRM (sample size)	Mean (m/s) ± SD
[17] **Boyce *et al.***	**UK 1999**	**107 (54/107,53/107) [20-83]**	**Horizontal – 50m, various floor coverings**	
			UA-NA(52)	0.95±0.32
			UA-CR2(6)	0.94±0.30
• Evacuation Trial • Unimpeded • People had real disabilities • Included blind participants • Observed by stopwatch (0.1 sec precision) • Other data included ramps and door transition. • Instructed to move in a "prompt manner" • Is it not clear how fully the assistants were trained.			UA-WS(33)	0.81±0.38
			UA-WF(10)	0.57±0.38
			UA-WC(12)	0.69±0.35
			UA-EWC(2)	0.89
			A-NA(18)	0.78±0.34
			A-WC(16)	1.3±0.34
			Vertical, 1 storey (37°-38°)	
			UA-NA(19)	0.36±0.14
			UA-CR1(1)	0.22
			UA-WS(9)	0.32±0.12
			UA-WF(1)	0.16
			A-NA(1)	0.13
			A-VI(3)	0.19

Author	Place, Year	No. Participants (%M. %F) [Age range]		
[216] **Jiang *et al.***	**China 2012**	**117 (58/117,59/117) [21-60+]**		
• Evacuation Trial • Unimpeded • Subway Station • People had real disabilities • Observed by video (0.04 sec precision) • Instructed to move "at the highest speed they could maintain" • Were assistants trained? Unknown • Other data assessed passage widths and gender differences, and compared with ambulant people.			**PRM (sample size)**	**Mean (m/s) ± SD**
			Horizontal – 40m	
			UA-NA(40)	1.27±0.19
			UA-CR1(20)	0.87±0.18
			UA-CR2(40)	0.78±0.22
			Vertical, 1 storey (17.7°) 22 steps, with mid landing	
			UA-NA(40)	0.85±0.19
			UA-CR1(20)	0.43±0.14
			UA-CR2(40)	0.33±0.13

Author	Place, Year	No. Participants (%M. %F) [Age range]
[82] **Sørensen and Dederichs**	**Denmark 2012**	**46 (30/46,16/46) [10-69]**

- Evacuation Trial
- Unimpeded
- Data collated from four New Zealand buildings
- People had real disabilities
- Observed by video
- Assumed unassisted.
- Paper also looks at speed and density

PRM (sample size)	Mean (m/s) ± SD
Horizontal – 40m	
UA-VI(46)	0.98
Vertical, 1 storey (17.7°) 22 steps, with mid landing	
UA-VI(46)	0.73±0.09

Author	Place, Year	No. Participants (%M. %F) [Age range]
[215]**Fujiyama and Tyler**	**Japan 2004**	**18 (33,66) [60-81]**

- Evacuation Trial
- Unimpeded
- People were elderly, therefore had reduced mobility but not specific disability
- 4 stairwells and 1 flat surface in UCL buildings. Only one flight of stairs.
- Only two minutes rest
- Observed by stopwatch (precision?)
- Instructed to move "normal" and at "fast" speeds
- Other data compared the physical capabilities of the participants with their speeds.

PRM (sample size)	Mean (m/s) ± SD
Horizontal – 8m	
UA-NA(18)	"normal" 1.31±0.23
	"fast" 1.71±0.29
Vertical, 38.8°	
UA-NA(18)	"normal" 0.60±0.16
	"fast" 0.79±0.22
Vertical, 35°	
UA-NA(18)	"normal" 0.72±0.20
	"fast" 0.86±0.22
Vertical, 30.5°	
UA-NA(18)	"normal" 0.73±0.17
	"fast" 0.96±0.21
Vertical, 24.6°	
UA-NA(18)	"normal" 0.91±0.26
	"fast" 1.15±0.30

Author	Place, Year	No. Participants (%M. %F) [Age range]
[218] **Shields *et al.***	**UK 1993**	**4 ("mix gender") [mix age]**

Data relayed from SFPE chapter

- Unannounced evacuation
- Hotel – carpeted floors
- Video observation

PRM (sample size)	Mean (m/s) ± SD
Horizontal	
UA-WC(4)	0.72

Author	Place, Year	No. Participants (%M. %F) [Age range]	*Ranges interpolated from graphs on paper.
[214] **Brand *et al.***	**Sweden 2001**	**48 ("mix gender") [>15]**	

- Evacuation Trial
- Unimpeded
- Public buildings (assumed Sweden)
- Non-wheelchair people had real disabilities. Unsure about others.
- Observation method not known.
- Instructed to move "at the highest speed they could maintain"
- Other data assessed the spacee required to turn 180 degrees for wheelchair users and door opening 'force'

PRM (sample size)	Mean (m/s) ± SD
Horizontal – 31m	
UA-NA(9)	RANGE 0.6-1.4, m=1.00
UA-WC(12)	RANGE 0.3-2.4, m=1.35
UA-EWC(15)	RANGE 1.2-2.5, m=1.85

Author	Place, Year	No. Participants (%M. %F) [Age range]	**(no gender info) [at least 83 were elderly]** • Other occupants and 45 fire fighters assisted. Possibility of training discrepancies as fire fighters were using it as training.
Kuligowski *et al.* [22]	**USA 2012**	**119**	

- Announced evacuation
- 13 Floor assisted living facility.
- Two stairwells.
- Video observation
- Also presents speeds per sub sections of floors.

PRM (sample size)	Mean (m/s) ± SD
Vertical 25.1 degrees [from SFPE approximation]	
UA-NA(83)	0.41±0.17
UA-WS (14)	0.23±0.08
A-NA(4)	0.25±0.13
A(F)-NA(3)	0.18±0.04
A-EC[2-3(F)](15)	0.21±0.03

Author	Place, Year	No. Participants (%M. %F) [Age range]	Only 21% of occupants were see throughout drill 1, 29% in drill 2 and 29% in drill 3. Wheelchair bound people stayed in place to wait to be rescued.
[217] **Proulx *et al.***	**Canada 1995**	**no ("mix gender") [mix age]**	

- "Unannounced" evacuation, but occupants were written to.
- Not sure if these people travelled all of these floors.
- Video observation
- Evacuated together, so not unimpeded, but speeds were measured through low density.
- Also presents

PRM (sample size)	Mean (m/s) ± SD
Building 1: Vertical 14 floors	
UA-NA(3)	0.88
Building 2: Vertical 14 floors	
UA-NA(8)	0.61
UA-NA(2) over 65	0.57
Building 3: Vertical 12 floors	
UA-NA(21)	0.57
UA-NA(18) >65yo	0.56

Author	Place, Year	No. Participants (%M. %F) [Age range]
[219] **Shields *et al.***	**UK 1997**	**no ("mix gender") [mix age]**

- Unannounced evacuation drill, wheelchair user assisted by two people (carried) down two flights of stairs. Wheelchair user and assistors had pre-knowledge of evacuation.
- Even though in an evacuation flow, was unimpeded as nobody overtook.
- They chose not to overtake – there was room (40cm). Caused considerable congestion.
- Corridor length not given.
- Video observation

PRM (sample size)	Mean (m/s) ± SD
Horizontal	
A-WC (1)	1.1
Vertical – two storeys 30°	
A-CWC[2] (1)	0.32
Only 21% of occupants were seen throughout drill 1, 29% in drill 2 and 29% in drill 3. Wheelchair bound people stayed in place to wait to be rescued.	

Author	Place, Year	No. Participants (%M. %F) [Age range]
[23] **Lavender *et al.***	**USA 2012**	**12 ("unknown") [unknown]**

*Mean values interpolated from graphs on paper.

- Experimental Trial
- Unimpeded
- 73kg mannequin used
- Urgent/Non urgent specified
- MC: 1120 staircase width
- 12 Professional Firefighters
- 2-3 flights of stairs
- Not specified number of repeated trips
- Unknown sample sizes for means.

PRM (sample size)	Mean (m/s) ± SD
Vertical	
AF-NA	0.32*
AF-CC	0.34*
AF-FS	0.45*
AF-ECC	0.75*
AEC4- 4 wheeled	0.66*
AECL- Long track	0.67*
AECR – Rear facing	0.69*
AECN - Narrow	0.82*
AEC2- 2 wheeled	0.86*

Author	Place, Year	No. Participants (%M. %F) [Age range]	*Ranges interpolated from graphs on paper.
[21] **Sano *et al.***	**Japan 2004**	**20 (70,30) [20-30]**	

- Data inferred from graphs, as outlined in the columns below.
- PRM weighed 65kg (reportedly the average weight in Japan).
- Stopwatches were used to record times
- All groups had oral training, but one group were classed as "trained" in the use of devices (10m/4f) and the other group were "untrained" (4m/2f)
- The same evacuation chair as was utlilised in the WTC evacuation was used (2 wheeled)
- It is inferred from the paper that male handlers were primarily used for the repeated experiments, although this is not clear.

Sano [21]	Figure 5		Figure 6		Figure 6		Figure 4		Figure 4	
Trial	Female 5 storey		Male 5 storey		Male 10 storey		Mixed? 10 storey		Mixed? 20 storey	
No. Trials	n=2	n=4	n=4	n=5	n=5	n=9	n=5	n=9	n=1	n=4
Training	N	Y	N	Y	N	Y	N	Y	N	Y
1 Floor	17	20	8	20	29	33	25	31	52	43
2 Floors	25	26	17	35	39	43	30	42	58	53
3 Floors	24	23	18	31	38	43	33	43	62	52
4 Floors	23	29	15	33	32	43	31	37	63	52
5 Floors	26	31	19	32	30	44	36	43	70	51
6 Floors					38	45	35	44	65	53
7 Floors					40	47	31	42	69	53
8 Floors					49	48	34	45	70	55
9 Floors					48	50	35	44	67	54
10 Floors					49	51	34	40	66	56
11 Floors									68	55
12 Floors									70	53
13 Floors									71	54
14 Floors									68	55
15 Floors									70	54
16 Floors									71	57
17 Floors									64	52
18 Floors									68	55
19 Floors									64	57
20 Floors									70	58
Av m/m	23	25.8	15.4	30.2	39.2	44.7	32.4	41.1	66.3	53.6
Av m/s	**0.38**	**0.43**	**0.26**	**0.50**	**0.65**	**0.75**	**0.54**	**0.69**	**1.11**	**0.89**
± SD m/s	**0.05**	**0.07**	**0.07**	**0.09**	**0.12**	**0.08**	**0.05**	**0.07**	**0.08**	**0.05**

D. Video Analysis Reference Points

The reference points used in the following tables were designated for ease of use by the video analyst, as well as for convenient data sorting. The program that extracted the data delivered a text file, listing each marker reference followed by its associated value (the time marked in the video file), separated by a space. Numerical sorting therefore was helpful in analysing the data, so this informed the marker values. The first table categorizes the times that were recorded for each trial, and the second table categorizes the additionally qualitative observations (e.g. stoppages). Video Analysis Reference Points

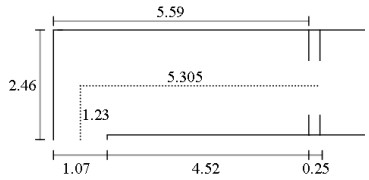
Table 9-1: Video Analysis Reference Points

Marker Ref #	Action of Active Device Team members
28	First member has both feet in Preparation Room
27	First member to make physical contact with PRM
26	First forward movement of PRM in device
25	First member crosses threshold of door 1
24	Last member crosses threshold of door 1
23	First member touches door 2
22	First member crosses threshold of door 2
21	Last member crosses threshold of door 2
20	First member touches door 3
19	First member crosses threshold of door 3
18	Last member crosses threshold of door 3
A	First member crosses assumed line
B	Last member crosses assumed line
17	First member touches door 4
16	First member crosses threshold of door 4
15	Last member crosses threshold of door 4
14	First member touches door 5
13	First member crosses threshold of door 5
12	Last member crosses threshold of door 5
11.8	First member's foot on top step from floor 11.
11.7	Last member's foot on top step from floor 11.
11.6	First member's foot on landing 11a.
11.5	Last member's foot on landing 11a.
11.4	First member's foot on top step from landing 11a.
11.3	Last member's foot on top step from landing 11a.
11.2	First member's foot on floor 10.
11.1	Last member's foot on floor 10.
10.8	First member's foot on top step from floor 10.
10.7	Last member's foot on top step from floor 10.
Marker Ref #	Action of Active Device Team members
10.6	First member's foot on landing 10a.

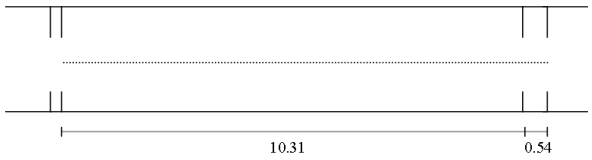
10.5	Last member's foot on landing 10a.
10.4	First member's foot on top step from landing 10a.
10.3	Last member's foot on top step from landing 10a.
10.2	First member's foot on floor 9.
10.1	Last member's foot on floor 9.
9.8	First member's foot on top step from floor 9.
9.7	Last member's foot on top step from floor 9.
9.6	First member's foot on landing 9a.
9.5	Last member's foot on landing 9a.
9.4	First member's foot on top step from landing 9a.
9.3	Last member's foot on top step from landing 9a.
9.2	First member's foot on floor 8.
9.1	Last member's foot on floor 8.
8.8	First member's foot on top step from floor 8.
8.7	Last member's foot on top step from floor 8.
8.6	First member's foot on landing 8a.
8.5	Last member's foot on landing 8a.
8.4	First member's foot on top step from landing 8a.
8.3	Last member's foot on top step from landing 8a.
8.2	First member's foot on floor 7.
8.1	Last member's foot on floor 7.
7.8	First member's foot on top step from floor 7.
7.7	Last member's foot on top step from floor 7.
7.6	First member's foot on landing 7a.
7.5	Last member's foot on landing 7a.
7.4	First member's foot on top step from landing 7a.
7.3	Last member's foot on top step from landing 7a.
7.2	First member's foot on floor 6.
7.1	Last member's foot on floor 6.
6.8	First member's foot on top step from floor 6.
6.7	Last member's foot on top step from floor 6.
6.6	First member's foot on landing 6a.
6.5	Last member's foot on landing 6a.
6.4	First member's foot on top step from landing 6a.
6.3	Last member's foot on top step from landing 6a.
6.2	First member's foot on floor 5.
6.1	Last member's foot on floor 5.
5.8	First member's foot on top step from floor 5.
5.7	Last member's foot on top step from floor 5.
5.6	First member's foot on landing 5a.
5.5	Last member's foot on landing 5a.
5.4	First member's foot on top step from landing 5a.
5.3	Last member's foot on top step from landing 5a.
5.2	First member's foot on floor 4.
5.1	Last member's foot on floor 4.
Marker Ref #	Action of Active Device Team members
4.8	First member's foot on top step from floor 4.
4.7	Last member's foot on top step from floor 4.
4.6	First member's foot on landing 4a.
4.5	Last member's foot on landing 4a.
4.4	First member's foot on top step from landing 4a.
4.3	Last member's foot on top step from landing 4a.

4.2	First member's foot on floor 3.
4.1	Last member's foot on floor 3.
3.8	First member's foot on top step from floor 3.
3.7	Last member's foot on top step from floor 3.
3.6	First member's foot on landing 3a.
3.5	Last member's foot on landing 3a.
3.4	First member's foot on top step from landing 3a.
3.3	Last member's foot on top step from landing 3a.
3.2	First member's foot on floor 2.
3.1	Last member's foot on floor 2.
2.8	First member's foot on top step from floor 2.
2.7	Last member's foot on top step from floor 2.
2.6	First member's foot on landing 2a.
2.5	Last member's foot on landing 2a.
2.4	First member's foot on top step from landing 2a.
2.3	Last member's foot on top step from landing 2a.
2.2	First member's foot on floor 1.
2.1	Last member's foot on floor 1.
1.8	First member's foot on top step from floor 1.
1.7	Last member's foot on top step from floor 1.
1.6	First member's foot on landing 1a.
1.5	Last member's foot on landing 1a.
1.4	First member's foot on top step from landing 1a.
1.3	Last member's foot on top step from landing 1a.
1.2	First member's foot on floor 0.
1.1	Last member's foot on floor 0.
0.4	First member touches exit door.
0.3	First member crosses threshold of exit door.
0.2	Last member crosses threshold of exit door.
0.1	First member reaches the outside finishing line.
ST1/ST1, ST2/ST2 etc	The device team has stopped for more than 2 seconds (two times extracted: start time – end time)
S	During stop, the handlers swapped position
Wh	During stop, the handlers wiped their hands
Wd	During stop, the handlers wiped the device handles
R	During stop, the handlers readjusted device
D	The handlers dropped the handles of device, causing them to stop and pick them up.

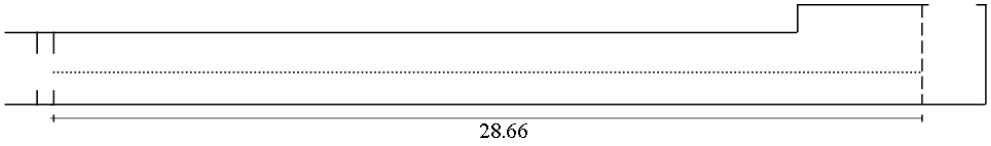
E. Central path measurements, per area.



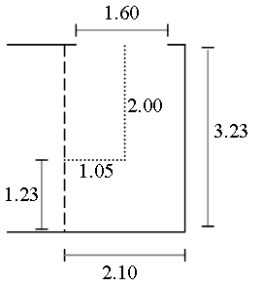
(i) Area 1: 6.535m

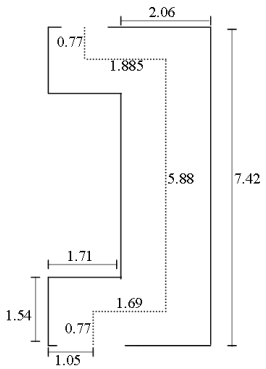


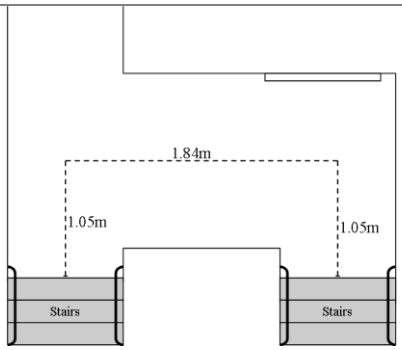
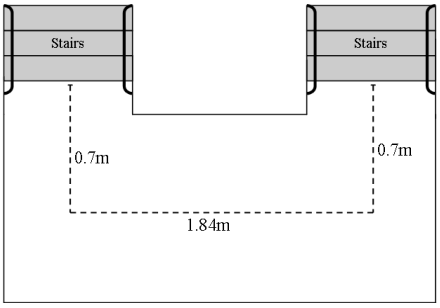
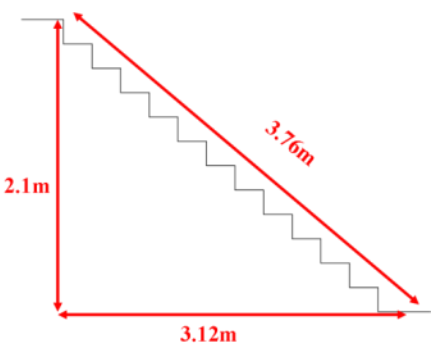
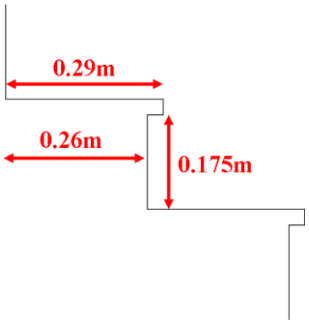
(ii) Area 2: 10.85m



(iii) Area 3: 28.66m





(iv) Area 4: 3.05m	(v) Area 5: 10.995m
	
(vi) Main landings: 3.94m	**(vii) Sub-landings: 3.24m**
	
(viii) Stair diagonal: 3.76m	

F. Participant Questionnaires

Universitair Ziekenhuis Gent

the UNIVERSITY of GREENWICH

Questionnaire for Evacuee PRM

Correct Mark: ☐ Trial Number:

☐ **Wednesday** 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐

9☐ 10☐ 11☐ 12☐ 13☐ 14☐ 15☐ 16☐

☐ **Thursday** 17☐ 18☐ 19☐ 20☐ 21☐ 22☐ 23☐ 24☐

25☐ 26☐ 27☐ 28☐ 29☐ 30☐ 31☐ 32☐

Team: ☐ **F1** ☐ **F2** ☐ **M1** ☐ **M2**

Device: ☐ **STRETCHER** ☐ **CARRY-CHAIR**

☐ **EVAC-CHAIR** ☐ **SLIDE SHEET / MATTRESS**

Group passing on stairs: ☐ **WITH GROUP** ☐ **WITHOUT GROUP**

Gender: ☐ **Male** ☐ **Female** Approximate weight (kg) : .....

Transfer to device.

1. **Did you experience any discomfort during transfer from the wheelchair to the evacuation device?**

Considerable discomfort ↔ **No discomfort**

1☐ 2☐ 3☐ 4☐ 5☐

2. **Did you experience any anxiety during transfer from the wheelchair to the evacuation device?**

Considerable anxiety ↔ **No anxiety**

1☐ 2☐ 3☐ 4☐ 5☐

3. **Once transferred to the device, did you feel secure?**

Very insecure	↔	Very secure
1☐ 2☐ 3☐ 4☐ 5☐		

4. **Once transferred to the device, did you feel safe?**

Very unsafe	↔	Very safe
1☐ 2☐ 3☐ 4☐ 5☐		

Travel down the stairs.

5. **Did you experience any discomfort while being evacuated down the stairs?**

Considerable discomfort	↔	No discomfort
1☐ 2☐ 3☐ 4☐ 5☐		

6. **Did you experience any anxiety while being evacuated down the stairs?**

Considerable anxiety	↔	No anxiety
1☐ 2☐ 3☐ 4☐ 5☐		

If you answered 5 (No anxiety) please go to Question 8.

7. **My anxiety was due to a concern (please select only one option) :**

☐ **Primarily for my own well being**

☐ **Primarily for the well being of the evacuation team**

☐ **For both the well being of myself and the evacuation team**

8. **Did you feel secure while being evacuated down the stairs?**

Very insecure	↔	Very secure
1☐ 2☐ 3☐ 4☐ 5☐		

9. **Did you feel safe while being evacuated down the stairs?**

Very unsafe	↔	Very safe
1☐ 2☐ 3☐ 4☐ 5☐		

If your team did not stop to rest while evacuating you down the stairs, please go to Question 15.

Rest Periods.

10. **Did you experience any discomfort while the team stopped to rest?**

Considerable Discomfort	↔	No discomfort
1☐ 2☐ 3☐ 4☐ 5☐		

11. **Did you experience any anxiety while the team stopped to rest?**

Considerable anxiety	↔	No anxiety
1☐ 2☐ 3☐ 4☐ 5☐		

If you answered 5 (No anxiety) please go to Question 13.

12. My anxiety was due to a concern (please select only one option) :

- ☐ **Primarily for my own well being**
- ☐ **Primarily for the well being of the evacuation team**
- ☐ **For both the well being of myself and the evacuation team**

13. Did you feel secure while the team stopped to rest?

Very insecure		↔		**Very secure**
1☐	2☐	3☐	4☐	5☐

14. Did you feel safe while the team stopped to rest?

Very unsafe		↔		**Very safe**
1☐	2☐	3☐	4☐	5☐

If your evacuation team was not overtaken by other stair users please go to Question 20.

Being passed by others.

15. Did you experience any discomfort while being passed by others?

Considerable discomfort		↔		**No discomfort**
1☐	2☐	3☐	4☐	5☐

16. Did you experience any anxiety while being passed by others?

Considerable anxiety		↔		**No anxiety**
1☐	2☐	3☐	4☐	5☐

If you answered 5 (No anxiety) please go to Question 18.

17. My anxiety was due to a concern (please select only one option) :

- ☐ **Primarily for my own well being**
- ☐ **Primarily for the well being of the evacuation team**
- ☐ **Primarily for the well being of the people passing the evacuation team**
- ☐ **For both the well being of myself and the evacuation team**
- ☐ **For the well being of everyone on the stairs.**

18. Did you feel secure while being passed by others?

Very insecure		↔		**Very secure**
1☐	2☐	3☐	4☐	5☐

19. Did you feel safe while the evacuation team was being passed by others?

Very unsafe	↔			Very safe
1☐	2☐	3☐	4☐	5☐

Travel on the flat floor.

20. Did you experience any discomfort while being evacuated along the floor?

Considerable discomfort	↔			No discomfort
1☐	2☐	3☐	4☐	5☐

21. Did you experience any anxiety while being evacuated along the floor?

Considerable anxiety			↔	No anxiety
1☐	2☐	3☐	4☐	5☐

If you answered 5 (No anxiety) please go to question 23.

22. My anxiety was due to a concern (please select only one option) :

☐ **Primarily for my own well being**

☐ **Primarily for the well being of the evacuation team**

☐ **For both myself and the evacuation team**

23. Did you feel secure while being evacuated along the floor?

Very insecure	↔			Very secure
1☐	2☐	3☐	4☐	5☐

24. Did you feel safe while being evacuated along the floor?

Very unsafe	↔			Very safe
1☐	2☐	3☐	4☐	5☐

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25. Did the Handling Team try to make you feel at ease; before transferring to the Device as well as before descending the stairs.

Not at all	↔			Several times
1☐	2☐	3☐	4☐	5☐

Own Remarks Evacuee PRM;

.....

.....

.....

.....**If needed use backside of this form too.**

Thank you for completing this form!

Please hand ALL 4 pages to the Research Assistant immediate after every trial.

G. Raw data from last foot measurements

Trial 1: Reference|Time (seconds)				Trial 2: Reference|Time (seconds)			
Ref#	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*
28	695.76	7.5	948.36	28	3.92	7.5	246.48
27	702.88	7.4	948.96	27	8.76	7.4	247.12
26	769.8	7.3	953.48	26	82.68	7.3	252.84
25	771.4	7.2	955.04	25	84.36	7.2	254.8
24	774.92	7.1	958.52	24	86.96	7.1	257.16
23	777.68	6.8	960.12	23	89.2	6.8	258.8
22	780.4	6.7	964.04	22	92.04	6.7	276.64
21	782.36	6.6	966.16	21	94.4	6.6	278.48
20	788	6.5	969	20	100.16	6.5	282.88
19	788.6	6.4	969.88	19	100.8	6.4	283.96
18	791.12	6.3	973.76	18	102.92	6.3	289.44
17	816.08	6.2	975.32	17	125.16	6.2	291.2
16	817.68	6.1	978.88	16	126.48	6.1	294.64
15	824.8	5.8	980.44	15	132.24	5.8	296.2
14	831.44	5.7	984.72	14	138.16	5.7	301.6
13	831.92	5.6	986.64	13	139.32	5.6	303.84
12	835.12	5.5	989.88	12	141.64	5.5	307.68
11.8	838.88	5.4	990.72	11.8	144.88	5.4	308.04
11.7	844.72	5.3	994.72	11.7	150.76	5.3	313.8
11.6	847	5.2	996.84	11.6	152.68	5.2	315.48
11.5	850.44	5.1	999.44	11.5	155.56	5.1	318.72
11.4	851.28	4.8	1000.68	11.4	157.28	4.8	320.04
11.3	856.28	4.7	1004.48	11.3	162.6	4.7	325.72
11.2	858.4	4.6	1006.64	11.2	164.48	4.6	327.44
11.1	861.84	4.5	1009.48	11.1	167.24	4.5	331
10.8	862.92	4.4	1010.44	10.8	169.28	4.4	331.76
10.7	867.52	4.3	1014.64	10.7	174.2	4.3	337.68
10.6	869.6	4.2	1016.68	10.6	174.92	4.2	339.56
10.5	873.24	4.1	1019.4	10.5	178.96	4.1	342.96
10.4	873.92	3.8	1020.48	10.4	180.12	3.8	344.4
10.3	878.72	3.7	1024.84	10.3	185	3.7	349.52
10.2	880.84	3.6	1025.88	10.2	185.68	3.6	350.64
10.1	884	3.5	1028.64	10.1	189.28	3.5	353.8
9.8	885.8	3.4	1030.2	9.8	191.04	3.4	354.68
9.7	889.92	3.3	1034.2	9.7	196.72	3.3	360.16
9.6	891.28	3.2	1035.2	9.6	198.12	3.2	361.08
9.5	895.52	3.1	1037.72	9.5	201.36	3.1	364.04
9.4	896.48	2.8	1039.28	9.4	202.52	2.8	365.28
9.3	910.8	2.7	1043.32	9.3	207.84	2.7	371
9.2	913.04	2.6	1045.24	9.2	209.84	2.6	372.84
9.1	916.28	2.5	1047.92	9.1	212.28	2.5	376.6
8.8	917.4	2.4	1049	8.8	213.32	2.4	377.4
8.7	921.56	2.3	1053.28	8.7	218.96	2.3	388.8
8.6	923.56	2.2	1054.88	8.6	220.88	2.2	390.64
8.5	926.96	2.1	1057.72	8.5	223.72	2.1	394.6
8.4	927.8	1.8	1059.52	8.4	224.76	1.8	396.04
8.3	932.4	1.7	1070.76	8.3	230.2	1.7	400.44
8.2	934.28	1.6	1072.72	8.2	232.12	1.6	402.16
8.1	937.68	1.5	1075.68	8.1	234.6	1.5	405.36
7.8	938.76	1.4	1076.68	7.8	236.04	1.4	406.44
7.7	943.04	1.3	1080.44	7.7	241.64	1.3	411.56
7.6	945.24	1.2	1082.08	7.6	243.64	1.2	413.28
		1.1	1084.72			1.1	415.92

Trial 3: Reference|Time (seconds)				Trial 4: Reference|Time (seconds)			
Ref#	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*
28	4.6	7.5	303	28	234.76	7.5	586.48
27	9.08	7.4	304.52	27	239.32	7.4	588.32
26	81.64	7.3	310.56	26	359.12	7.3	595.36
25	83.6	7.2	312.76	25	361.16	7.2	597.36
24	86.64	7.1	315.88	24	364	7.1	600.4
23	89.44	6.8	317.44	23	366.96	6.8	603.2
22	93.12	6.7	323.28	22	371	6.7	610.32
21	94.48	6.6	325.16	21	372.76	6.6	612.24
20	100.08	6.5	328.96	20	378.92	6.5	615.72
19	101.08	6.4	330.2	19	379.52	6.4	618.04
18	102.68	6.3	335.92	18	381.68	6.3	640.44
17	125.8	6.2	338.28	17	407.72	6.2	642.88
16	128.72	6.1	341.2	16	409.52	6.1	646.64
15	134.56	5.8	343.24	15	417.56	5.8	649.92
14	142.36	5.7	348.52	14	425.8	5.7	657.48
13	143.48	5.6	350.56	13	426.84	5.6	659.56
12	146.04	5.5	353.68	12	429.56	5.5	663.92
11.8	150.12	5.4	355.4	11.8	433.32	5.4	665.68
11.7	156.88	5.3	361.44	11.7	441.12	5.3	674.2
11.6	159	5.2	363.28	11.6	443.2	5.2	676.32
11.5	162.96	5.1	366.08	11.5	446.8	5.1	680.24
11.4	165.28	4.8	368	11.4	448.76	4.8	682.04
11.3	172.44	4.7	380	11.3	457.08	4.7	701.32
11.2	174.64	4.6	382	11.2	459.56	4.6	703.4
11.1	178.24	4.5	385.04	11.1	463.88	4.5	707.4
10.8	180.96	4.4	386.2	10.8	465.92	4.4	708.88
10.7	188.44	4.3	392.24	10.7	473.76	4.3	717.24
10.6	190.44	4.2	394.44	10.6	475.76	4.2	719.08
10.5	195.2	4.1	397.44	10.5	481.12	4.1	723.08
10.4	197.2	3.8	399.08	10.4	482	3.8	724.76
10.3	204.16	3.7	405.32	10.3	489.68	3.7	734.32
10.2	206	3.6	406.44	10.2	492.16	3.6	735.36
10.1	209.96	3.5	409.84	10.1	496.24	3.5	739.72
9.8	212.96	3.4	412.04	9.8	498.28	3.4	742.28
9.7	226.28	3.3	418.16	9.7	505.44	3.3	762.92
9.6	228.28	3.2	419.36	9.6	507.84	3.2	764.04
9.5	232.16	3.1	422.04	9.5	512	3.1	766.8
9.4	234.36	2.8	424.8	9.4	513.8	2.8	769.68
9.3	240.76	2.7	441.56	9.3	535	2.7	775.84
9.2	242.92	2.6	443.48	9.2	537.2	2.6	777.68
9.1	246.48	2.5	447	9.1	541.48	2.5	781.16
8.8	249.72	2.4	448.92	8.8	543.96	2.4	783.2
8.7	256.28	2.3	454.88	8.7	551.04	2.3	790.56
8.6	258.24	2.2	456.72	8.6	553.16	2.2	792.84
8.5	262.28	2.1	459.68	8.5	557.04	2.1	796.6
8.4	264.4	1.8	462.4	8.4	559.36	1.8	799.08
8.3	271.44	1.7	467.64	8.3	566.16	1.7	817.72
8.2	273.44	1.6	469.48	8.2	568.28	1.6	819.44
8.1	276.48	1.5	473.28	8.1	571.8	1.5	822.72
7.8	279.4	1.4	475.16	7.8	574.64	1.4	824.56
7.7	296.96	1.3	481.04	7.7	580.76	1.3	831.08
7.6	298.92	1.2	482.8	7.6	582.92	1.2	833.24
		1.1	485.6			1.1	837.12

Trial 5: Reference|Time (seconds)				Trial 6: Reference|Time (seconds)			
Ref#	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*
28	285.88	7.5	448.64	28	404.52	7.5	580.72
27	289.24	7.4	450.52	27	409.44	7.4	582.84
26	320.48	7.3	452.12	26	441.88	7.3	585.28
25	325.6	7.2	455.24	25	446.68	7.2	588.92
24	326.88	7.1	457.04	24	447.6	7.1	590.44
23	AO	6.8	459.12	23	AO	6.8	592.6
22	329.88	6.7	460.84	22	451.52	6.7	594.4
21	330.84	6.6	463.88	21	452.64	6.6	597.52
20	AO	6.5	465.6	20	AO	6.5	599.36
19	336.52	6.4	467.44	19	459.44	6.4	601.56
18	337.6	6.3	469.08	18	460.64	6.3	603.48
17	AO	6.2	471.76	17	AO	6.2	607.12
16	359.24	6.1	473.64	16	479.28	6.1	608.48
15	360.32	5.8	475.76	15	480.64	5.8	610.48
14	AO	5.7	477.24	14	AO	5.7	612.12
13	365.52	5.6	480.44	13	486.08	5.6	615.8
12	367	5.5	482	12	487.16	5.5	617.36
11.8	375.16	5.4	483.8	11.8	496.4	5.4	619.24
11.7	377.84	5.3	485.28	11.7	498.4	5.3	621.04
11.6	381.16	5.2	488.52	11.6	503.08	5.2	624.24
11.5	382.28	5.1	490.08	11.5	504.52	5.1	626.08
11.4	384.08	4.8	492.04	11.4	506.68	4.8	628.04
11.3	385.84	4.7	493.68	11.3	508.64	4.7	630
11.2	388.68	4.6	497.12	11.2	511.84	4.6	633.96
11.1	390.48	4.5	498.48	11.1	514.72	4.5	635.52
10.8	392.4	4.4	500.52	10.8	516.96	4.4	637.24
10.7	394.08	4.3	502.12	10.7	519	4.3	639.68
10.6	397.2	4.2	505.2	10.6	522.8	4.2	643.08
10.5	398.88	4.1	506.76	10.5	524.12	4.1	645.16
10.4	400.92	3.8	508.64	10.4	526.2	3.8	647.56
10.3	402.64	3.7	510.12	10.3	528.24	3.7	649.28
10.2	405.4	3.6	512.84	10.2	531.92	3.6	652.72
10.1	407.2	3.5	514.2	10.1	533.92	3.5	654
9.8	409.12	3.4	516.44	9.8	535.88	3.4	656.32
9.7	411	3.3	518	9.7	538	3.3	658.24
9.6	414.52	3.2	520.44	9.6	541.88	3.2	661.2
9.5	415.68	3.1	521.92	9.5	543.6	3.1	662.52
9.4	417.44	2.8	524.2	9.4	545.56	2.8	665.04
9.3	418.96	2.7	525.96	9.3	547.44	2.7	667.2
9.2	421.4	2.6	529.52	9.2	550.76	2.6	670.6
9.1	423.32	2.5	530.84	9.1	552.24	2.5	672.52
8.8	425.24	2.4	532.92	8.8	554.4	2.4	674.52
8.7	426.8	2.3	534.48	8.7	556.4	2.3	676.44
8.6	430.12	2.2	537.72	8.6	559.8	2.2	679.6
8.5	431.48	2.1	539.16	8.5	561.64	2.1	681
8.4	433.32	1.8	541.32	8.4	563.64	1.8	683.72
8.3	435	1.7	542.68	8.3	565.72	1.7	685.76
8.2	438.16	1.6	545.76	8.2	569.2	1.6	689.52
8.1	439.72	1.5	547.12	8.1	571.12	1.5	691.48
7.8	441.92	1.4	549.4	7.8	573.12	1.4	693.44
7.7	443.64	1.3	551.16	7.7	575.36	1.3	695.4
7.6	447	1.2	554.68	7.6	578.72	1.2	700.28
		1.1	556.36			1.1	701.72

Trial 7: Reference|Time (seconds)				Trial 8: Reference|Time (seconds)			
Ref#	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*
28	287.6	7.5	481.96	28	179.24	7.5	349.48
27	292.72	7.4	484.36	27	182.88	7.4	352.12
26	334.4	7.3	486.08	26	212.72	7.3	353.44
25	337.8	7.2	490.2	25	216.84	7.2	356.6
24	339	7.1	491.48	24	217.8	7.1	357.96
23	AO	6.8	493.84	23	AO	6.8	361.08
22	343.32	6.7	495.44	22	222.16	6.7	362.52
21	344.56	6.6	499.52	21	223.2	6.6	365.96
20	AO	6.5	501	20	AO	6.5	367.16
19	351.4	6.4	503.12	19	229.16	6.4	369.52
18	352.44	6.3	504.76	18	230.28	6.3	370.8
17	AO	6.2	508.44	17	AO	6.2	374.36
16	373.48	6.1	509.72	16	253.08	6.1	375.4
15	375.04	5.8	512.04	15	254.32	5.8	377.96
14	AO	5.7	513.44	14	AO	5.7	379.16
13	381.52	5.6	517.8	13	259.96	5.6	382.96
12	382.72	5.5	518.8	12	261.08	5.5	383.96
11.8	391.24	5.4	520.64	11.8	271.44	5.4	386.08
11.7	394.48	5.3	522	11.7	273.52	5.3	387.32
11.6	399.48	5.2	525.76	11.6	277.4	5.2	390.28
11.5	402.12	5.1	526.84	11.5	278.48	5.1	391.64
11.4	404.64	4.8	528.96	11.4	280.64	4.8	393.96
11.3	406.96	4.7	530.36	11.3	282.4	4.7	395.32
11.2	410.92	4.6	534.56	11.2	285.6	4.6	398.52
11.1	413.04	4.5	535.44	11.1	286.72	4.5	399.56
10.8	416	4.4	537.24	10.8	289.56	4.4	401.8
10.7	418.2	4.3	538.6	10.7	291.32	4.3	403.24
10.6	422.32	4.2	541.92	10.6	294.76	4.2	405.96
10.5	423.56	4.1	542.96	10.5	295.92	4.1	407.52
10.4	425.92	3.8	545.04	10.4	298.68	3.8	409.92
10.3	427.96	3.7	546.52	10.3	300.28	3.7	411.24
10.2	431.84	3.6	548.92	10.2	303.52	3.6	413.64
10.1	433.76	3.5	550.48	10.1	304.96	3.5	415.36
9.8	436.16	3.4	552.8	9.8	307.8	3.4	417.24
9.7	438.08	3.3	554.2	9.7	309.36	3.3	418.68
9.6	441.96	3.2	557.08	9.6	312.72	3.2	421
9.5	443.6	3.1	558.12	9.5	314.12	3.1	422.32
9.4	446.72	2.8	560.52	9.4	316.8	2.8	425
9.3	448.64	2.7	561.96	9.3	318.16	2.7	426.48
9.2	452.6	2.6	565.76	9.2	321.48	2.6	429.48
9.1	453.84	2.5	567.12	9.1	322.92	2.5	430.8
8.8	456.4	2.4	569.12	8.8	325.4	2.4	433.48
8.7	457.96	2.3	570.72	8.7	326.88	2.3	435.08
8.6	461.96	2.2	574.36	8.6	330.28	2.2	437.76
8.5	463.4	2.1	575.44	8.5	331.72	2.1	439.6
8.4	465.8	1.8	577.68	8.4	334.44	1.8	442.04
8.3	467.08	1.7	579.04	8.3	335.92	1.7	443.44
8.2	470.84	1.6	582.8	8.2	339.16	1.6	446.48
8.1	472.28	1.5	583.96	8.1	340.6	1.5	447.76
7.8	474.76	1.4	586.04	7.8	343.28	1.4	453.76
7.7	476.2	1.3	587.64	7.7	344.76	1.3	455.08
7.6	480.64	1.2	591.64	7.6	348.36	1.2	458.48
		1.1	592.88			1.1	459.24

Trial 17: Reference|Time (seconds)				Trial 18: Reference|Time (seconds)			
Ref#	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*
28	139.2	7.5	382.8	28	269.28	7.5	462.68
27	143.92	7.4	385.6	27	272.36	7.4	464.88
26	176.52	7.3	389.4	26	304	7.3	467.92
25	179.92	7.2	395.24	25	307.28	7.2	472.24
24	181.28	7.1	397.32	24	308.04	7.1	474.16
23	AO	6.8	400.16	23	AO	6.8	476.32
22	183.96	6.7	403.72	22	311.24	6.7	479.8
21	184.56	6.6	409.68	21	312.32	6.6	484.24
20	AO	6.5	411.68	20	AO	6.5	486.44
19	191.12	6.4	413.96	19	317.32	6.4	488.36
18	192.12	6.3	417.44	18	318.08	6.3	492.68
17	AO	6.2	423.52	17	AO	6.2	496.84
16	215.84	6.1	426.28	16	336.12	6.1	499.36
15	217	5.8	437.24	15	337.52	5.8	501.48
14	AO	5.7	442.92	14	AO	5.7	504.68
13	221.68	5.6	449	13	341.68	5.6	508.92
12	222.72	5.5	451.44	12	342.68	5.5	510.92
11.8	228	5.4	464.76	11.8	350.44	5.4	512.84
11.7	237.76	5.3	470.4	11.7	355	5.3	516.04
11.6	242.4	5.2	475.88	11.6	359.36	5.2	520.28
11.5	245.36	5.1	478.6	11.5	361.56	5.1	522.28
11.4	248	4.8	489.32	11.4	364.92	4.8	524.52
11.3	253.64	4.7	491.36	11.3	368.2	4.7	528.2
11.2	259.2	4.6	496.32	11.2	371.88	4.6	532.12
11.1	261.52	4.5	498.72	11.1	374.24	4.5	534.48
10.8	264.4	4.4	502.32	10.8	376.6	4.4	539.8
10.7	269.24	4.3	505.76	10.7	379.28	4.3	542.24
10.6	274.24	4.2	510.96	10.6	383.24	4.2	545.4
10.5	277.04	4.1	513.2	10.5	385.56	4.1	547.44
10.4	280.04	3.8	526.8	10.4	387.92	3.8	549.8
10.3	285.12	3.7	532.4	10.3	390.72	3.7	552.28
10.2	290.04	3.6	535.64	10.2	394.96	3.6	555.2
10.1	292.44	3.5	538.2	10.1	396.84	3.5	557.12
9.8	296.4	3.4	542.4	9.8	400	3.4	559.8
9.7	300.8	3.3	545.4	9.7	402.72	3.3	562.72
9.6	306.24	3.2	549.76	9.6	407.04	3.2	565.28
9.5	308.72	3.1	552.64	9.5	408.96	3.1	567.08
9.4	311.68	2.8	556.6	9.4	411.72	2.8	570.64
9.3	317.64	2.7	578.48	9.3	414.36	2.7	573.8
9.2	323.44	2.6	583.24	9.2	418.68	2.6	577.44
9.1	326.84	2.5	585.52	9.1	420.92	2.5	579.44
8.8	338.6	2.4	588.28	8.8	423.4	2.4	581.56
8.7	344.32	2.3	591.44	8.7	426.4	2.3	584.08
8.6	350.64	2.2	596.28	8.6	430.72	2.2	587.72
8.5	353.28	2.1	599.16	8.5	432.56	2.1	590.4
8.4	355.68	1.8	609.52	8.4	434.8	1.8	592.92
8.3	359.28	1.7	614.04	8.3	437.44	1.7	595.88
8.2	362.88	1.6	618.24	8.2	441.88	1.6	599.56
8.1	368.2	1.5	620.56	8.1	443.88	1.5	602.2
7.8	370.88	1.4	622.72	7.8	453.4	1.4	604.6
7.7	374.28	1.3	625.48	7.7	456.4	1.3	607.48
7.6	380.36	1.2	630.28	7.6	460.36	1.2	611.12
		1.1	631.96			1.1	613.8

Trial 19: Reference|Time (seconds)				Trial 20: Reference|Time (seconds)			
Ref#	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*
28	436.8	7.5	628.44	28	375.56	7.5	586
27	440.72	7.4	630.84	27	378.48	7.4	588.48
26	490.88	7.3	632.64	26	428.88	7.3	591.16
25	494.92	7.2	635.32	25	432.64	7.2	594.92
24	495.52	7.1	636.76	24	433.36	7.1	596.68
23	AO	6.8	640.56	23	AO	6.8	600.44
22	499.2	6.7	642.76	22	436.56	6.7	602.52
21	500.52	6.6	645.52	21	437.68	6.6	606.44
20	AO	6.5	647.36	20	AO	6.5	608.44
19	506.04	6.4	652.08	19	443.32	6.4	611.8
18	507.48	6.3	654.56	18	444.28	6.3	614.28
17	AO	6.2	657.48	17	AO	6.2	617.8
16	529.48	6.1	659.04	16	466.72	6.1	619.64
15	531.16	5.8	670.64	15	468	5.8	623.12
14	AO	5.7	672.24	14	AO	5.7	625.56
13	536.24	5.6	674.8	13	472.36	5.6	629
12	537.08	5.5	676.36	12	473.48	5.5	630.76
11.8	543.72	5.4	678.88	11.8	484.76	5.4	634.04
11.7	548.72	5.3	680.96	11.7	486.72	5.3	653.96
11.6	551.52	5.2	683.8	11.6	489.8	5.2	657.48
11.5	553	5.1	685.2	11.5	491.2	5.1	659.08
11.4	554.68	4.8	687.76	11.4	493.92	4.8	662.04
11.3	556.84	4.7	689.44	11.3	496.44	4.7	664.24
11.2	559.32	4.6	692.2	11.2	499.88	4.6	668.2
11.1	560.84	4.5	694.12	11.1	501.36	4.5	669.76
10.8	563.32	4.4	696.56	10.8	504.24	4.4	672.6
10.7	565.16	4.3	698.76	10.7	506.56	4.3	675.4
10.6	567.96	4.2	701.44	10.6	510.08	4.2	678.92
10.5	569.32	4.1	702.8	10.5	511.8	4.1	680.56
10.4	571.68	3.8	712.36	10.4	513.56	3.8	683.68
10.3	573.6	3.7	713.96	10.3	517.08	3.7	685.84
10.2	576.56	3.6	715.48	10.2	520.56	3.6	688.44
10.1	577.8	3.5	717.16	10.1	522.32	3.5	690
9.8	580	3.4	719.6	9.8	525.48	3.4	692.88
9.7	581.92	3.3	721.72	9.7	527.72	3.3	711.28
9.6	584.84	3.2	723.56	9.6	531.44	3.2	713.6
9.5	586.2	3.1	724.52	9.5	533.52	3.1	715.16
9.4	588.52	2.8	727.96	9.4	536.08	2.8	719.28
9.3	590.64	2.7	729.92	9.3	538.64	2.7	721.24
9.2	593.64	2.6	732.6	9.2	542.16	2.6	724.84
9.1	595.16	2.5	733.4	9.1	543.64	2.5	726.76
8.8	605.64	2.4	736.92	8.8	545.96	2.4	730.08
8.7	607.6	2.3	738.84	8.7	548.44	2.3	732.44
8.6	610.12	2.2	741.52	8.6	552.04	2.2	736
8.5	611.6	2.1	742.88	8.5	553.92	2.1	737.92
8.4	613.76	1.8	745.76	8.4	556.84	1.8	741.04
8.3	616.28	1.7	747.76	8.3	559.32	1.7	743.36
8.2	618.24	1.6	750.64	8.2	563.04	1.6	746.2
8.1	619.76	1.5	752.28	8.1	564.56	1.5	748.2
7.8	622.72	1.4	754.84	7.8	567.12	1.4	751.24
7.7	624.6	1.3	757.24	7.7	580.16	1.3	753.72
7.6	626.24	1.2	760.16	7.6	583.84	1.2	756.92
		1.1	761.4			1.1	760.64

Trial 21: Reference|Time (seconds)				Trial 22: Reference|Time (seconds)			
Ref#	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*
28	230.32	7.5	429.12	28	278.08	7.5	488.84
27	237.36	7.4	431.08	27	284.12	7.4	490.6
26	288.72	7.3	434.96	26	343.84	7.3	494.64
25	290.72	7.2	436.2	25	345.64	7.2	495.08
24	292.8	7.1	438.48	24	348.04	7.1	498.56
23	295.88	6.8	439.92	23	350.24	6.8	500.16
22	300.72	6.7	442.76	22	359.44	6.7	503.84
21	302.28	6.6	444	21	360.64	6.6	504.6
20	306.8	6.5	446.64	20	364.04	6.5	507.08
19	307.68	6.4	447.76	19	364.48	6.4	508.92
18	309.24	6.3	450.6	18	369.6	6.3	512.84
17	331.84	6.2	451.76	17	387.2	6.2	513.96
16	338.2	6.1	453.84	16	389.92	6.1	516.84
15	340.72	5.8	456	15	393.76	5.8	518.76
14	345.68	5.7	458.64	14	397.36	5.7	524.84
13	346.4	5.6	459.92	13	398.56	5.6	525.56
12	348.28	5.5	461.96	12	401.56	5.5	528.4
11.8	351.04	5.4	463.4	11.8	405.56	5.4	529.96
11.7	356.32	5.3	466.04	11.7	409.96	5.3	538.04
11.6	356.8	5.2	467.72	11.6	411.2	5.2	538.48
11.5	359.44	5.1	470.28	11.5	414.36	5.1	540.92
11.4	360.96	4.8	472.08	11.4	416.32	4.8	543.16
11.3	363.88	4.7	477.48	11.3	420.84	4.7	546.72
11.2	364.76	4.6	478.72	11.2	421.64	4.6	547.16
11.1	367.28	4.5	481.32	11.1	424.48	4.5	549.8
10.8	370.2	4.4	482.6	10.8	426.48	4.4	551.28
10.7	374.76	4.3	485.2	10.7	430.52	4.3	555.84
10.6	375.8	4.2	486.56	10.6	431.28	4.2	556.88
10.5	377.76	4.1	488.32	10.5	434.28	4.1	558.68
10.4	379.52	3.8	490.32	10.4	436.2	3.8	560.56
10.3	381.84	3.7	493.76	10.3	439.84	3.7	565.56
10.2	382.6	3.6	494.92	10.2	441	3.6	565.84
10.1	384.72	3.5	496.32	10.1	443.6	3.5	568.2
9.8	386.52	3.4	498.36	9.8	445.04	3.4	570.12
9.7	390	3.3	500.88	9.7	448.48	3.3	573.36
9.6	391.4	3.2	501.6	9.6	449.6	3.2	573.44
9.5	395.32	3.1	503.68	9.5	452.52	3.1	575.84
9.4	396.4	2.8	505.4	9.4	454.08	2.8	578.08
9.3	400.16	2.7	515.6	9.3	458.08	2.7	582.08
9.2	401.4	2.6	517.04	9.2	458.88	2.6	582.76
9.1	404.24	2.5	519	9.1	461.48	2.5	584.88
8.8	406.76	2.4	520.32	8.8	463.32	2.4	586.56
8.7	410	2.3	522.88	8.7	467.64	2.3	590.48
8.6	410.76	2.2	523.88	8.6	467.92	2.2	591.36
8.5	413.12	2.1	525.92	8.5	470.88	2.1	593.52
8.4	414.36	1.8	527.52	8.4	472.52	1.8	595.8
8.3	417	1.7	530.28	8.3	477.28	1.7	600.36
8.2	418.16	1.6	531.32	8.2	477.96	1.6	601.24
8.1	421.16	1.5	533.68	8.1	480	1.5	603.4
7.8	422.64	1.4	535.68	7.8	481.56	1.4	605.96
7.7	425.6	1.3	538.44	7.7	485.64	1.3	609.52
7.6	426.6	1.2	539.6	7.6	486.32	1.2	609.96
		1.1	541.16			1.1	612.52

Trial 23: Reference|Time (seconds)				Trial 24: Reference|Time (seconds)			
Ref#	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*	*Ref#*	*Time (s)*
28	197.28	7.5	511.8	28	286.16	7.5	622.64
27	207.96	7.4	514	27	295.96	7.4	625.52
26	291.88	7.3	520.6	26	362.96	7.3	630.8
25	293.96	7.2	521.84	25	365.72	7.2	632.08
24	295.96	7.1	524	24	369.24	7.1	635.96
23	299.08	6.8	526.84	23	372.6	6.8	638.32
22	304.48	6.7	532.4	22	376.56	6.7	648.04
21	305.68	6.6	533.76	21	378.56	6.6	649.04
20	310.96	6.5	536.44	20	384.28	6.5	652.68
19	315.52	6.4	538.72	19	385.36	6.4	656.36
18	317.28	6.3	545.64	18	388	6.3	665.6
17	342.24	6.2	547.24	17	427.88	6.2	666.64
16	347.92	6.1	549.64	16	445.64	6.1	670.28
15	351.96	5.8	551.92	15	449.6	5.8	673.76
14	358.28	5.7	557.4	14	456.56	5.7	679.28
13	359.4	5.6	558.92	13	457.36	5.6	680.52
12	363.16	5.5	561.48	12	462.32	5.5	684.36
11.8	372.08	5.4	564	11.8	472	5.4	687.12
11.7	382.64	5.3	569.48	11.7	488	5.3	692.04
11.6	383.12	5.2	570.88	11.6	488.84	5.2	692.8
11.5	388.68	5.1	573.4	11.5	493.36	5.1	696.04
11.4	391.2	4.8	575.6	11.4	499.88	4.8	698.84
11.3	397.36	4.7	581.16	11.3	510.68	4.7	704.6
11.2	398.36	4.6	582.56	11.2	512	4.6	705.76
11.1	402.88	4.5	585.36	11.1	515.72	4.5	709.08
10.8	406	4.4	587.96	10.8	520.4	4.4	711.96
10.7	415.4	4.3	592.52	10.7	527.68	4.3	716.08
10.6	416.08	4.2	594.12	10.6	528.4	4.2	717
10.5	421.72	4.1	597.08	10.5	533.28	4.1	720
10.4	423.72	3.8	598.8	10.4	535.56	3.8	723.16
10.3	432.16	3.7	603.96	10.3	540.44	3.7	728.4
10.2	434.08	3.6	604.28	10.2	541.08	3.6	728.6
10.1	438.92	3.5	607.96	10.1	544.72	3.5	732.32
9.8	440.56	3.4	610.44	9.8	547.56	3.4	735.64
9.7	447.8	3.3	615.6	9.7	558.6	3.3	740.24
9.6	448.96	3.2	616.36	9.6	559	3.2	740.52
9.5	453.6	3.1	619	9.5	563.12	3.1	744.12
9.4	455.48	2.8	622.8	9.4	565.72	2.8	747.56
9.3	463.76	2.7	628.64	9.3	571.76	2.7	754.72
9.2	465.16	2.6	629.64	9.2	572.68	2.6	755.16
9.1	468.48	2.5	632.64	9.1	576.32	2.5	758.48
8.8	471.24	2.4	635.44	8.8	579.64	2.4	761.72
8.7	478.64	2.3	640.84	8.7	586.36	2.3	767.4
8.6	479.76	2.2	642.6	8.6	587	2.2	768.2
8.5	482.92	2.1	645.4	8.5	593.16	2.1	772.88
8.4	486.48	1.8	647.68	8.4	596.24	1.8	776.16
8.3	494.16	1.7	653.16	8.3	602.16	1.7	781.88
8.2	495.68	1.6	654.36	8.2	603.48	1.6	782.68
8.1	499.36	1.5	657.72	8.1	607.92	1.5	786.48
7.8	501.08	1.4	660.08	7.8	610.52	1.4	790.08
7.7	506.96	1.3	663.84	7.7	617.72	1.3	795.16
7.6	508.08	1.2	665.44	7.6	618.6	1.2	795.68
		1.1	669.04			1.1	806.2

H. Horizontal device speeds per area (metres/second)

Area 1 (6.54 metres)	Stretcher	Evac Chair	Carry Chair	Rescue Sheet
Male 1	0.73	1.53	1.62	0.65
Male 1	0.74	0.97	1.62	0.87
Male 2	0.85	1.35	1.65	0.47
Male 2	0.86	1.53	1.38	0.67
Female 1	0.69	1.18	1.53	0.62
Female 1	0.78	1.40	1.42	0.59
Female 2	0.66	1.23	1.67	0.60
Female 2	0.70	1.31	1.76	0.25
Male Average	0.79	1.30	1.56	0.64
Female Average	0.70	1.27	1.58	0.44
Overall Average	0.74	1.29	1.57	0.52

Area 2 (10.85 metres)	Stretcher	Evac Chair	Carry Chair	Rescue Sheet
Male 1	1.32	1.63	1.52	1.56
Male 1	1.36	1.67	1.60	1.65
Male 2	1.24	1.37	1.78	2.15
Male 2	1.29	1.67	1.50	1.30
Female 1	1.36	1.34	1.59	0.98
Female 1	1.27	1.43	1.46	1.29
Female 2	1.27	1.55	1.61	1.23
Female 2	1.27	1.47	1.61	0.96
Male Average	1.30	1.58	1.59	1.61
Female Average	1.29	1.44	1.56	1.10
Overall Average	1.30	1.51	1.58	1.31

Area 3 (28.66 metres)	Stretcher	Evac Chair	Carry Chair	Rescue Sheet
Male 1	1.12	1.36	1.29	1.36
Male 1	1.24	1.50	1.32	1.36
Male 2	1.25	1.64	1.71	1.34
Male 2	1.37	1.70	1.54	1.48
Female 1	1.23	1.45	1.36	1.19
Female 1	1.27	1.53	1.31	1.23
Female 2	1.13	1.37	1.36	0.71
Female 2	1.16	1.33	1.30	0.65
Male Average	1.25	1.54	1.44	1.38
Female Average	1.19	1.42	1.33	0.87
Overall Average	1.22	1.47	1.39	1.07

(cont.)

Area 4 (3.05 metres)	Stretcher	Evac Chair	Carry Chair	Rescue Sheet
Male 1	0.89	1.86	1.23	0.32
Male 1	0.94	2.24	1.39	0.53
Male 2	1.14	1.31	1.53	0.76
Male 2	1.23	1.14	1.66	0.70
Female 1	0.71	1.31	1.25	0.37
Female 1	1.07	1.47	1.14	0.60
Female 2	0.67	1.02	1.34	0.15
Female 2	0.69	1.06	1.47	0.15
Male Average	1.03	1.53	1.43	0.52
Female Average	0.75	1.19	1.29	0.23
Overall Average	0.87	1.33	1.36	0.32

Area 5 (10.99 metres)	Stretcher	Evac Chair	Carry Chair	Rescue Sheet
Male 1	0.77	1.75	1.88	1.34
Male 1	0.93	1.88	1.61	1.40
Male 2	0.86	1.62	1.98	1.27
Male 2	1.14	1.78	1.81	1.33
Female 1	0.74	1.37	1.63	0.96
Female 1	0.86	1.25	1.83	0.77
Female 2	0.63	1.60	1.95	0.94
Female 2	0.75	1.39	1.67	0.83
Male Average	0.90	1.75	1.81	1.33
Female Average	0.74	1.39	1.76	0.87
Overall Average	0.81	1.55	1.78	1.05

I. Door Transition Experiment Greenwich

As outlined in Chapter 3, the Ghent trials did not establish door transition times for the Evacuation Chair because in these trials the teams opened doors ahead of the devices. Therefore 39 additional trials were conducted at the University of Greenwich, as outlined here. Male and female participants repeatedly pushed the evacuation chair device through doors with the same attributes as door 2 and door 3 of the Ghent trials (see Table 4-8). The door at the University as depicted in Figure 9-1 had the same configuration as in the Ghent trials. Two methods were used: firstly the door was approached where the handler opened the doors towards them by opening the left leaf followed by the right leaf. In the second experiment, the door was approached from the other side and so the handler opened the doors away from their direction of travel by opening the right leaf followed by the left leaf.

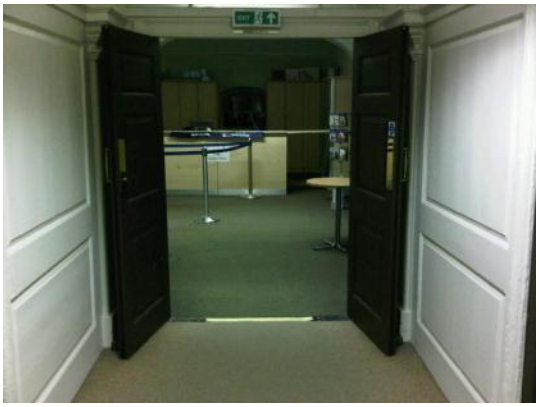


Figure 9-1: Double door configuration for supplementary trials

In each trial, an individual male or female pushed the evacuation chair towards the door, turned around in order to open the door and push the chair into the next corridor section. As far as possible, the conditions in the Ghent trials were replicated. The experiment was filmed as specified in section 3.2.1, with a roaming cameraman behind the moving device. For analysis, the same observations were utilised as specified in Figure 4-4, where video observations were made as to the point at which the handling team member touched the door, and the point at which the whole team had fully crossed the threshold of the door. These are labelled as

observation points 18, 20, 21 and 23 in Appendix D. As the Ghent participants were trained in the handling of devices, participants in the Greenwich experiment were given as much training and practise in using the evacuation chair as they required ensuring proficiency in the use of the chair on the horizontal. The person in the device weighed 70kg, to correlate with the Ghent participant. Furthermore, the same evacuation chair product (Evac+Chair: 300H AMB) was used. It was fully set up and with the PRM participant secured into the seated position before the commencement of each trial.

In the first trial, three male and three female participants were recorded in their three attempts to open the door towards them (door type 2). In the second trial, four male and three female participants were recorded in their three attempts to open the door away from them (door type 3). The average times and standard deviation are presented in Table 9-2 and the data from all 39 trials documented in Table 9-3.

Table 9-2: Average Male and Female Door Transition Times using Evacuation Chair

No. of leaves	Opening direction	Door bolt	Leaf opening Order	Male Average Speed (s)	Female Average Speed (s)
2	**Toward**	**N**	**Left, right**	**5.1 ±0.8**	**5.9 ±1.0**
2	**Away**	**N**	**Right, left**	**4.2 ±0.7**	**6.1 ±1.5**

Table 9-3: Door Transition Times for the Evacuation Chair

Trial no.	Door Type	Handler (M/F)	Touch door (s) (ref # 23)	Last part to cross line (s) (ref # 23)	Door Transition Time (s)	Average Door Transition Time per Participant (s)	
1	2	M1	41.56	47.74	6.18	Male 1	5.61
2	2	M1	33.52	38.40	4.88		
3	2	M1	59.63	65.41	5.78		
4	2	F1	26.59	34.69	8.10	Female 1	6.68
5	2	F1	25.84	31.45	5.61		
6	2	F1	30.26	36.58	6.32		
7	2	M2	29.32	34.72	5.40	Male 2	5.20
8	2	M2	22.35	28.02	5.67		
9	2	M2	30.72	35.26	4.54		
10	2	F2	40.14	45.40	5.26	Female 1	5.57
11	2	F2	26.63	31.43	4.80		
12	2	F2	25.01	31.67	6.66		
13	2	M3	29.71	33.40	3.69	Male 3	4.36
14	2	M3	31.19	35.25	4.06		
Trial no.	Door Type	Handler (M/F)	Touch door (s) (ref # 23)	Last part to cross line (s) (ref # 23)	Door Transition Time (s)	Average Door Transition Time per Participant (s)	
15	2	M3	24.46	29.79	5.33		
16	2	F3	34.93	39.92	4.99	Female 3	5.59
17	2	F3	27.64	34.11	6.47		
18	2	F3	25.99	31.30	5.31		
19	3	F4	16.13	21.12	4.99	Female 4	6.46
20	3	F4	14.81	20.67	5.87		
21	3	F4	9.10	17.61	8.51		
22	3	F5	9.55	14.24	4.70	Female 5	4.56
23	3	F5	12.23	17.73	5.50		
24	3	F5	10.89	14.36	3.47		
25	3	F6	10.87	17.83	6.97	Female 6	7.22
26	3	F6	11.53	18.45	6.91		
27	3	F6	9.17	16.94	7.77		
28	3	M4	9.18	13.01	3.83	Male 4	4.00
29	3	M4	8.45	12.87	4.42		
30	3	M4	10.97	14.72	3.75		
31	3	M5	9.40	13.18	3.77	Male 5	3.52
32	3	M5	8.24	11.40	3.16		
33	3	M5	9.12	12.76	3.64		
34	3	M6	8.84	13.85	5.00	Male 6	5.09
35	3	M6	8.56	13.80	5.23		
36	3	M6	8.27	13.30	5.03		
37	3	M7	8.30	13.50	5.20	Male 7	4.92
38	3	M7	12.26	17.72	5.46		
39	3	M7	9.93	14.03	4.10		

J. Device speeds per floor (metres/second)

M1 = Male Team 1

M2 = Male Team 2

F1 = Female Team 1

F2 = Female Team 2

Table 9-4: Device speeds per floor (m/s)

(I) STRETCHER					(II) EVACUATION CHAIR				
FLOOR	**M1**	**M2**	**F1**	**F2**	**FLOOR**	**M1**	**M2**	**F1**	**F2**
11TO10	0.64	0.63	0.47	0.45	**11TO10**	0.91	0.71	0.62	0.83
10TO9	0.66	0.65	0.39	0.46	**10TO9**	0.87	0.77	0.74	0.81
9TO8	0.46	0.66	0.49	0.32	**9TO8**	0.93	0.80	0.74	0.84
8TO7	0.68	0.65	0.36	0.49	**8TO7**	0.87	0.78	0.81	0.82
7TO6	0.70	0.42	0.56	0.50	**7TO6**	0.85	0.77	0.76	0.83
6TO5	0.71	0.59	0.58	0.31	**6TO5**	0.90	0.83	0.82	0.88
5TO4	0.74	0.61	0.47	0.34	**5TO4**	0.89	0.82	0.87	0.91
4TO3	0.72	0.62	0.58	0.45	**4TO3**	0.89	0.76	0.91	0.92
3TO2	0.78	0.67	0.40	0.35	**3TO2**	0.91	0.81	0.94	0.95
2TO1	0.54	0.50	0.56	0.35	**2TO1**	0.88	0.79	0.86	0.87
(III) CARRY CHAIR					**(IV) RESCUE SHEET**				
FLOOR	**M1**	**M2**	**F1**	**F2**	**FLOOR**	**M1**	**M2**	**F1**	**F2**
11TO10	0.47	0.61	0.89	0.74	**11TO10**	0.80	0.71	0.45	0.37
10TO9	0.47	0.63	0.88	0.69	**10TO9**	0.96	0.82	0.45	0.48
9TO8	0.34	0.62	0.57	0.71	**9TO8**	0.74	0.77	0.48	0.53
8TO7	0.49	0.49	0.86	0.46	**8TO7**	0.94	0.82	0.52	0.47
7TO6	0.50	0.63	0.81	0.66	**7TO6**	0.86	0.81	0.58	0.48
6TO5	0.38	0.59	0.50	0.64	**6TO5**	0.93	0.70	0.59	0.47
5TO4	0.30	0.62	0.85	0.38	**5TO4**	0.78	0.67	0.62	0.58
4TO3	0.36	0.61	0.60	0.68	**4TO3**	0.90	0.78	0.64	0.62
3TO2	0.31	0.67	0.91	0.41	**3TO2**	0.66	0.88	0.59	0.55
2TO1	0.41	0.67	0.82	0.66	**2TO1**	1.00	0.80	0.60	0.54

K. Stoppage duration per Floor

M1 = Male Team 1

M2 = Male Team 2

F1 = Female Team 1

F2 = Female Team 2

Table 9-5: Stoppage duration, per device, per floor (seconds)

(I) STRETCHER					(II) EVACUATION CHAIR				
FLOOR	M1	M2	F1	F2	FLOOR	M1	M2	F1	F2
11TO10	0.00	0.00	0.00	0.00	11TO10	0.00	0.00	0.00	0.00
10TO9	0.00	0.00	9.72	0.00	10TO9	0.00	0.00	0.00	0.00
9TO8	10.32	0.00	0.00	16.44	9TO8	0.00	0.00	0.00	0.00
8TO7	0.00	0.00	13.12	0.00	8TO7	0.00	0.00	0.00	0.00
7TO6	0.00	14.04	0.00	0.00	7TO6	0.00	0.00	0.00	0.00
6TO5	0.00	0.00	0.00	18.08	6TO5	0.00	0.00	0.00	0.00
5TO4	0.00	0.00	8.44	14.96	5TO4	0.00	0.00	0.00	0.00
4TO3	0.00	0.00	0.00	0.00	4TO3	0.00	0.00	0.00	0.00
3TO2	0.00	0.00	13.80	16.52	3TO2	0.00	0.00	0.00	0.00
2TO1	8.32	8.28	0.00	15.54	2TO1	0.00	0.00	0.00	0.00
(III) CARRY CHAIR					(IV) RESCUE SHEET				
FLOOR	M1	M2	F1	F2	FLOOR	M1	M2	F1	F2
11TO10	0.00	0.00	0.00	0.00	11TO10	0.00	0.00	3.68	0.00
10TO9	0.00	0.00	0.00	0.00	10TO9	0.00	0.00	2.88	2.64
9TO8	8.96	0.00	6.52	0.00	9TO8	0.00	0.00	0.00	0.00
8TO7	0.00	8.48	0.00	9.72	8TO7	0.00	0.00	0.00	0.00
7TO6	0.00	0.00	0.00	0.00	7TO6	0.00	0.00	0.00	0.00
6TO5	5.28	0.00	8.92	0.00	6TO5	0.00	0.00	0.00	0.00
5TO4	17.68	0.00	0.00	17.04	5TO4	0.00	0.00	0.00	0.00
4TO3	8.04	4.08	7.00	0.00	4TO3	0.00	0.00	0.00	0.00
3TO2	13.68	0.00	0.00	15.56	3TO2	8.04	0.00	0.00	0.00
2TO1	5.24	0.00	0.00	0.00	2TO1	0.00	0.00	0.00	0.00

L. Stoppage analysis per Device

The following tables show the details of the stops that were noted in the video footage. For each team (e.g. M1=Male Team 1 and F2=Female Team 2), the position of the stoppage on the stair is noted, as per the reference points in Appendix D. Also included is the duration of each individual stop. To track the position of the handling teams around the device, the labels A-D in figure were used to define each team member. For person tracking, it is assumed that the person's label is individual to them; therefore consecutive moves are described with the label representing the individual's new position. However, for position tracking, the labels are used to define the change from the previous position of the handlers.

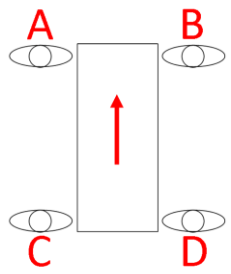
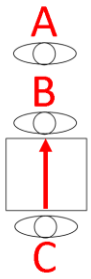
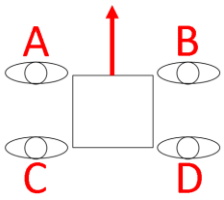
Stretcher	Carry Chair (M)	Carry Chair (F)	Rescue Sheet
			

Figure 9-2: Handling team position labels with direction of travel.

To describe the actions taken by the teams, and the level of clearance on the landing and stairs during the stops, the following codes are used:

S = Swapped Position
Wh = Wiped Hands
Wd = Wiped Device Handles
R = Readjusted Device
D = Dropped the handles of device
P = The team maintained their position, but simply paused.
L = Whole landing is blocked
HL = Half of the landing is blocked
S = A portion of the device is on the stairs.
TB = Total blockage has resulted from the stop (i.e. there is not enough room for individuals to pass)
PB = Partial blockage has resulted from the stop (i.e. there is enough room for individuals to pass)

Stretcher Trials						
Team	**Stop #**	**Stair Position (duration [s])**	**Person Tracking**	**Position Tracking**	**Actions**	**Clearance**
M1	1	9.4 (10.32)	ABDC	ABDC	S	HL+S - TB
	2	1.8 (8.32)	ABCD	ABDC	S	L+S - TB
M2	1	6.8 (14.04)	DCAB	DCAB	S	L+S - PB
	2	2.4 (8.28)	DCBA	ABDC	S	HL+S - TB
F1	1	9.8 (9.72)	ABDC	ABDC	S + Wh	L+S - TB
	2	7.8 (13.12)	CDBA	DCBA	S	L+S - TB
	3	4.8 (8.44)	CDAB	ABDC	S	L+S - PB
	4	2.8 (13.8)	ABDC	CDBA	S	L+S - PB
F2	1	9.4 (16.44)	BADC	BADC	S + Wh	HL+S - TB
	2	6.4 (18.08)	DCBA	CDAB	S + Wh	HL+S - TB
	3	4.8 (14.96)	DCAB	ABDC	S + Wh	L+S - TB
	4	3.4 (16.52)	ABDC	CDAB	S + Wh	HL+S - TB
	5	1.8 (15.64)	BACD	BADC	S + Wh	L+S - PB

Carry Chair Trials						
Team	**Stop #**	**Stair Position (duration [s])**	**Person Tracking**	**Position Tracking**	**Actions**	**Clearance**
M1	1	9.1 (8.96)	ACB	ACB	S + Wh	L+S – PB
	2	6.1 (5.28)	ABC	ACB	S + Wh	L+S – PB
	3	5.5 (10.4)	ABC	ABC	Wh + Wd	HL+S - PB
	4	5.1 (7.28)	CAB	CAB	S + Wh	L+S – PB
	5	4.1 (8.04)	BAC	CBA	S + Wh	L+S – PB
	6	2.8 (13.68)	ABC	BAC	S + Wh + Wd	L+S – PB
	7	2.1 (5.24)	CAB	CAB	S + Wh	L+S – PB
M2	1	8.1 (8.48)	BCA	BCA	S	L+S – PB
	2	4.5 (4.08)	CBA	BAC	S	HL+S – PB
F1	1	9.1 (6.52)	BADC	BADC	S	L+S – TB
	2	6.1 (8.92)	CDAB	DCBA	S	L+S – TB
	3	4.1 (7.00)	DCBA	BADC	S	L+S – TB
F2	1	7.8 (9.72)	BADC	BADC	S + Wh	L+S – TB
	2	5.4 (17.04)	ABDC	BACD	S + Wh	HL+S – TB
	3	3.4 (15.56)	BADC	BACD	S + Wh	HL+S – TB

Rescue Sheet Trials						
Team	**Stop #**	**Stair Position (duration [s])**	**Person Tracking**	**Position Tracking**	**Actions**	**Clearance**
M1	1	2.8 (8.04)	AB	AB	R	HL+S - TB
F1	1	10.8 (3.68)	AB	AB	R	L+S - TB
	2	10.6 (2.88)	AB	AB	D	HL - TB
F2	1	9.8 (2.64)	AB	AB	P	L+S - PB

M. Average rated factors in device performance

As the average performance is used to calculate the ratings, as presented in Table 9-6, a set of additional factors is introduced which measures the difference in gender performance. Ideally, the device performance should be gender-independent, as this represents a minimum discrepancy in physical difficulty. Thus the gender factor measures the degree to which the device is gender-independent. The device which is closest to gender-independence as measured by a particular factor will have the highest normalised gender factor. For example, for the preparation time factor, the device with the largest relative difference in preparation time is the rescue sheet with a 47% relative difference between male and female performance.

In contrast, the evacuation chair, with a relative difference of 24% in male/female preparation time has the smallest relative difference. Thus the normalised gender factor for preparation time for the rescue sheet is 1.0 while for the evacuation chair it is 2.0. As the normalised gender factors can be quite large, in one case as large as 37, in order not to swamp the other factors, normalised gender performance differences greater than or equal to 2.0 will be assigned the value of 1.0 and all values less than 2.0 will be assigned the value of 0.0. Presented in Table 9-6 are the various factors for each device and the sum of the normalised performance factors assuming all factors are equally weighted to 1.0. Assuming all the performance factors carry equal weight, the evacuation chair comes out a clear winner, scoring 139% better than the stretcher, 100% better than the rescue sheet and 42% better than the carry chair.

Table 9-6: Performance metric using average rated factors

		STRETCHER	EVACUATION CHAIR	CARRY CHAIR	RESCUE SHEET
	PREP TIME (S)	78	33	42	65
NPR_1	**NORM PREP TIME**	**1**	**2.4**	**1.9**	**1.2**
	GENDER PERFORMANCE DIFF (%)	30	24	40	47
NPR_2	**NORM GPD**	**0.0 (1.6)**	**1.0 (2.0)**	**0.0 (1.2)**	**0.0 (1.0)**
	NO. PREP OPERATORS	2	2	2	2
NPR_3	**NORM PREP OPERATORS**	**1.0**	**1.0**	**1.0**	**1.0**
	H. SPEED (M/S)	1.04	1.46	1.50	0.89
NPR_4	**NORM H. SPEED**	**1.2**	**1.6**	**1.7**	**1.0**
	GENDER PERFORMANCE DIFF (%)	9	10	5	38
NPR_5	**NORM GPD**	**1.0 (4.2)**	**1.0 (3.8)**	**1.0 (7.6)**	**0.0 (1.0)**
	NO. H. OPERATORS	4	1	1	2
NPR_6	**NORM H OPERATORS**	**1**	**4**	**4**	**2**
	V. SPEED (M/S)	0.53	0.83	0.58	0.67
NPR_7	**NORM V. SPEED**	**1.0**	**1.6**	**1.1**	**1.3**
	GENDER PERFORMANCE DIFF (%)	30	1	32	37
NPR_8	**NORM GPD**	**0.0 (1.2)**	**1.0 (37)**	**0.0 (1.2)**	**0.0 (1.0)**
	NO. V. OPERATORS*	4	1	3.5	2
NPR_9	**NORM V. OPERATORS**	**1.0**	**4.0**	**1.1**	**2.0**
	NO. LANES OCCUPIED	2	1	1	1.5
NPR_{10}	**NORM LANES**	**1.0**	**2.0**	**2.0**	**1.3**
	SUM NORM RATING	**8.2**	**19.6**	**13.8**	**9.8**

*** Number of operators based on the Essential and Major roles.**

N. Steps of the horizontal navigation and orientation algorithms

Table 9-7: Test 1 steps of the horizontal navigation and orientation algorithms

		Connected Node (Type)	**P Potential**	**M Values (Y=within range of LNP, N= outside range of LNP)**	
STEP 1		P0(F)	102.414	M01	102.664(N)
LNP=	102.207	P1(F)	102.914	M12	103.018(N)
up bound=	102.414	P2(F)	103.121	M23	103.371(N)
low bound=	102	P3(F)	103.621	M34	103.518(N)
Next step=	p0	P4(F)	103.414	M45	103.311(N)
Angle=	M70	P5(B)	103.207	M56	102.957(N)
		P6(B)	102.707	M67	102.457(N)
		P7(B)	102.207	M70	102.311(Y)
		Connected Node (Type)	**P Potential**	**M Values (Y=within range of LNP, N= outside range of LNP)**	
STEP 2		P0(F)	102.207	M01	102.457(N)
LNP=	101.707	P1(F)	102.707	M12	102.811(N)
up bound=	101.914	P2(F)	102.914	M23	103.018(N)
low bound=	101.5	P3(F)	103.121	M34	103.018(N)
Next step=	p0	P4(F)	102.914	M45	102.811(N)
Angle=	P7	P5(B)	102.707	M56	102.457(N)
		P6(B)	102.207	M67	101.957(N)
		P7(B)	101.707	M70	101.957(N)
		Connected Node (Type)	**P Potential**	**M Values (Y=within range of LNP, N= outside range of LNP)**	
STEP 3		P0(F)	102	M01	102.25(N)
LNP=	101.5	P1(F)	102.5	M12	102.604(N)
up bound=	101.707	P2(F)	102.707	M23	102.811(N)
low bound=	101.293	P3(F)	102.914	M34	102.664(N)
Next step=	P7	P4(F)	102.414	M45	102.311(N)
Angle=	P7	P5(B)	102.207	M56	102.207(N)
		P6(B)	102.207	M67	101.854(N)
		P7(F)	101.5	M70	101.75(N)

		Connected Node (Type)	P Potential	M Values (Y=within range of LNP, N= outside range of LNP)	
STEP 4		P0(F)	101.5	M01	101.75(N)
LNP=	101	P1(F)	102	M12	102(N)
up bound=	101.207	P2(F)	102	M23	102.104(N)
low bound=	100.793	P3(F)	102.207	M34	101.957(N)
Next step=	P6/P7	P4(B)	101.707	M45	101.457(N)
Angle=	P6	P5(B)	101.207	M56	101.104(Y)
		P6(F)	101	M67	101(Y)
		P7(F)	101	M70	101.25(N)
		Connected Node (Type)	**P Potential**	**M Values (Y=within range of LNP, N= outside range of LNP)**	
STEP 5 (if P6 chosen in previous step 4)		P0(F)	101	M01	101.25(N)
LNP=	100.5	P1(F)	101.5	M12	101.5(N)
up bound=	100.707	P2(F)	101.5	M23	101.604(N)
low bound=	100.293	P3(B)	101.707	M34	101.457(N)
Next step=	P6/P7	P4(B)	101.207	M45	100.957(N)
Angle=	P6	P5(B)	100.707	M56	100.604(Y)
		P6(F)	100.5	M67	100.5(Y)
		P7(F)	100.5	M70	100.75(N)
		Connected Node (Type)	**P Potential**	**M Values (Y=within range of LNP, N= outside range of LNP)**	
STEP 5 if P7 chosen in Step 4)		P0(B)	101.207	M01	101.457
LNP=	100.5	P1(B)	101.707	M12	101.604
up bound=	100.707	P2(F)	101.5	M23	101.5
low bound=	100.293	P3(F)	101.5	M34	101.25
Next step=	P5/P6	P4(F)	101	M45	100.75
Angle=	P6	P5(F)	100.5	M56	100.5
		P6(F)	100.5	M67	100.604
		P7(B)	100.707	M70	100.957

O. Interpolated "smoothed" device speeds per floor (metres/second)

M1 = Male Team 1

M2 = Male Team 2

F1 = Female Team 1

F2 = Female Team 2

Table 9-8: Interpolated device speeds per floor (m/s)

(I) STRETCHER					(II) EVACUATION CHAIR				
FLOOR	**M1**	**M2**	**F1**	**F2**	**FLOOR**	**M1**	**M2**	**F1**	**F2**
11TO10	0.64	0.63	0.47	0.45	**11TO10**	0.91	0.71	0.62	0.83
10TO9	0.66	0.65	0.48	0.46	**10TO9**	0.87	0.77	0.74	0.81
9TO8	0.67	0.66	0.49	0.48	**9TO8**	0.93	0.80	0.74	0.84
8TO7	0.68	0.65	0.52	0.49	**8TO7**	0.87	0.78	0.81	0.82
7TO6	0.70	0.62	0.56	0.50	**7TO6**	0.85	0.77	0.76	0.83
6TO5	0.71	0.59	0.58	0.48	**6TO5**	0.90	0.83	0.82	0.88
5TO4	0.74	0.61	0.58	0.46	**5TO4**	0.89	0.82	0.87	0.91
4TO3	0.72	0.62	0.58	0.45	**4TO3**	0.89	0.76	0.91	0.92
3TO2	0.78	0.67	0.57		**3TO2**	0.91	0.81	0.94	0.95
2TO1			0.56		**2TO1**	0.88	0.79	0.86	0.87
(III) CARRY CHAIR					**(IV) RESCUE SHEET**				
FLOOR	**M1**	**M2**	**F1**	**F2**	**FLOOR**	**M1**	**M2**	**F1**	**F2**
11TO10	0.47	0.61	0.89	0.74	**11TO10**	0.80	0.71		0.37
10TO9	0.47	0.63	0.88	0.69	**10TO9**	0.96	0.82		0.45
9TO8	0.48	0.62	0.87	0.71	**9TO8**	0.74	0.77	0.48	0.53
8TO7	0.49	0.62	0.86	0.68	**8TO7**	0.94	0.82	0.52	0.47
7TO6	0.50	0.63	0.81	0.66	**7TO6**	0.86	0.81	0.58	0.48
6TO5		0.59	0.83	0.64	**6TO5**	0.93	0.70	0.59	0.47
5TO4		0.62	0.85	0.66	**5TO4**	0.78	0.67	0.62	0.58
4TO3		0.65	0.88	0.68	**4TO3**	0.90	0.78	0.64	0.62
3TO2		0.67	0.91	0.67	**3TO2**	0.95	0.88	0.59	0.55
2TO1		0.67	0.82	0.66	**2TO1**	1.00	0.80	0.60	0.54

P. Time to traverse each landing (seconds)

M1 = Male Team 1

M2 = Male Team 2

F1 = Female Team 1

F2 = Female Team 2

(I) STRETCHER					(II) EVACUATION CHAIR				
LANDING	**M1**	**M2**	**F1**	**F2**	**LANDING**	**M1**	**M2**	**F1**	**F2**
11A-10	4.3	4.6	6.3	5.6	**11A-10**	2.9	3.6	5.2	3.2
10-10A	4.5	4.8	6.3	6.4	**10-10A**	3.7	5.1	5.1	4.0
10A-9	4.3	5.2	6.8	6.2	**10A-9**	3.7	3.4	3.6	3.9
9-9A	5.0	5.4	7.0	6.1	**9-9A**	3.7	4.0	4.3	4.3
9A-9	5.2	4.4	6.1	6.0	**9A-9**	2.9	3.7	4.8	4.1
8-8A	4.4	3.5	6.8	6.8	**8-8A**	3.8	3.6	3.8	3.9
8A-7	4.2	3.9	6.2	6.2	**8A-7**	3.2	3.8	3.8	4.2
7-7A	4.5	3.9	6.0	6.4	**7-7A**	3.8	3.9	3.9	4.1
7A-6	3.7	3.5	5.6	5.4	**7A-6**	3.5	4.1	3.7	3.8
6-6A	5.1	4.0	4.7	5.8	**6-6A**	3.9	3.7	3.6	4.5
6A-5	3.7	5.5	5.0	5.8	**6A-5**	3.6	4.0	3.6	3.6
5-5A	5.1	5.0	5.0	7.0	**5-5A**	4.0	3.4	3.6	3.6
5A-4	4.1	4.2	4.8	6.1	**5A-4**	3.4	3.4	2.8	3.1
4-4A	3.8	4.6	4.7	5.7	**4-4A**	3.5	3.8	3.2	3.7
4A-3	3.8	4.3	4.2	5.5	**4A-3**	3.4	3.3	2.7	3.3
3-3A	3.8	4.8	4.6	5.7	**3-3A**	3.4	4.5	3.1	4.0
3A-2	4.3	4.0	5.6	6.9	**3A-2**	3.6	3.6	3.9	3.6
2-2A	4.1	4.2	5.4	5.6	**2-2A**	3.8	3.8	3.4	4.0
2A-1	3.8	4.6	5.4	5.5	**2A-1**	3.4	3.9	3.4	4.0
1-1A	4.6	5.4	5.7	6.2	**1-1A**	3.6	4.1	3.3	4.3
1A-0	4.0	4.3	5.7	5.1	**1A-0**	3.6	3.9	3.2	7.3

Continued.

(III) CARRY CHAIR					(IV) RESCUE SHEET				
LANDING	**M1**	**M2**	**F1**	**F2**	**LANDING**	**M1**	**M2**	**F1**	**F2**
11A-10	5.6	5.6	3.2	4.1	**11A-10**	4.2	5.1	8.1	11.0
10-10A	5.2	4.7	4.0	4.4	**10-10A**	5.4	4.8	7.6	8.4
10A-9	5.8	4.7	3.7	3.5	**10A-9**	3.7	4.9	7.6	7.2
9-9A	6.4	5.0	3.4	4.9	**9-9A**	3.9	4.0	6.5	6.5
9A-9	5.4	4.7	3.7	4.6	**9A-9**	5.0	4.5	6.5	6.7
8-8A	15.2	4.7	12.0	3.8	**8-8A**	5.4	4.4	6.1	7.0
8A-7	5.0	4.1	3.6	4.8	**8A-7**	3.6	4.6	6.7	9.2
7-7A	8.0	11.5	4.5	4.1	**7-7A**	4.5	3.6	5.4	7.0
7A-6	5.2	4.5	4.6	4.6	**7A-6**	4.5	4.3	5.9	6.9
6-6A	4.9	4.1	5.2	5.5	**6-6A**	3.7	5.1	5.0	6.2
6A-5	4.3	4.1	6.6	5.4	**6A-5**	3.8	4.3	5.0	7.3
5-5A	13.7	4.6	13.2	5.3	**5-5A**	4.2	4.8	4.7	7.1
5A-4	15.8	3.9	4.1	5.0	**5A-4**	3.5	4.4	5.1	6.6
4-4A	13.4	4.2	4.0	4.6	**4-4A**	4.4	4.7	4.7	6.0
4A-3	6.0	7.7	4.4	4.4	**4A-3**	3.9	4.1	5.4	6.2
3-3A	15.8	4.4	10.9	4.8	**3-3A**	3.8	3.7	4.7	6.2
3A-2	6.8	4.6	4.1	4.4	**3A-2**	3.4	4.3	6.2	7.0
2-2A	6.8	5.4	4.4	5.7	**2-2A**	3.8	4.6	6.4	7.0
2A-1	5.0	4.1	4.3	5.2	**2A-1**	3.3	3.8	5.8	6.6
1-1A	13.2	5.2	4.2	5.0	**1-1A**	3.6	4.4	5.1	8.0
1A-0	4.5	5.0	4.2	5.0	**1A-0**	4.4	4.7	5.7	7.4