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Safe evacuation for all - Fact or Fantasy? Past experiences, current understanding and future challenges

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ABSTRACT

Statistics show that significant proportions of our global populations have a disability. Demographically we are an ageing and an increasingly obese society which, with increased accessibility, means that buildings are likely to be frequented by an ever increasing proportion of persons with reduced mobility. There is therefore a need to ensure that we can provide an accessible means of egress and a safe evacuation for all. Design guidance related to exit widths varies internationally but in the main has its origins in studies conducted with populations who were able bodied and fit. Furthermore the relationships between speed/density/flow used in hand calculations and computer models have been recognised as being outdated and not necessarily reflective of society today. This paper considers the evacuation of mixed ability populations in the context of increasing accessibility and changing demographics, reviews the basis for current design guidance and explores the design options for persons with reduced mobility. The current understanding of the evacuation capabilities of persons with reduced mobility is critically assessed and lessons from real evacuation experiences and other studies of mixed ability populations are drawn. In so doing, the sufficiency of current design guidance and challenges associated with implementing current approaches are considered and gaps in understanding and future research needs identified.

1. Introduction

The World Health Organisation (WHO) estimates that 15% of the world's population live with some form of disability and that this percentage will increase in the future due to aging and a global increase in chronic health conditions [1]. The establishment of access for all in the regulations of developed countries internationally means that building populations are now more diverse, spanning the spectrum of ability with respect to evacuation. Clearly, the traditional definition of means of escape as a "structural means whereby a safe route is provided for persons to travel from any point in a building to a place of safety by their own unaided efforts" [2] is insufficient for those who may access upper floors of a building using a lift, but may not be able to evacuate independently via stairs.

Internationally, means of escape is designed by adhering to prescriptive codes or following design guidance in support of functional regulations. In order to accommodate those with limited mobility, approaches involving the use of refuge areas, assisted escape and/or evacuation lifts are adopted in addition to traditional direct evacuation via stairs [3]. Additionally, in countries with functional regulations, design decisions are supported by safety analyses involving engineering calculations related to movement and the use of computer evacuation models [4,5]. The generalized nature of prescriptive codes has arguably ne-

cessitated the adoption of assumptions regarding flows and suitable flow times but these have their origins in research/events from many decades ago [6–8]. Furthermore, the most significant data sets used in engineering analysis of movement are derived from research conducted mainly between the 1950s and 1980s [9,10]. Indeed, the originators of what are considered the most significant North American data sets [11,12] have asked that their data be removed from future design guides stating that they are no longer applicable to building populations today [13].

In a context of increasing access and changing demographics, it is pertinent and timely to review our understanding of mixed ability evacuation and consider whether we are really providing safety for all. This paper will briefly consider access and egress provision in buildings, including the basis for current design guidance and evacuation options for persons with reduced mobility. It will consider the prevalence of disability and current demographic trends as well as current understanding of the evacuation capabilities of those with reduced mobility and the potential impact on flow dynamics. Experiences from real evacuations and studies investigating human factors associated with the use of refuges and options for vertical evacuation (assisted escape and lifts) will also be discussed. In so doing, the sufficiency of current design guidance and challenges associated with implementing current approaches will be considered and future research needs identified.

2. Access and egress

Until the second half of the 20th century people with disabilities were discriminated against in relation to welfare and job opportunities; access to and within buildings was difficult and this in itself was a barrier to participation in society [14]. Access was perceived by many to be too difficult, largely because of the view that the benefits associated with proposed accessibility measures did not justify the costs [15]. From the mid-20th century onwards, due to human rights movements, campaigning and lobbying of parliaments the social and political climates began to change. Comprehensive guides with respect to minimum standards in relation to access were produced, eg. [16], but their voluntary nature meant limited impact in the absence of legal enforcement [14]. In the UK, there was no legal obligation to provide access to buildings until 1987 when the Building Regulations [17] required that 'reasonable' provision be made for people to gain access to and use new buildings but it was not until 1991 that this extended to upper stories of public buildings, given concerns about the safe evacuation of people with disabilities from upper stories in the absence of guidance in this respect.

Concern for the life safety of people with disabilities in fire was first marked by a seminar held in Edinburgh in 1975 [18]. In 1979 and 1980, the newly formed National Task Force on Life Safety and the Handicapped, USA also organised conferences to address issues related to egress, emergency preparedness, education, and building design [19]. During the late 1980s standards committees and institutions eg National Institute of Standards and Technology, USA (NIST) and Building Research Establishment, UK (BRE), commissioned research into issues surrounding the evacuation of people with disabilities [20,21], recognising that traditional means of escape from upper floors, i.e. stairs was clearly insufficient in light of increasing accessibility. A useful chronological review of key meetings, events and literature related to procedures/technologies for people with disabilities during the period 1975–1988 is provided in [22], while an overview understanding and new research is presented in [21].

In 1988, BS 5588 Part 8: Code of Practice for Means of Escape for Disabled People [23] was published. Finally, there was recognition that persons with disabilities had the right, not only to access buildings, but also to be afforded what was hoped to represent equitable life safety options in the event of an emergency. BS5588 Part 8 (superseded by BS9999 [24]) recommended the use of refuges to temporarily accommodate persons with mobility difficulties, the use of appropriately designed lifts as a means of vertical evacuation and recognised the key responsibilities of management in developing and implementing evacuation procedures, i.e. concepts which are now accepted and integrated in many guidance documents across the world.

The introduction of the Disability Discrimination Act 1995 [25] in the UK (superseded by the Equality Act 2010 [26], and similar acts elsewhere, e.g. the Americans with Disabilities Act [27] and the Australian Disability Discrimination Act 1992 [28]), were game changing with respect to the provision of equal opportunities for access to buildings and services. These regulations not only applied to new buildings but placed a responsibility on providers of existing buildings to make 'reasonable' adjustments to the premises [26] or make adjustments except where this would involve 'unjustifiable hardship' [28]. For the first time there was a real expectation that all buildings would be populated with persons with more diverse capabilities with respect to evacuation.

An accessible environment has been defined [29] as "*one which facilitates equal opportunity independently to participate in the full range of activities and responsibilities which define our society. It is an environment free of barriers which exclude, endanger or inconvenience those with acquired or inherited physical impairments*". This definition reinforces that

the provision of access to and within buildings and the need to provide egress from those buildings, particularly in an emergency such as fire, are inextricably linked; indeed the need for accessible emergency egress has been identified internationally [30–32]. The nature of current design guidance with respect to escape provision, with examples, is discussed in the following section.

3. Current design guidance and performance based design

Although regulatory frameworks, codes of practice and design guidance vary internationally, recognition of the need to provide an egress system (travel paths and protected spaces) that ensure the safety of those exposed to fire is inherent across the globe. An excellent overview of the concepts, methods and strategies currently used globally in egress system design is provided in the recently published SFPE Handbook [8].

Internationally the general principles of escape provision are that there will be alternative means of escape from most locations, the distances of travel to a storey exit will be limited (and appropriate to the occupancy) and that sufficient exit capacity (storey exits, stairs and final exits) will be provided to allow the safe passage of occupants deemed likely to use them (based on occupancy load factors or actual design figures).

Detailed historical reviews of the evolution of emergency egress provision in relation to storey exit sizing and stair widths in both the US and UK have been presented previously [6–9]. Similarities have been noted across the globe [7], albeit that some stair widths are based on the number of occupants served on an individual floor whilst others are determined by the total number of occupants deemed likely to use them [7]. According to Pauls [6,11] the minimum stair widths proposed in US codes (44 in or 1120 mm) have their origins in work conducted in the early 1900s with underlying assumptions of flows of 45 people per unit width (22 in.) per minute. The current 44 in. minimum width is intended to support two 22 in (560 mm) queues of occupants either standing still or moving down a stair whilst allowing counter-flows, with the 22 in. (560 mm) lane dimension supposedly originating from work in 1914 representing the shoulder width of soldiers standing in line [8,11]. The choice of flows as a basis for recommendations were primarily based on a consideration of studies of movement of people in government buildings during fire drills and exiting railway terminals during rush hour [33]. Although the lane model was subsequently challenged (based on the work of Fruin [12] and Pauls [11]) and has been largely eliminated from building code requirements in the US over the last decades, it is still the most widely used basis for regulating minimum stair widths in the US today, albeit that a wider minimum exit stairs (56 in or 1425 mm) are recommended for certain high occupancy contexts to facilitate counter flow [13]. In the UK, current guidance for both storey exit sizing and stair sizing is based on the same historic evidence. The Post War Building Studies Report [34] which informed the development of guidance reviewed the rationale for codes developed in the US including the report by NBS [33] and considered the results of tests conducted in France in 1938 and 1945 [34]. Codes that followed were based on similar assumptions to those being developed in the US [7]. The current 5 mm/person exit width [35] is based on an assumption of an exit flow of 80 people/m/min and an aim to restrict the flow time to 2.5 mins (a time deemed acceptable following what was considered a successful evacuation of the Empire Palace Theatre, Edinburgh in 1911) [7,34]. Current guidance with respect to stairs adopts the same underlying assumptions with regards to flow in the stair whilst making assumptions regarding the holding capacity of the stair (between 2 and 3 persons/m²) [7].

A basic tenet of building law is that access provision should be complemented by egress provision and it was in this vein that egress codes and standards started to address the needs of people with disabilities.

Recommendations for the safe egress of people with disabilities, eg, [23] have been in place since 1988 and been addressed in design codes to a greater or lesser extent internationally since [8]. A recent study in Japan compares regulations, codes and standards of evacuation safety for 'physically challenged people' across 16 countries [36]. Such provisions recognise the temporary use of refuges for those who cannot use stairs and the need for assistive measures and/or provision of evacuation lifts for vertical descent, i.e. reliance is on a combination of structural provisions and management input [8,24].

In the UK, a place of refuge is defined as "*an area that is both separated from the fire by fire-resisting construction and provided with a safe route to a storey exit, thus constituting a temporarily safe space for disabled persons to await assistance for their evacuation*" [35]. It is recommended that one refuge space be provided for each protected stairway affording egress from each storey [24,35] and that there is a 2-way voice communication system between the refuge and a central control point. A refuge should be '*sized to accommodate and allow for the manoeuvrability of a wheelchair*' (900×1400 mm) and it should not reduce the width of the required escape route or obstruct the flow of others. Although it is recognised that in some premises groups of wheelchair users are likely to be present, no guidance is given as to how this should impact the number or size of refuges. A brief review of the literature suggests wide variation in standards internationally. In Japan, for example, there is no national guidance on the provision of refuge areas, although some local guidelines issued by the fire department in Tokyo are adopted in high-rise buildings [36]. In Italy, codes only give generic descriptions on how refuge spaces should be effectively designed [37]. In Sweden, a refuge space should be provided for one small outdoor wheelchair per 100 persons [38].

Internationally, there is no requirement to provide evacuation lifts as the means by which persons with disabilities can transfer to the ground floor, although they are currently recognised as the preferred (albeit not mandated) method in the UK [24]. In the UK it is also suggested that fire-fighting lifts could be used for the evacuation of people with disabilities before the fire service arrive and that other lifts remote from the fire may be used after appropriate risk assessments have been conducted [24]. It is widely recognised of course that the technical challenges associated with structural protection of lifts have been overcome and hence evacuation lifts are now considered as options for all building occupants in some countries [39] and have been approved in many (particularly tall) buildings as part of performance based designs [8]. The fact remains, though, that in many buildings the cost of lifts as an evacuation option can be prohibitive.

In the absence of lifts, a person who is unable to use stairs must be assisted down stairs by others. In the UK this is clearly defined as the responsibility of building management [40], albeit that it has not always been recognised as such [41]. A range of options for assisting those who are ambulant and non-ambulant exist and include cradle carry, swing or chair carry, in-chair carry (one, two or three person assist) [42]. The use of assistive devices characterised as carry, track and sled-type [43] have also been identified and suggested.

Some countries eg China, Hong-Kong, Qatar, Korea and Singapore also require the provision of refuge floors in tall buildings; the objectives are (among others) to act as a safe place for a short rest before continuing downwards, act as a place of assembly should all staircases become unusable and act as an area for those requiring assistance to wait a safe passage [44]. It is suggested [44,45] that the positioning of refuge floors (20–25 floor intervals) is based on an assumption that occupants would '*experience fatigue after 300 s of downward descent*' (from [46]) and that the time to traverse one storey is 16 s (from [47]).

It is important to note that there is wide recognition that management has a key role to play in successful evacuation generally and in evacuations involving the use of refuges, assisted escape, and evacuation lifts in particular [24]. Legislation related to buildings in use in the

UK [40] and elsewhere, eg [48], requires that regular risk assessments are conducted, evacuation procedures are in place, staff are designated to perform duties (such as assisted escape, managing lift evacuation) and that appropriate training is provided.

3.1. Performance based design

As noted previously many countries accept the quantification of egress performance as part of an engineering design solution and guidance exists to support engineers in their decision making [4,5,49]. Such egress analysis can comprise simple hand calculations (the hydraulic model [9]) or more complex computer based simulation models [50]. It has been noted [11] that guidance documents typically refer to datasets of speed and flow from the 1950s–1980s which were derived from observations of the movement of mainly able-bodied commuters (Hankin and Wright [51], Fruin, [12]; Ando et al. [52]), pedestrians in normal circulation (Predtechenskii and Milinskii [53]) or during evacuation drills in buildings (Pauls [11]; Predtechenskii and Milinskii [53]). From these data sets, design curves relating speed and flow to density have been derived and have become established in design practice.

A detailed overview of computer based simulation models has been presented by Kuligowski et al. [50,54]. Although these models vary in sophistication, it has been noted [10], that with only a few exceptions (among the spatial proximity models), all movement algorithms in generations of computer models assume uniform crowd flow parameters and utilise speed density relationships derived from largely the same data sets as mentioned above; even those that do not still use such data sets for calibration purposes [10].

Although the populations from which the most widely used design curves have been derived have not been characterised, it is safe to assume (given their timing and limited access for people with disabilities) that they represent mainly able-bodied persons and may not necessarily be reflective of building populations of today. A discussion of the prevalence of disability and changing demographics is provided in the following paragraphs.

4. Disability definitions, prevalence and changing demographics

It is important in the context of this work to consider the prevalence of disability, demographic trends and the implications in terms of capability to evacuate. Definitions of disability vary internationally and indeed have evolved over time. The WHO, under its International Classification of Impairments, Disabilities and Handicaps (ICIDH) originally defined disability as "*any restriction or lack of ability (resulting from an impairment) to perform an activity in the manner or within the range considered normal for a human being*" [55], i.e. disability was benchmarked against some expectation of what was normal. A more modern understanding of disability is reflected in the International Classification of Functioning, Disability and Health [56] which recognises it as a more complex phenomenon reflecting the interaction between the features of a person's body (impairments), activity limitations (difficulty executing a task) and participation restrictions (problem experienced in involvement in life situations). This recognises not just body functionality/structure but the social and environmental context and suggests that disability can be permanent or transitory.

The prevalence of disability varies internationally.¹ For example, latest national estimates suggest that 20% [57], 22.2% [58] and 24% [59] of the populations of GB, USA and New Zealand respectively have a disability, which can be associated with a range of physical, mental or sensory impairments. Without exception, the most prevalent impair-

¹ Care should be taken in direct comparison of statistics since different definitions of disability/mobility impairment used.

ment is mobility which is, arguably, the most critical in the event of a fire emergency. In GB, 10.6% of the population have a mobility impairment, whilst 7.8% have issues with stamina/breathing/fatigue [57]. In the USA, 13% have a mobility disability (serious difficulty walking or climbing stairs) [58], whilst in Sweden, 8% of those aged 16–84 are estimated to have a mobility impairment [60]. Those with mobility impairments often use some form of assistive device, however, statistics can vary significantly and depend on whether ownership or regular usage is considered. In the USA, 0.61% of the non-institutionalised population use a wheelchair (90% of which are manual) [61]. In Sweden and GB higher figures are reported, i.e. 1.6% [62], and 1.9% [57] respectively with 1.2% in GB considered to be regular users. Information on other walking aids is sparse; as an example, however, it has been suggested that 1.8% of the non-institutionalised population of the USA use a cane whilst 0.7% use a walker [61].

Globally we are an ageing society with virtually every country in the world experiencing growth in the number of older persons, a situation which is predicted to accelerate in the decades to come, particularly in urban areas [63]. The proportions of older people within the population are also increasing due to a reduction in birth rates, advancements in public health, medical technologies and improved living conditions [63]; for example, in 2015 it was estimated that 1 in 8 people worldwide was aged 60 years or over but by 2050 this is predicted to be 1 in 5 [63]. Although people are living longer this does not mean they are living free from impairments that limit daily living. Age is directly related to a deterioration of physical, mental and neurological functions [64,65]. Chronic conditions of aging include cardiovascular disease, stroke, diabetes, cancer, arthritis and osteoporosis [63]. It is not surprising therefore that the prevalence of disability increases with age [66]. In GB, for example, 45% of adults of state pension age have a disability compared to 17% of working age [57]. The nature of the impairment is also age related, with mobility impairments being more prevalent in older age groups, i.e. 7.6% of working age adults have a mobility impairment compared to 30% of state pension age [57].

As well as being an ageing society, obesity has become more common in some countries [67]. The WHO [68] defines obesity as “*abnormal or excessive fat accumulation that may impair health*” (25% body fat for a man and 33% for a woman). Those who are obese are at a higher risk of having a mobility impairment due to “*a combination of musculoskeletal, neurological, cognitive, personal and environmental factors*” [69]. In the USA, for example, 41% of those who are obese have a consequential disability [70] i.e. almost double the prevalence of disability in the general population. Although challenged by some [71], the most common way to estimate and classify obesity is by using Body Mass Index, i.e. weight divided by height squared (kg/m^2) with a BMI >25 and BMI >30 being classified as overweight and obese respectively [68]. Between 1980 and 2014, obesity doubled worldwide, with 39% of adults considered overweight and 13% considered obese [68]. Projections vary, with some studies suggesting stabilisation in some countries [67], whilst others suggesting levels will continue to increase. It is predicted, for example, that, by 2050, obesity will affect 60% of males and 50% of females in the U.K [72] and 47% of males and 58% of females in the USA² [73].

It is clear from the above that significant proportions of society have a disability, with approximately 8% having a mobility impairment. Since the prevalence of disability increases with age and obesity, these percentages are likely to increase in the future. In an important and comprehensive overview of the health literature, Spearpoint and MacLennan [74] citing Ayis et al. [75] note that reduced walking

capacity is likely to result in reduced walking speed and maximum walking times before stopping. Reduced walking capacity also increases risk of falling [76], particularly in older persons where there may also be a parallel reduction in cognitive processing; risk also increases with longer travel distances, attributed to fatigue [77]. Demographic trends also suggest change in body size, shape and space requirements. Current understanding of speed, need to stop for rests, space and behavioural considerations related to those with a range of ability are discussed below. First, lessons learned from real evacuations involving those with reduced mobility are explored.

5. Evacuations involving people with disabilities

In the following paragraphs two real evacuations which provide insights into issues associated with the evacuation of people with disabilities in high density populations are discussed, namely, the evacuation of the World Trade Center on 9/11 [78,79] and an evacuation of a museum in Northern Ireland in 1988 [80].

The US study of the events of 9/11 [78], estimated that 1000 surviving occupants (6%) had “*a limitation that impacted their ability to evacuate*”, mostly due to recent injury to knee/ankle or chronic illnesses. Investigations confirmed that many with mobility impairments and those injured in the attacks were able to successfully evacuate with assistance from co-workers and that other evacuating occupants allowed the passage of those being assisted. In the UK study [79], 6 of the 273 participants (2.2%) declared that they had a mobility impairment (due to knee surgery, partially paralysed leg, sprained ankle, sciatica). An analysis of the accounts of their evacuations [81] suggested that the evacuation of 5 of the 6 proceeded without any particular difficulty. The evacuation of the 6th, a 54 year old female located on the 20th floor of WTC1, proved more challenging. This evacuee reported having had recent knee surgery, hypertension and severe arthritis; she used a cane for short and a scooter for longer distances and it was common for her to wheel herself around her office in her chair. Despite having had disaster training (whilst working as a nurse) and suggesting that she was fire safety aware, she had no Personal Emergency Evacuation Plan (PEEP). Notwithstanding, shortly after the initial cues, she organised assistance from three colleagues. Together they entered the stair (44 in.) where her colleagues formed a protective shield around her (one male at the front and rear and a female to the side) whilst she held onto the handrail with her right hand and used her cane in her left. She described her evacuation thus: “*we took up the whole stairway and joined the procession going down at a staccato pace*”. She referred to the position of her female assistor - “*she could cuddle up to me and let people by or if she needed to she could move out and control people coming alongside of us*” - and noted the need for the group to stop - “*both had asthma - we had to stop so we would go over to a corner on the landing and huddle*”. Whilst many evacuees passed her group, she noted that 6–8 people remained behind her - “*so people without talking to me had taken a responsibility behind me - not going when they could*”. Her stair descent rate was estimated to be 0.8 floors/min which is much lower than the mean and median normalised travel speeds of 1.3 and 1.2 floors/min respectively estimated for the population [78].

Averill et al. [78] also noted slower moving occupants on the stairs and reported that 51% and 33% of occupants of WTC1 and WTC2 respectively suggested that injured and disabled persons in the stairwell were “*a constrained to evacuation*”. For example: “*we saw an [occupant] who was hyperventilating. [The occupant] was walking down the stairs with assistance. We slowed down and came to a stop [because] we couldn't get around the two [occupants]*” (Interview 1000556 [78]). Another evacuee who assisted an ‘overweight’ occupant in WTC2 reported on his descent that “*we took up the entire width of the stairway and no-one could get around us until we came to a landing*” (Interview 1000093 [78]).

² Care should be taken in comparing figures directly due to differences in the way data is collected and given the concerns in use of BMI.

Several occupants reported mobility impaired occupants waiting on stairs/landings for assistance. Indeed the presence of a mobility impairment was cited as a reason to leave the stairs and a specific floor in WTC1 (exact location unknown but between floors 12 and 20) was designated by emergency responders to hold mobility impaired occupants until such times as the stairwells had cleared [78]. It was estimated that 40–60 persons waited here for instruction or assistance [78]; those with mobility limitations only accounted for half, with the remainder being friends and co-workers who had decided to wait with them. It was apparent, however, that not all mobility impaired occupants followed instructions to locate there, eg. one wheelchair user who was being assisted from a floor in the 60 s by two previously unknown occupants who 'wandered onto my floor' was directed to the holding floor by emergency responders but ignored the instruction as two other persons began to assist and they continued their journey [78].

It is important to consider the experience of John Abruzzo located on the 69th floor of WTC1 [82]. John is a quadriplegic and user of an electric wheelchair. His evacuation had been pre-planned with the intention to use an evacuation chair. He was transferred into the chair with the assistance of co-workers, 9 of whom worked in shifts of 3–4 to carefully assist him down the stairs, whilst another scouted ahead; at one stage they moved stairs when smoke was reported ahead. John's evacuation took over 1.5 h, leaving only minutes before the collapse of WTC1. John had evacuated WTC previously in 1993; then he was carried in his electric wheelchair before being transferred to a stretcher, a process which took approximately 6 h. Although his evacuation on 9/11 was much faster than previously, his experience highlights the considerable manpower required to effect an evacuation using an evacuation chair over such long distances.

Lifts were used on 9/11 in WTC2 but usage was not dominated by those with mobility impairments [78]. Specific note has been made [78] of just two individuals with a disability who used the lift. The first, who initiated their evacuation after the attack on WTC1, had what was described as a medical disability. On hearing the announcement in WTC2 he/she decided to continue and was helped down the stairs by a fellow occupant before taking a lift to the ground floor. The second, located on the 95th floor, suggested that they chose the lift because they were taking new medication and could not use the stairs.

The evacuation of the Ulster Museum occurred in 1988 during an exhibition to recognise the 300th anniversary of the defeat of the Spanish Armada [80]. The exhibition was designed such that visitors followed a pre-defined route, accessing the start of the exhibition on the 3rd (top) floor via stairs or a lift, and ending on the 2nd floor directly below their starting point. The alarm was raised when a smoke detector on the ground floor activated and a full evacuation ensued. At the time of the alarm it was estimated that 1200 persons occupied the two exhibition floors, including groups of school children, teachers and 20 staff who had responsibilities in an emergency. Also present was a group from a local day centre, comprising 9 people with disabilities accompanied by 3 carers. Although the exact nature of the disabilities is unknown, 4 of the group were wheelchair users, and one used a walking stick. At the time of the alarm this group was positioned near the end of the exhibition route on the 3rd floor, and subsequently were almost the first occupants to enter the lift/stair lobby at that level. On entering the lobby, 3 members of the disabled group, including one wheelchair user, evacuated immediately via the lift, which was then taken out of service by a member of staff. Two others evacuated via the stairs with 2 care assistants whilst 3 wheelchair users remained on the landing with one carer. The exact dimensions of the landing are not known but it was clear that, although it was sufficient to hold the 3 wheelchair users and carer, the presence of this group severely obstructed the passage of the floor occupants towards the stairs. Staff reported considerable backup onto the floor and anxiety, particularly among teachers/parents and children, as they became separated from

one another whilst attempting to exit the floor. During this time one staff member and one carer assisted one of the wheelchair users down the stairs, returning to assist another. The space freed in the lobby facilitated the passage of occupants but staff reported restricted flow on the stairs due to the assisted evacuation of the wheelchair users and the counter-flows on the stairs as the assistants returned. Despite the assistants having no training, 2 wheelchair users were successfully evacuated down the stairs. The 3rd wheelchair user, however, refused assistance by staff. Although unable to walk, he insisted on taking control of his own evacuation by bumping his way down the stairs. Understandably the staff members involved were annoyed by this incident, considering that the gentleman was being rather fractious in refusing their offer of assistance. Interestingly the author of this paper met the gentleman concerned in another context and he had a very different interpretation of the situation; he told how he had become distressed as he sat in the lobby for around 15 min listening to the alarm, witnessing an anxious crowd as they tried to evacuate past his group and, importantly, the attempts by staff members to assist his friends down the stairs. His main reason for taking control of his own evacuation was simply that he lacked confidence in the abilities of staff to safely assist him down the stairs and felt it was reasonable that he should be allowed to evacuate himself. It is estimated that the evacuation of the building (excluding the wheelchair user just discussed) took in the region of 15–20 min. An evacuation reportedly would normally have taken in the region of 3–4 min.

6. Impact of changing demographics on flow dynamics

Design guidance regarding exit and stair sizing generally makes assumptions of optimum flows derived from data on largely able-bodied homogeneous populations. Although design and procedural measures are frequently implemented in multi-storey buildings to aid those who are unable to use or find stairs difficult, it is clear that many with mobility limitations will attempt to use stairs irrespective of those limitations. Additionally, in the absence of evacuation lifts, individuals may be required to be accompanied down stairs using various assistive techniques. The reality is that many persons of different shapes, sizes and abilities will be using stairs and other components of the escape route. It is important therefore to review our understanding of parameters that may affect the flow dynamics i.e. speed of movement and space requirements. These and other behaviours associated with mixed ability evacuation are considered below.

6.1. Individual walking speeds

A recent comprehensive review of published data on travel speeds on the horizontal and stairs is provided in the latest edition of the SFPE Handbook [89] and an excellent overview of stair travel speeds is provided in [90]. Both suggest wide variation in unimpeded walking speeds on the horizontal (0.3–2.5 m/s), stairs descent (0.1–2.1 m/s)³ and stairs ascent (0.1–1.3 m/s). The typical unimpeded horizontal walking speed suggested in design codes and guidance documents, however, is in the region of 1.2 m/s [4]. This figure has its origins in work by Pauls [11], Fruin [12] and Predtechenskii and Milinski [53] involving mainly able-bodied individuals in evacuation drills and everyday movement. Suggested walking speeds on stairs is more variable, with recognition that speeds will depend on stair design (faster speeds with smaller rise height) [4]. Reference is typically made to studies by Ando et al. [57] who suggested speeds of 0.8 m/s (descent)

³ Incline speeds presented here; other published speeds are based on vertical distance, and may or may not include distance on landing.

and 0.7 m/s (ascent) and Fruin [13] who suggested descent speeds ranging from 1.01 m/s (young males) to 0.6 m/s (females > 50).

A detailed summary of data, including unassisted and assisted unimpeded walking speeds of disability groups on the horizontal, ramps and stairs (ascent and descent) is provided in [83]. This source contains descriptive statistics for each data set, as well as information on the original source of the data, the nature of the study, sample size and the spatial configuration of the spaces in which the observations were made. An excellent commentary on studies of movement of people with disabilities and elderly and new data is also provided in [32]. The data reviewed from various sources [84–87] suggests that unimpeded horizontal walking speeds for people with disabilities are wide ranging (0.1–1.72 m/s). Significant differences between those using/not using a walking aid have also been reported [84] with, eg, the mean speed of those not using an aid being 0.95 m/s (range 0.24–1.68 m/s) compared 0.57 m/s (range 0.1–1.0 m/s) for those using a walking frame; mean speed of wheelchair users on the horizontal was found to be in the region of 0.7 m/s [84]. Speeds on stairs tend to be lower with mean descent speeds of those using an aid typically in the region of 0.3–0.4 m/s [84,85]. Reported mean speeds of those not using an aid are wider ranging with the stair descent and ascent speeds suggested by Jiang et al. [85] (mean: 0.85 m/s (descent) and 0.76 m/s (ascent)) being more than double that suggested by Boyce et al. [84] (mean: 0.33 m/s (descent) and 0.34 m/s (ascent)). The reasons for differences lie potentially in the different stair inclines involved (17.7° in [85] compared to 37–38° in [84]) and the instructions given ('at highest speed can maintain' [85] compared to 'in a prompt manner' [84]).

It has been recognised that walking speed varies by age [13,52], with early studies [52] suggesting a 20–25% reduction in speed for over 65 compared to adults aged 18–40 years. Recent research has suggested relatively high mean walking speeds of older adults (60–81 years) [88] walking on the horizontal at 'normal' and 'fast' pace, i.e. 1.31 m/s and 1.71 m/s respectively; however, it is important to note that these measurements were made over very short distances (8 m). The mean horizontal speeds of larger samples of older adults with lower limb musculoskeletal pain walking 'as fast but as safely as you can' were also determined to vary with age, i.e. 0.75 m/s (aged 65–74 year, n=321) compared to 0.59 m/s (75–84 years, n=78). The mean descending speeds of older adults over short distances on stairs were determined [88] to be in the range 0.6 m/s to 1.15 m/s depending on stair dimensions, and whether walking at 'normal' or 'fast' pace. However, Kuligowski et al. [32] reported a much lower mean speed of older adults traversing longer distances (13 storeys) during an evacuation drill on a 25.1° stair (mean: 0.41 m/s, range 0.14–0.91).

Little data exists with respect to the speed of those who are overweight or obese, although a review of health literature has suggested that the walking speed of those who are obese is approximately 90% of non-obese and that walking speed reduces as a function of BMI [74]. A recent study [89] of a small sample (n=18) of overweight persons walking 135 m 'as if exiting a building during an evacuation' reported relatively high speeds of 1.81 + 0.16 m/s and 1.76 + 0.27 m/s for males and females respectively; although these high speeds were attributed to the fact that BMIs were in the lower range. Despite this, a significant correlation between BMI and the distance covered in a standard 6 min walking test was reported. Another study [75] determined the mean horizontal speed of overweight and obese persons with lower limb musculoskeletal pain over short distances (6 m) to be 0.86 m/s and 0.78 m/s respectively. There is little data on speeds of overweight or obese individuals on stairs, although one study reported ascent speeds of a small number (n=5) of overweight participants to be in the range of 0.56 m/s to 1.31 m/s depending on the stair incline and whether walking at 'normal' or 'fast' pace [90]. It seems that the impact of obesity on speed is still relatively unknown. One issue is that BMI has been

challenged as a method to determine obesity as it cannot distinguish between muscle or fat mass and is not necessarily reflective of one's level of fitness [71]; indeed it has been argued [89] that other measures of obesity which consider body fat should be adopted in future studies.

It is an important limitation of most experimental studies mentioned above that speeds were measured over relatively short distances; stair speeds, for example, tend to be measured over only one flight [84,85]. When considered together with the nature of the instructions given, the data arguably may not be reflective of speeds of travel which are initially chosen, nor indeed those that can be maintained over longer distances in an emergency. Care must be taken in extrapolating these results into other situations; different terminology is used throughout (eg locomotion disability, mobility impaired) and samples are often small and poorly characterised with little information on participants' age profile, fitness levels, or severity of disability. The importance of understanding the extent to which fitness, older age, obesity and other morbidities coexist is essential in our understanding of functional capacity of individuals and groups [74].

In addition to unimpeded travel speed of unassisted ambulant persons, a number of studies have considered speeds of movement that can be achieved by those using different assistive techniques/devices descending stairs [32,43,91]. Studies suggest [43,91] that relatively high speeds can be achieved using specifically designed evacuation chairs compared to other types of carry chair or manual wheelchair. Mean speeds for an evacuation chair are in the region of 0.7–0.8 m/s whilst speeds using other types of carry chair are in the region of 0.3–0.6 m/s (for mid-weight person being assisted by firefighters [43] or trained hospital personnel [91]). The mean speed of manual carry in a wheelchair over a short distance (in ascent and descent) is in the region of 0.3–0.4 m/s [43,93,94]. Comparison of data for use of an evacuation chair hints at the impact of training, with participants in one study where assistors were highly trained [91] achieving higher speeds than in another with untrained assistors [92], despite lighter weights. However, the impact of training and weight of person being assisted has not been investigated at any length thus far.

6.2. Stopping/fatigue

It is important today, given the propensity for taller buildings, to understand the performance of those with reduced mobility over longer distances. The impact of fatigue in evacuations involving longer distances viz walking speed, frequency and duration of rests is relatively unknown [95,96]. Research by Choi et al. [95] for example, was inconclusive with respect to the impact of fatigue (based on walking speed) in stair descent, i.e. speed over 50 storeys decreased for 50% of participants but increased for others. Reduction in speed, however, is more likely in ascent than descent due to increased physical workload [96]; Choi et al. [95] reported on average a 60% decrease in ascent speeds over 20 floors, with Delin et al. [97] also noting significant decreases, particularly over the first 40 m of ascent. It is important to note, however that both studies involved young participants with no suggestion of any mobility issues.

A review of the literature revealed only one study which sought to investigate the impact of fatigue on persons with reduced mobility [32]; although an analysis of speeds on different portions of the escape route suggested a general trend downwards, statistical tests indicated that these were not significant. The impact of fatigue for those with reduced mobility cannot, however, be discounted. A study by Ayis et al. [75] explored the self-reported times to walk on flat ground before stopping for 1066 persons of mixed gender, age and BMI with lower limb, musculoskeletal pain. Comparison with measured walking speeds determined in a 6 m walking test (walking 'as fast but as safely as they could'), suggested a clear positive correlation between walking speed

and duration of walking before stopping; for example, a mean speed of 0.55 m/s for those able to walk for less than 5 min compared to mean speeds of 0.68 m/s (those who could walk up to 15 min), 0.83 m/s (up to 30 mins) and 0.94 m/s (more than one hour). A useful graphical illustration is provided in [74].

Stopping to rest was not particularly evident in the studies of individual movement discussed above but this is not surprising given the short distances covered in most cases. The only study to quantify stoppages of individuals moving unassisted was that of Boyce et al. [84] who noted that 14% of those with a 'locomotion disability' required at least one rest over the relatively short 50 m distance in the horizontal plane; no rests were reported on stairs over one flight. Hunt et al. [91] noted frequent stoppages for each of the devices used in assisted escape (over 13 storey descent) in order to change handling positions, handlers or to rest. It was noted that all stops (greater than 2 s) occurred when the handling team was partly on a flight of stairs and partly on a landing and that female teams generally required more stops than male teams. The only device with which stops were not required was the evacuation chair. The average stopping duration of the other devices for male and female handling teams respectively was 10 and 14 s (stretcher), 8 and 11 s (carry chair) and 8 and 3 s (rescue sheet). The need to stop was also evident in WTC on 9/11 [78,79]. Individuals reported stopping to rest for short periods of time, sometimes on stairs, but often on landings, which also facilitated overtaking. Importantly this included not only those with mobility impairments but others who were described as having respiratory problems, being overweight, elderly as well as helpers and fire fighters.

6.3. Spatial requirements

One potential impact of changing demographics on flow is the spatial requirements of individuals. Changing body size and shape, the use of assistive devices such as wheelchairs, scooters, crutches and walkers to overcome mobility limitations and the need for assisted escape all have space implications. These may affect local densities, influence interaction with other pedestrians and restrict movement, depending on the width of escape routes and whether overtaking is possible. The potential impacts of increased body size have been discussed previously [10,74], although it has been recognised that absolute impact is difficult to quantify. Some [10] have referred to the work of Pauls [11] who noted a 10–20% reduction in the mean evacuation flow (persons/s/m of effective stair width) for an evacuating population when coats were used compared to no coats; this, at least from a spatial perspective, hints at the impact of increased body size. The negative impact of winter clothing on flow was also observed by Predtechnskii and Milinski [53], who defined density, not in the usual units of people/m² but in terms of the ratio of the total horizontal projected area of individuals to the area of the flow (m²/m²). Increased body size, in this approach, results in an effective increase in density, impacts inter-person spacing and hence possible restrictions on movement.

Anthropometric projections relating to obesity vary internationally, and therefore, whilst it is likely that the percentile values in any given population in relation to abdominal circumference/depth are changing, it is not possible to provide definitive data on such. It is, however, recognised that body fat usually accumulates around the mid-region of the body and MacLennan [77] has reported body ellipses of up to 0.44 m², i.e. much higher than the 0.123 m² suggested previously [53]. Traditionally shoulders have been recognised as the widest dimension to be considered in relation to movement. However, according to [8], citing recent anthropometric data, the shoulder width of the 97.5th percentile US adult male is reaching 510 mm, and the width at the hip is approaching the width at the shoulder. This narrowing of the gap between hip width and shoulder width, particularly in women, has also been noted by Pheasant [98].

The most readily available information on the spatial requirements of individuals using mobility aids is in guidance documents relating to access. UK guidance on the spatial requirements of those using mobility aids in relation to access suggests widths of 750 mm (for a person using a walking stick [99]), 900 mm (walking frame [99]), and 1200 mm (for a person using crutches, a blind person using a cane [100] and a visually impaired person being guided [99]). Many sources provide information on dimensions and space requirements of wheelchair users. As an example, the 90th percentile values for occupied space (reflecting projection of users' feet beyond footrests and projections of upper limbs/clothing beyond the armrests or wheels) of self-propelled and electric wheelchairs are 720×1190 mm and 760×1384 mm respectively [100]. The length of a wheelchair user with an assistor (when stationary) is between 1200 and 1570 mm [99]. The width allowance for an ambulant person passing a wheelchair user on an access route has been suggested as 1500 mm [99].

Clearly individuals using such aids require significantly more space to traverse travel paths than others. It is important to note, however, that information on spatial needs of those using mobility aids (with the exception of wheelchair users) relates only to widths; information on length, which is also important with respect to flow, is missing. Furthermore, the footprint may vary depending on whether movement is in the horizontal or vertical plane, as well as on the direction of travel and handrail use. It has been noted [84] that many persons with disabilities seek support from handrails in movement; this was particularly evident in one study on stairs with 91% and 94% utilising the hand-rail for support in ascent and descent respectively. Although not quantified, differences in the location of individuals relative to the handrail in ascent/descent have also been noted [84]; in ascent individuals located close to the handrail as they used it to assist them in the physical challenge of the ascent, whilst in descent they located further from the handrail with an outstretched arm for support. This is not currently recognised in assumptions regarding stair use which form the basis of codes or evacuation modelling.

As noted previously, there are many techniques for assisting wheelchair users and others to evacuate via stairs [42,101]. Although information exists on the dimensions of the assistive equipment [91], little exists on the actual footprint of assistors using different devices and techniques or space required for manoeuvrability. Dimensions relate only to width; for example, 900 mm for a 2 person wheelchair roll evacuation [102], 1300 mm of clear width for a 3 person carry of an occupied wheelchair on a stair [103] and 1500 mm for a 4 person wheelchair carry [102]. The width for an evacuation chair, with assistor at the rear is the dimension of the device itself, which is in the region of 520 mm.

6.4. Behavioural considerations

The potential impact of changing demographics on flow dynamics may not be restricted solely to reduced movement speed and increased space. Flow may be impacted by how others relate to those with reduced mobility during escape. Altruistic behaviour is common during evacuations; slower movers are likely to be moving as part of a group [104] even if they do not require physical assistance. It is also common for assistors or others to form a 'human cage' around a slower moving individual to protect them from undue 'pressure' from other evacuees [81,105]. In WTC on 9/11 one evacuee noted that 6–8 others who were not her assistors remained behind her for much of the descent even though they had ample opportunity to pass [81]; similar behaviour was exhibited by persons moving behind a wheelchair user being assisted on stairs during an evacuation drill despite there being sufficient free width of stair to pass [94].

A recent study by Thompson et al. [106] has also indicated potential differences in how older adults and younger individuals locate

themselves relative to one another. In treadmill experiments, older adults and young adults walked at their preferred speed (and 25% above and below) and distance behind a man-shaped object (intended to mimic an evacuating person moving at the same speed); distance was measured precisely using a state of the art motion capture system. Notably, although the preferred walking speed of the younger group was significantly greater than that of the older group, older adults chose to leave significantly more space than younger adults (at least double) across all conditions. Although all subjects reduced their distance when a barrier (to mimic a person approaching from behind) was in place, this adjustment was greater in the younger group; whilst not found to be significant, it was suggested that older adults may be keener to maintain their distance despite perceived pressure from behind due to a reduced capacity to adapt. Despite the limitations of this study in terms of external validity, results suggest that the preferred inter-person spacing of older and younger adults may differ and should be investigated further.

6.5. Experimental and modelling studies of changing demographics on flow

The impact of demographic variations on flow has been studied both experimentally [107,108] and through computer modelling [74,109]. Shurin and Apakov [107] studied experimentally flow/density relationships for groups of able-bodied, elderly and disabled persons on stairs. The results showed reduced flows for given densities for elderly/disabled persons compared to able-bodied; the differences, however, reduced as densities increased, i.e. when movement was influenced by the proximity to one another rather than individual unimpeded walking speeds. Shimada and Naoi [108] studied the movement of able-bodied students and wheelchair users in different proportions through an opening in an experimental rig. Not surprisingly, their results show reductions in flow with increased proportions of wheelchair users, i.e. 20% and 50% reduction in flow with 10% and 30% wheelchair users respectively. Spearpoint and MacLennan [74] used a Monte Carlo network evacuation model, to consider whether predicted demographic changes (2006–2031) in the New Zealand population impacted total evacuation time from a typical high rise building. Whilst recognising limitations of their study in relation to obesity predictions and speeds for older age groups, the results indicated that at low occupant numbers (and resultant densities) the total evacuation time increased by 5–8% but with higher densities the differences were negligible. The latter was attributed to the fact that queuing dictated the overall evacuation time rather than individual walking speeds. When compared to simulations utilising Canadian data for gender and age profiles in 1971, up to 20% differences in evacuation times were suggested. Thompson et al. [109] also investigated the effects of elderly people (mobilityimpaired) and body dimensions (use of life jackets) on flow rates in an attempt to consider the consequences of demographic change. The results indicated that a population group with 40% mobilityimpaired occupants produced a much lower flow rate than a fit, able-bodied population group (53 people/m/min and 95 people/m/min respectively). Although, arguably, the experiments above are limited in terms of external validity and the adopted evacuation models are limited by their ability to accommodate the complex dynamics of mixed ability movement, the studies, at very least, suggest potential for demographic change to impact flow dynamics.

7. Human factors related to the use of refuges, lifts and assisted escape

As noted earlier, refuge areas are commonly recognised as an integral part of the evacuation strategy for those with mobility limitations. The first study to consider human behaviour aspects of the use of refuge areas (including willingness to use, implications for emergency

planning and changes/additions to make refuges safe and acceptable to users) was conducted in 1992 [20] on behalf of the General Services Administration (GSA), who had recently retrofitted six offices buildings with refuge areas, a relatively new concept at that time. Levin and Groner [23] concluded that intended users would accept the concept if implemented properly. However, they recognised that the use of refuge areas added complexity to design and emergency response procedures and suggested that refuge areas only be used if attention was paid to the informational needs of building occupants, which they concluded was severely lacking. In particular, the psychological and physical needs of users needed attention; lack of vision and seating were noted, the latter since not all potential users were wheelchair users but others for whom standing for long periods of time would be unreasonable/impossible. They also noted that users were generally uninformed about the features of the refuge areas and additional information was needed to increase confidence in their use.

More than 15 years later, UK researchers consulted with building professionals (designers and managers) and users who had a disability to consider the success and appropriateness of refuges and associated management procedures [41]. Although the sample of users was small, the study confirmed the lack of understanding and concerns among people with disabilities regarding the use of refuge areas and strategies for their evacuation. The accounts of wheelchair users who had used a refuge under real emergency conditions highlighted some of the problems:

- *.. If someone answered the phone they generally did not know what to do...It was never clear what the procedure would be ... i.e. if and how I would be evacuated from the building.” User 3 [41]*
- *“I was left on the stairwell by the usher who told me that I had to wait there on my own while my friend was to be evacuated with everyone else ... I was both shocked and horrified at the idea of being left alone in the hope that someone outside would remember that I was still in there” User 4 [41]*

These accounts point to lack of clarity regarding how the evacuation was to proceed and feelings of isolation due to lack of appropriate communication. Another account, from a wheelchair user who had used refuges previously and reported being happy being carried in his wheelchair demonstrates how lack of communication forced him to take control of his own evacuation despite obvious mobility limitations:

- *“it was the middle of the night, I was on the 5th or 6th floor or higher. No-one told us what was going on until I finally managed to ring on a mobile. No-one waited with me. I felt extremely unhappy and tried to make my way down the stairs after about 15 – 30 min, but had to give up. . .” [User 6] [41]*

Not all experiences, however, were negative. One user noted: *“I’ve used a refuge many times. I was on the 7th floor... I was happy using the refuge area and usually someone waited with me. I felt safe waiting there and would be happy to do it again.*

The concerns expressed in this study prompted more significant studies in the UK [110], Sweden [38] and Italy [37]. McConnell et al. [110] explored the level of awareness, understanding, concerns and willingness of 83 persons (19–70 years) who ‘would find it difficult’ or ‘would not be able’ to descend one storey using stairs without assistance, i.e. those who may need to use a refuge in an emergency. It was disturbing to note that only 59% had ever heard of the term refuge and of those who had, just under half only loosely understood its meaning; results in Sweden and Italy were even lower (44% [38] and 17% [37] respectively). Once the concept of a refuge was explained, 78.6% expressed their willingness to use it [110]. The main concerns in all studies related to being forgotten, being left alone and the safety of the

refuge. The time that participants were willing to wait in a refuge with and without information about what was happening was also considered. McConnell and Boyce [110] found that, in the absence of information, only 35.3% of participants who were unable to use stairs and 51.2% of those who would find it difficult to descend one storey using stairs would wait more than 10 min. Although the percentages varied from study to study all noted increased waiting times when communication was provided. Andree et al. [38] also explored management of refuge areas and concluded that there was a lack of understanding of who had responsibility to assist persons from the refuge area; this has been evident elsewhere [41] with building owners refusing wheelchair users entry during a strike by fire fighters because building management considered they would be unable to evacuate them.

The studies noted above with respect to the use of refuges also explored views of wheelchair users and others regarding their vertical evacuation, specifically being assisted in an evacuation chair or in their own wheelchair (if applicable). Whilst it is accepted that it may not be appropriate for all wheelchair users to be transferred to an evacuation chair, confidence in using an evacuation chair was higher than using their own wheelchair [38,110]. Fears related to wheelchair usage included falling, being injured or putting others in danger. A more recent study of wheelchair users working in medium to high rise office buildings in the USA confirms these fears but also notes the loss of the mobility device as another concern [111]. The experience of the wheelchair user in the evacuation of the Ulster Museum [80], who refused assistance and bumped his way down the stairs, would suggest that such fears are exaggerated when one lacks confidence in the assistors. Indeed, this conflict between the perceived risk of injury being carried in a wheelchair and the desire to have independence and control over one's own destiny has been highlighted recently in other studies [111]. Another comment by a wheelchair user: *"I am well used to being carried about by my friends so I am confident enough in situations like that"* [41] suggests confidence can be developed through training and practice.

A number of studies have considered human factors with respect to the general use of lifts for evacuation [112–115]. The largest and most recent survey [113] suggests that there are still concerns with the use of lifts for evacuation, with two-thirds of the sample suggesting that they would not consider using a lift to evacuate even if they were informed it was safe to do so. Interestingly, the willingness to use lifts in preference to stairs increased with both age and BMI, however, these differences were not found to be statistically significant [113]. Whilst there seemed to be cultural differences (related to propensity for tall buildings and familiarity with the use of lifts) all studies suggested that willingness to use lifts increased with floor height (stabilising at 40 storeys according to [113]). Although not statistically significant, Kinsey et al. [113] suggested that the decision to use a lift may be influenced in part by recognition of one's physical limitations. This is supported by findings elsewhere [111] which suggested that 73.5% of those who were 'unable' or would 'find it difficult' to use stairs would be 'reasonably/very' confident using a lift. For those who were not confident the reasons given were fear of 'failure of the power supply', 'the doors opening onto the fire floor', 'overloading of the lift' and 'being trapped'. Although concerns were expressed by some, the many benefits were also recognised [111]; these included providing safety (compared to being carried or making own way down), feelings of relief regarding reduced waiting times, recognition that they could leave with their mobility device, increased communication capabilities, speed, independence and efficiency.

8. Discussion

A significant proportion (approximately 20%) of our society has a disability and this percentage is likely to increase in the future given

current demographic trends relating to aging and obesity. This, fact, together with increased accessibility, means that building populations are becoming more and more diverse, i.e. it is no longer safe to assume that they only comprise individual who are able-bodied and fit.

An accessible environment has been defined [29] as one which is *"free of barriers which exclude, endanger or inconvenience those with acquired or inherited physical impairments"* By definition, individuals should be able, not simply to access buildings but to do so without danger; thus the link between access and safe egress is established. It is important to note that, statistically, there is no evidence that those with disabilities and/or older people are at any greater risk in fires in public buildings or workplaces than others, albeit that disability and older age are known risk factors in residential premises [116]. Although on 9/11, at least two persons with disabilities (one waiting at a rest stop and the other with a friend on stairs) were unable to evacuate before the building collapsed, it was concluded [78] that there was no significant over-representation of those with mobility impairments among the deceased.

This paper has set out to explore, in the context of changing demographics and increasing accessibility to buildings, whether we are indeed providing safety for all. It has set out to explore whether, in the spirit of inclusive design [117], we recognise the diverse nature of those who use our buildings and design such that everyone, irrespective of ability, can use buildings safely, easily and with dignity.

In the context of design it is important to be able to characterize the population of any building [4, 118, 119]. However, it is difficult to translate statistical data related to disability in society directly into proportions of building populations that may experience some difficulty in evacuation for design purposes. For example, the most common type of impairment relates to mobility (8%) but definitions of such often includes benchmarking against factors involved in daily living which may not necessarily translate to difficulties in evacuation; some occupants in WTC, for example, who reported having difficulties with mobility, seemingly experienced no particular difficulties in evacuating relative to others [81]. Furthermore not all people with disabilities are active beyond their homes (although this proportion is relatively small [38,120]); Boyce et al. [110] accounting for this fact, estimated that approximately 8% of regular adult users of public buildings in Northern Ireland had a locomotion disability and suggested that this figure could be used as a benchmark for occupant characterization for design purposes. Occupant characterization, however, may not be that simple, given increased accessibility across the globe. For example, it is common for public buildings (shopping centres, theatres, cinemas) to be visited by large groups of persons with disabilities. Design therefore needs to be more flexible to accommodate diversity in building populations both in terms of ability and numbers which vary from day to day.

It has long been recognised that safe escape is dependent on both building design and management. However, whilst there are many gaps in our understanding, there is much evidence to suggest that there are issues with respect to both in relation to mixed ability evacuation. With respect to design, arguably, we cater for just two groups of people - able-bodied persons and wheelchair users. Firstly, although design guidance with respect to exit/stair width varies internationally, it tends to assume flows which have their origins in historical studies of movement; although the populations have not been characterised in detail it is safe to assume (given the timing of the studies) that they comprised mainly able-bodied persons and thus flows may not be reflective of building populations of today. Indeed the assumption of flows which form the basis of design guidance (45 people/min/unit width (22 in.) or 80 people/m/min) has been challenged often. Bukowski and Tubbs [8] note that, even from very early days, this flow was considered optimal and deemed to be unsuitable as others (Togawa and Pauls) suggested more typical rates of movement on stairs of 26–27 people/min/unit width. Secondly, whilst many countries recognise that some occu-

pants will not be able to use stairs and suggest the provision for refuge areas as temporary safe spaces to await onward assistance, these areas tend to be sized based on the assumption that they will only be used by wheelchair users [35,38] when this is clearly not the case. There is therefore no consideration given in design assumptions to the fact that building occupants will have a spectrum of ability.

It has been evidenced here that many will attempt to use stairs, irrespective of their limitations, and this can significantly alter the flow dynamics compared to that of homogenous, able-bodied populations. The fact is that some within our building populations will move more slowly and may need to stop for rests. As presented here, speeds on the horizontal and stairs, particularly of those using mobility aids, can be significantly lower than those suggested in design guides. Reduced walking ability results not just in reduced walking speed but also maximum walking times before stopping [75], i.e. slower moving individuals more often need to stop for rests which can vary in frequency and duration [78,81,84]. Aging and obesity affects the functional capacity of individuals in movement and demographic trends in this respect suggest that the distribution of speeds within building populations may shift downwards in the future. Obesity also results in larger body sizes with suggestions of body ellipses of up to 0.44 m² being reported [77] and it has been established that those with mobility impairments often use devices to aid their movement. Therefore, in addition to expected lower movement speeds, many will require more space than one evacuating without such aids. Slow movers are also more likely to be accompanied by family/friends and moving as part of a group. Such groups often exhibit altruistic behaviour, not just offering physical assistance but protecting the slower moving individual from the pressure of the crowd [81] and can comprise as many as 10 people [81,82]. Although evidence from real evacuations and research presented here points to the potential impacts of changing demographics on flow, these impacts still need to be quantified. Arguably modelling studies discussed here have assumed high, and perhaps unrealistic, proportions of persons with disability and are limited by the current ability of the models to accommodate the complexities of mixed ability flow. Recent drills involving stair evacuations [120] have reported movement data that is regarded as being 'reasonably consistent' with historical data. However, these were conducted mostly in office buildings, and arguably may not have included as wide a demographic as could be found in public buildings of today.

It is important to recognise that the impacts of changing demographics on flow may be more significant at lower densities; as space becomes more congested the proximity to others rather than independent walking speed may be the determining factor. Notwithstanding, the validity of previously derived relationships between speed and density need to be considered in light of changing demographics. Significantly, the continued use of historical data and relationships thus derived have been questioned by the original authors [13] who have recommended that their data and derived relationships be removed from guidance documents in recognition of changing demographics and urged that new empirical studies be conducted and improvements in modelling of pedestrian movement made. Recent studies [120], have also suggested that simple algebraic formulas for the prediction of speed as a function of density is a significant over-simplification of the process; put simply these relationships mask the complexity of mixed ability movement [13]. Such sentiments have been expressed by Thompson et al. [106] who go further to suggest the need to disregard such simple relationships entirely in favour of an emergent model of crowd movement. Such a model based on detailed biomechanical, ergonomic and behavioural research would be able to predict the speeds based on an understanding of functional capabilities, space requirements of individuals and groups, and decisions that individuals make relative to their positioning in the crowd, rather than being defined relative to density at any given point in time. Whilst it is recognised that

there have been significant developments in evacuation modelling in recent years, limitations still exist [50], not least in the ability to model those with disabilities moving unassisted or assisted, space requirements, overtaking behaviour, fatigue, counterflows etc., albeit that some are moving in this direction eg. [91,106,121].

Clearly the development of computer evacuation models to accommodate the complexity of mixed ability evacuation is a significant challenge but essential for the future safety of building populations. So too is the sufficiency of escape route widths currently recommended in design guides and codes. Clearly, if escape routes are of insufficient width to facilitate passing of slower moving individuals and accommodate counter-flows on stairs caused by those ascending to offer assistance, this will impact the safe evacuation of the entire population, not least those evacuating from floors affected by fire. The need for increased stair widths is not new; decades ago, for example, Pauls et al. [13], suggested that minimum widths should be in the region of 1320–1520 mm to allow for body projections and lateral sway, whilst 1400 mm has been proposed by others [122]. Guidance related to access [100], suggests that 1500 mm is required to facilitate an ambulant person overtaking a wheelchair user on an escape route. Pauls et al. [13] have recently once again challenged stair design urging that new anthropometric and ergonomic data, particularly with respect to maximum lateral dimensions and lateral body sway needs to be collected. Although international variations are expected, this is deemed particularly important in light of the obesity epidemic and suggestions that hip width in some countries is approaching that of the shoulder (traditionally assumed to be the widest dimension) [8].

Changing demographics and accessibility also challenges us to consider the design of refuge areas. Arguably, even where recognised and specified in design codes, the sizing of refuge space is wholly unsatisfactory. In the UK for example, space is recommended for one wheelchair user for each protected stair at each level [35]; considered together with other recommendations that permit 2 stairs for up to 600 people (provided travel distances can be met) suggests an underlying assumption that wheelchair users will comprise just 0.3% of the building population, which is far below the percentage of regular wheelchair users (estimated to be 1.2%). The need for refuge spaces to be sized to accommodate persons other than wheelchair users was recognised over 25 years ago [20] yet is still not reflected in design guidance today. Whilst the proportion of any given building population needing to use a refuge is unknown, it has been estimated [119] that 5% of the active adult population in a UK region would not be able to, or would have difficulty, using stairs. Additionally, since some people with disabilities have difficulty standing (33% can stand for less than 5 min [99]) one might argue that space for seating should also be considered, as should space for accompanying persons. Clearly the sizing of refuges is an area for consideration and indeed a challenge. However, the negative implications of not having sufficient refuge space are significant as highlighted in the evacuation of the Ulster Museum [80] in which a disabled group and their carers entered the refuge area at the forefront of the crowd and restricted the progress of floor occupants into the stairs; arguably, had the fire been on that floor, there could have been significant loss of life. It is interesting to note that UK guidance [24] suggests that the number of refuge spaces need not necessarily equal the number of wheelchair users present in the building with the suggestion that users will pass through a single refuge as they are assisted down stairs as part of the evacuation procedure. This assertion, however, is fundamentally flawed and inconsistent with assumptions regarding stair capacity. i.e. on the one hand there is an assumption of optimum flow on stairs consistent with able bodied evacuation yet on the other an assumption that persons with disabilities will be assisted down stairs as the evacuation progresses.

It is widely accepted that evacuation safety can only be achieved through a combination of design and management. Indeed many coun-

tries have separate regulations which require evacuation planning and implementation through the development of procedures, education and training. Underlying the provision of refuges and use of assisted escape or lifts is the assumption that they will be incorporated into strategies and procedures and that staff will be available in sufficient numbers and trained in their use. However, the incorporation of refuge areas, and lifts to the design and need for assisted escape adds much complexity to emergency response procedures [20]. Evidence summarised here with respect to real evacuations gives rise to many concerns with respect to the management of such, with one study [41] suggesting that “*management of evacuation procedures including refuges and their alternatives requires a major overhaul*” and another [78] concluding that “*mobility impaired occupants were not universally accounted for by existing evacuation procedures*” [78]. It is indeed ironic that issues raised in the early 1990s [20] regarding advanced planning and attention to the informational needs of buildings users still seem to be issues in buildings today and begs the question as to whether we are consistently prepared for managing the evacuation of mixed ability populations. Issues giving cause to concern evidenced here include lack of communication with users of refuges leading them to abandon the refuge and take control of their own evacuation (clearly an undesirable and unacceptable outcome), lack of understanding of whose responsibility it is to provide assistance (building management or fire services), and lack of training with respect to assisted escape which could lead to injury. Whilst there is an expectation in some occupancies that individuals can and should take responsibility for their own safety, clearly lack of advance planning and training may have negative consequences. It is recognised that an evacuation system based on the use of refuges is only effective if the end users of that system fully understand it and are confident to use it. Studies alluded to here suggest that there is much education needed in this respect and that communication and the reduction of waiting times is key.

Managing the assisted evacuation of those who cannot use stairs is of course a major challenge, particularly in public buildings where numbers and needs of users are unknown. Managers need to identify those who need assistance and have trained staff available in sufficient numbers to provide it. The evacuation of John Abruzzo from WTC on 9/11 is a reminder of the considerable manpower this may require and management often may be in a difficult situation, attempting to balance legal responsibilities regarding access whilst at the same time facilitating safe escape. Although there are examples of building occupants demonstrating altruistic behaviour, which has to some degree overcome the failings of management, this is not a situation which is desirable or sustainable. Clearly management must take responsibility for planning, education and training to ensure that the evacuation system operates efficiently, effectively and safely; at the same time future escape provision should be based on realistic expectations regarding what can actually be achieved.

Many of the issues with respect to manpower required for assisted escape can of course be overcome by the use of lifts. Indeed lifts fulfil many of the principles of inclusive design [117], namely inclusivity (can be used safely, easily and with dignity by all), convenience (used without effort or separation from others and indeed aids), accommodating (without fuss, regardless of age, gender, mobility). Lifts allow those who cannot use stairs to be treated with respect and represent a real viable option when a single design solution (stairs) cannot meet all needs. Internationally, however, there is no requirement to provide evacuation lifts as the means by which persons with disabilities can make their descent. Whilst some studies would suggest that there is still some adverse reaction to the use of lifts across the demographic [113], others have shown a willingness among those with reduced mobility [110,111,113]; indeed lifts are the preferred option for those for whom stair use is difficult [110].

The review of current understanding of mixed ability evacuation presented here has identified a number of key areas where further research is required, some of which has been identified previously [13,32,123]. The need for improved understanding and egress data which considers the movement dynamics of people with mixed abilities is vital to inform developments in evacuation modelling and guidance documents of the future. Key areas where further research is required include:

- understanding of the extent to which age, fitness levels, obesity and other morbidities coexist, what factors really impact functional capability with respect to evacuation and data associated with such
- the characterization of occupancies for design purposes based on the above and associated movement parameters accounting for anthropometrical and cultural differences;
- space requirements (footprint) resulting from changing body sizes and shape including body sway. Space requirements associated with the use of various mobility aids, assistive escape devices and techniques (eg by number of assistors) by escape route component. In both cases accounting for directional differences (ascent/descent stairs) and handrail use;
- understanding of the impact of fatigue and the ability to sustain movement over longer distances in both ascent and descent, particularly for those with limited mobility; understanding of the relationship between speed and stopping behaviour;
- understanding of behaviours associated with mixed ability evacuation including inter-personal space, passing, altruistic behaviours such as assisting, protecting and the propensity for group formation;
- understanding of the speeds associated with assisted escape across the range of assistive devices and interrelationships with weight (of person being assisted), training and fitness;
- human factors associated with the use of lifts to optimise evacuation for all.

9. Concluding remarks

This paper has considered current understanding of mixed ability evacuation in the context of accessible buildings and demographic change. In an attempt to understand the sufficiency of current egress provision and the challenges that mixed ability evacuation presents, it has considered the basis for current design guidance, options for the evacuation of those with limited mobility and lessons learned from real evacuations and other studies. The title of the paper includes the question - ‘Safe Evacuation for All - Fact or Fantasy?’ In light of the review presented here it is suggested that the answer to that question currently is ‘neither’.

Safe evacuation must stem from appropriate design and complementary management; good management cannot compensate for bad design and vice versa. Whilst it has not been possible to review all guidance and experiences internationally, the review presented here challenges us to consider the validity of the assumptions that underpin some design guidance with respect to, for example, stairs and refuges. Furthermore, there are sufficient examples of management issues relating to evacuation planning, training, communication and assisted escape that lead us to question whether management are consistently prepared for undertaking the complex task of mixed ability evacuation. The need for assisted escape, in the absence of requirements for evacuation lifts for those of limited mobility, is certainly a challenge and potentially a resource issue. Given the above, it is not difficult to envisage evacuation scenarios in which the safety of many in buildings could be compromised and therefore we cannot say with any certainty that currently we consistently provide safety for all.

However, safe evacuation should not be dismissed as a 'fantasy' or something that is not achievable. The provision of safe evacuation for all is certainly a challenge, but should be achievable with the appropriate efforts made from many different quarters. It suggested that this requires the responsibility of:

- researchers: to develop understanding of mixed ability evacuation and quantify performance across the spectrum of ability that be used in engineering calculations and models,
- code developers: to consider, in light of changing demographics and ongoing research, whether exit provision (including stair width) and refuge space is sufficient for today's and future society; also to consider the use of lifts as mandatory for those with limited mobility,
- fire safety engineers: to develop realistic occupancy profiles and scenarios and use the most appropriate data for their application, recognising that this may not always be reflected in current guidance documents which may become outdated,
- evacuation modellers: to continue to develop models such that they can accommodate the complexity of movement dynamics and behaviours associated with mixed ability evacuation,
- building management: to develop and implement emergency plans which are consistent with building design and users needs; inform, educate and train staff in sufficient numbers to manage the process; where possible involve those with disabilities in the planning and perform realistic drills,
- building users, particularly those with reduced mobility: to engage in the planning process and take responsibility in so far as is practicable for understanding options and planning their own evacuation.

Uncited references

[112,118].

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