VERIFICATION AND VALIDATION OF BUILDINGEXODUS BASED ON THE WALKING SPEED OF PEOPLE WITH DISABILITIES (PWD)

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SCHOOL OF CIVIL ENGINEERING
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To my loved ones

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By

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ABSTRAK

Orang kurang upaya (OKU) sering diabaikan dalam reka bentuk bangunan walaupun mereka lebih terdedah kepada bahaya dan menghadapi kesukaran untuk mengakses bangunan seperti stesen keretapi. Kehadiran OKU dalam aliran pejalan kaki mempengaruhi aliran pejalan kaki dengan ketara kerana mereka mempunyai kelajuan berjalan yang lebih lambat, keperluan ruangan yang lebih besar dan kecenderungan berkelompokan. Namun, perilakuan OKU jarang dikaji dalam model simulasi pejalan kaki akibat kekurangan data empirikal. Bagi mewakili perilakuan OKU dalam program simulasi pejalan kaki buildingEXODUS dengan tepat, kajian ini dijalankan untuk mengesahkan keupayaan asas buildingEXODUS, menjalankan eksperimen yang melibatkan pelbagai kategori OKU di pelan lantai berdasarkan stesen keretapi, dan mensahihkan keupayaan buildingEXODUS untuk mewakili OKU. Pengesahan asas model dilakukan dengan menggunakan ujian dari National Institute of Standards and Technology (NIST). Tujuh kategori OKU telah dikaji, iaitu seorang buta, seorang buta dengan pembantu, dua orang buta, tiga orang buta, kerusi roda elektrik, kerusi roda manual, dan kerusi roda manual dengan pembantu. Kelajuan berjalan dan masa jalan keluar OKU yang dipengaruhi pejalan kaki biasa dan tanpa pengaruh telah ditentukan. Dengan data yang dikumpul, senario eksperimen telah dicipta semula dalam buildingEXODUS. Masa jalan keluar yang dihasilkan dalam simulasi dibanding dengan masa eksperimen untuk mensahihkan model simulasi. Secara keseluruhannya, buildingEXODUS dapat mewakili komponen utama yang diperiksa dalam ujian pengesahan NIST. Hasil eksperimen menunjukkan bahawa kehadiran orang biasa akan perlahankan OKU yang berpenglihatan, manakala proses pensahihan membuktikan bahawa buildingEXODUS dapat mensimulasikan OKU dengan hasil yang sebanding dengan fenomena sebenar, dengan syarat demografi penghuni diketahui.

ABSTRACT

People with disabilities (PWD) are often overlooked in building design although they are more vulnerable to hazards and face greater difficulties in accessing buildings such as train stations. The presence of PWD has a significant influence on pedestrian flow due to their slow walking speed, high space requirements and grouping tendencies, but their behaviours are rarely explored in pedestrian simulation models due to lack of empirical data. In an effort to accurately represent the behaviours of PWD in the buildingEXODUS pedestrian simulation model, this study aims to verify the core abilities of buildingEXODUS; conduct an experiment involving different types of PWD based on a train station layout; and validate buildingEXODUS' capacity to simulate PWD. Verification of the model was done using selected standard tests from the National Institute of Standards and Technology (NIST). Seven categories of blind and wheelchair-bound people were studied, namely blind, blind with an able-bodied assistant, two-blinds, three-blinds, electric wheelchair, manual wheelchair and manual wheelchair with assistance. The walking speed and egress time of PWD with and without the presence of normal people was then determined from the experiment. Using the data collected, the experiment scenario was recreated in buildingEXODUS. The simulation egress time was then compared with the experimental egress time to validate buildingEXODUS. Overall, buildingEXODUS was able to represent the selected main core components of evacuation models that were scrutinised in the NIST verification tests. Experiment results indicated that the walking speed and egress time of sighted individuals were negatively influenced by the presence of other pedestrians. Subsequently, the ability of buildingEXODUS to simulate PWD was validated. The simulation can produce comparable results to real-life phenomena given that the occupant demographics are sufficiently understood.

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AN_VERIF	Analytical Verification
BUMMPEE	Bottom-Up Modelling of Mass Pedestrian flows—implications for the Effective Egress of individuals with disabilities
CAD	Computer-aided Design
CM	Cumulative Mean
CO_2	Carbon Dioxide
DXF	Drawing Exchange Format
EB_VERIF	Verification of Emergent Behaviour
ECRL	East Coast Rail Link
fps	Frames per Second
HSR	High-speed Rail
ICT	Information and Communications Technology
IMO	International Maritime Organisation
KJ	Kelana Jaya
KLCC	Kuala Lumpur City Centre
KVMRT	Klang Valley Mass Rapid Transit
LRT	Light Rail Transit
MS	Malaysian Standards
NIST	National Institute of Standards and Technology
NKRA	National Key Results Area
occ	Occupant
OKU	Orang Kelainan Upaya
PET	Personal Egress Time
ppm	Pedestrian per Minute

PWD	People with Disabilities
SD	Standard Deviation
SE	Standard Error
TET	Total Evacuation Time
UD	Universal Design
USM	Universiti Sains Malaysia
WHO	World Health Organisation

CHAPTER 1

INTRODUCTION

1.1 Background

Rail-based travel is seeing a worldwide revival as policy-makers seek to make their transportation system more sustainable, cities more liveable, economies more resilient to future shocks from oil vulnerability, and from the need to reduce CO_2 emissions in the face of global warming (Newman and Kenworthy, 2015).

Malaysia is rapidly expanding its railroads to provide world-class rail travel to its citizens in order to improve sustainability, connectivity and liveability of the city, starting in the Klang Valley area. Since the announcement of the 6 National Key Results Areas (NKRA) in 2009, which includes "Improving Urban Public Transport" as one the six NKRAs, development of the urban rail network in Malaysia has been in full swing. This is evident with the ongoing construction of the Klang Valley Mass Rapid Transit (KVMRT), High-speed Rail (HSR) connecting Kuala Lumpur to Singapore and East Coast Rail Link (ECRL) (Performance Management & Delivery Unit, n.d.).

As Malaysia and the world shift to a rail transit system to alleviate traffic congestion, train stations are becoming important congregation places of the masses. When a high volume of people accesses a place, safety and accessibility become crucial issues. It is imperative that walking facilities be designed to reflect heterogeneity in pedestrian composition as different types of pedestrians behave differently. These differences need to be taken into account for the safety and comfort of the built environment. Pedestrian behaviour has been extensively studied but few studies have been done with vulnerable population groups such as people with disabilities (Christensen et al., 2006).

In Malaysia, there are approximately 409,269 (1.31%) registered PWDs, and possibly more not registered in the system (Department of Social Welfare, 2016). Although PWDs are a minority in the pedestrian flow, their presence has a profound impact on crowd behaviour and egress time (Christensen et al., 2006). However, many traditional codes and guidelines overlook PWDs and consider pedestrians as a homogeneous group (Sharifi et al., 2015).

Pedestrian simulation models provide a means to model and study pedestrian flow holistically, taking into account pedestrian walking characteristics, interactions between pedestrians and interactions with the environment. However, simulations with PWD are not common, as their behaviours are less understood. Human behaviour needs to be accurately represented in a simulation model in order to improve the accuracy of egress models, accessibility of the built environment, and ultimately the safety of pedestrians (Muhdi, et al., 2009). Therefore, this study aims to verify and validate an existing building evacuation simulation software - buildingEXODUS' - ability to simulate disabled people by considering the egress of PWD and normal pedestrians in an experimental setup based on the layout of a train station.

The outcomes of this study can be used to better understand the behaviours of different groups of PWD. Henceforth, buildingEXODUS can be used to represent PWD with greater confidence and accuracy. The pedestrian flow of a train station with the presence of PWD in different scenarios can then be examined. This will enable designers, engineers, planners and policymakers to make informed, procedural decisions on the design of train stations to ensure that facilities remain safe and accessible during normal and emergency situations, ultimately contributing to creating a universal design suitable for all.

1.2 Problem Statement

The presence of people with disabilities (PWD) poses a challenge to the safe evacuation of pedestrians at a train station. A heterogeneous population has different behaviours such as slower egress time when compared to homogeneous populations. However, the presence of PWD is largely neglected in the design of train stations although their presence impacts the pedestrian flow significantly. There are less or incomplete facilities for PWD at train stations, and many are added as an afterthought. Therefore, PWDs face great difficulties when accessing train stations. PWDs that are particularly affected are those with visual impairments and wheelchair users which constitutes 43.8% of the people with disabilities in Malaysia (Department of Social Welfare, 2016).

The presence of PWD in different scenarios can be considered and played out with the use of simulation software. But to accurately model people with disabilities in a pedestrian simulation software such as buildingEXODUS, verification and validation need to be done. This is to ensure that the behaviour of the pedestrians simulated in the model corresponds to real life. However, the lack of well documented experimental data-sets for validation is a stumbling block to enable all aspects of evacuation modelling tools to be validated (Ronchi et al., 2014). Hence, a controlled experiment involving different types of disabled people in a train station setting is justified in order to collect the empirical data required to validate a pedestrian simulation model.

Furthermore, this study presents a chance to gather localised data on the walking behaviour of disabled people by considering different groups of disabled people in the presence and absence of normal people. Ultimately, the verification and validation of buildingEXODUS for disabled people allow for more rigorous simulations to be done so that better universal design principles can be devised to improve safety and accessibility at train stations for PWDs.

1.3 Objectives

This study aims to:

1. Verify the ability of buildingEXODUS software to represent the walking speed of people with disabilities (PWD) in the experimental setup.
2. Determine the walking speed for different groups of people with disabilities (PWD) in the experimental setup of the study.
3. Validate the buildingEXODUS model by comparing the simulation model and experiment data based on the walking speed of people with disabilities (PWD).

1.4 Scope of Work

The verification of the buildingEXODUS software was done using the standard tests suggested by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce to ensure that theories were correctly implemented in the simulation model. Only six tests that relate to the functions of buildingEXODUS in this application were carried out.

Two broad categories of PWD were examined in this study, specifically people with visual impairments and wheelchair users. Other categories such as the deaf and mentally impaired were not studied as their movement is less restricted by the environment.

The experiment conducted was modelled after the concourse area of the KLCC LRT station which is located at the heart of Kuala Lumpur and part of the Kelana Jaya LRT line. Within its vicinity is the Avenue K shopping mall, Suria KLCC Shopping Mall, Petronas Twin Towers and Kuala Lumpur Convention Centre. Its strategic location means that it experiences high ridership as well as a large number of PWDs on a daily basis. Facilities such as tactile lines and gates for the disabled were already in place here. Table 1.1 provides the layout of the station.

Table 1.1: Layout of levels in KLCC LRT station (KJ10).

Level	Name	Features
G	Street Level	Taxi Stand, Bus Hub, Entrance to Suria KLCC, Landmarks
C	Concourse	Fare Gates, Ticketing Machines, Station Control, Shops, Avenue K (Shopping Centre)
P	Platform 1	Kelana Jaya Line towards KJ1 Gombak (→)
	Platform 2	Kelana Jaya Line towards KJ37 Putra Heights (←)

The layout of the experiment was a scaled-down version of the concourse level of the KLCC LRT station as the actual size of the station was too large to fit into the hall and the range of the video recording equipment was limited. However, the size of the layout does not influence the validation process as the aim was to compare the simulation with the experiment results.

Furthermore, the pedestrian modelling in buildingEXODUS was done under normal circumstances only. Emergency evacuation situations were not considered. The pedestrians in the experiment were asked to walk at their normal comfortable walking speeds and no hazards such as fire, smoke and alarms were used. In addition, the experiment and ensuing simulation did not delve into the effects of gender, age and other physical and psychological traits in the walking speed of PWD.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, the characteristics of people with disabilities (PWD) are examined in terms of accessibility and pedestrian characteristics such as walking speed and group behaviour. The aspect of pedestrian simulation is explored, starting with the fundamentals of simulation models, followed by explanations on the use of various conventional simulation models in understanding heterogeneous pedestrian groups. A brief introduction to the buildingEXODUS model is also included. Previous studies on verification and validation of pedestrian simulation models are then explained.

2.2 People with Disabilities (PWD) in Malaysia

The World Health Organisation (2011), defines disabilities as *"an umbrella term for impairments, activity limitations, and participation restrictions, denoting the negative aspects of the interaction between an individual (with a health condition) and that individual's contextual factors (environmental and personal factors)"*. In Malaysia, people with disabilities are known as "orang kurang upaya" (OKU). They are defined as *"those who have long term physical, mental, intellectual or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society"* (Persons with Disabilities Act, 2008). There were approximately 409,269 registered persons with disabilities in Malaysia in 2016, and possibly more not registered in the system. It is interesting to note that Selangor and Kuala Lumpur have the highest concentration of PWD in Malaysia (Department of Social Welfare, 2016).

2.3 Accessibility and Universal Design

People with disabilities face difficulties carrying out actions that are associated with access to, movement within and egress from buildings such as using stairs, steps, going through doors and turning doorknobs (Boyce et al., 1999a). More often than not, it is the environment that "dis-ables" people, making them aware of the impairments they have. The challenge then is to design public spaces that integrate the needs of all people regardless of their impairment, so that everyone can move around independently (de Jong, 2014).

The Malaysian Plan of Action for People with Disabilities 2016-2022 outlined 10 strategic cores to uphold the rights of PWDs. These cores include increasing the accessibility of PWDs and increase PWD participation in the planning and decision making (Abdul Rahim et al., 2017). Furthermore, the "Person with Disabilities Act 2008" stipulates that access to public transport facilities is a right of persons with disabilities and providers of public transport facilities shall provide facilities, amenities and services that conform to universal design to facilitate access and use by persons with disabilities. The Department of Standards Malaysia has also established accessible design standards, MS 1184:2014, Universal Design and Accessibility in The Built Environment – Code of Practice (Second Revision), that specifies design requirements for PWD such as width of walkways and doors for wheelchair access, provision of tactile tiles, adequate signage, braille signage, et cetera.

However, Hussien and Yaacob (2012) examined the development of accessible design in Malaysia and found that the transportation system in Malaysia was not fully accessible to PWD in general. Padzi and Ibrahim (2012) also state that design of facilities at the Kelana Jaya LRT stations did not comply fully with the Malaysian Standards. The audit of the stations showed that some tactile lines and guiding blocks installed lacked continuity and their sizes differed from the guidelines. This impeded people with visual impairments from accessing the LRT.

Universal design (UD) as defined by Mace (1988) is *"the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design".* This definition is still widely accepted until today.

Universal design is about democracy, designing for everybody, from children to adults, young and old, men and women, people with disabilities and so on (Iwarsson and Ståhl, 2003). In the context of pedestrian planning and facility design, universal design and accessibility are sometimes used interchangeably, referring to facilities designed to accommodate people with disabilities (Litman, 2017).

2.4 Walking Speed of People with Disabilities (PWD)

In pedestrian flow characterisation, walking speed is defined as the distance travelled per unit time. Walking speed is vital in the study of the functions and design of pedestrian facilities, especially in confined spaces with high pedestrian flows such as train stations that may become a hazard in case of fire (Fridolf et al., 2011).

Boyce et al. (1999b) studied the walking speed of people with locomotion disabilities and wheelchair users on a level plane. The time needed for each participant to traverse a 50 m long corridor was measured using a stopwatch to determine their walking speed. The findings of the experiment in Table 2.1 indicate that PWD had slower speed than normal people except in the case of assisted manual wheelchair users. The PWD using a walking frame had the slowest walking speed at 0.57 m/s, followed by unassisted manual wheelchair PWD at 0.69 m/s.

Table 2.1: Mean speed on a horizontal plane for different disabled population groups (Boyce et al., 1999b).

Type	Categories	Mean Speed (m/s)
-	Non-disabled	1.25
Locomotion disability	No aid	0.95
	Crutches	0.94
	Walking stick	0.81
	Walking frame	0.57
Wheelchair users	Unassisted electric wheelchair	0.89
	Unassisted manual wheelchair	0.69
	Assisted manual wheelchair	1.30

Meanwhile, Tsuchiya et al. (2007) compared the individual walking speed of wheelchair users with normal pedestrians on a 15 m or 20 m straight walkway using a stopwatch. From the 268 wheelchair users and 273 normal people that participated, the walking velocity of normal people are found to be between 1.29 m/s and 1.33 m/s with a mean of 1.31 m/s, while wheelchair users have a walking speed between 1.04 m/s to 1.08 m/s and a mean of 1.06 m/s. The results indicate that the wheelchair users have a lower walking speed compared with normal individuals.

Jiang et al. (2012), conducted an experiment to measure unimpeded free walking speed of the mobility impaired on a horizontal plane ascending stairs and descending stairs. 40 people with no supporting tools, 20 people using a single crutch, 40 people using two crutches, as well as 17 healthy people participated in the experiment. The results summarised in Table 2.2 are consistent with the speeds measured by Boyce et al. (1999b), where healthy and non-aided people had the fastest walking speeds compared to those who were depending on supporting tools. The use of supporting tools slowed down the walking speed of the participants.

Table 2.2: Mean unimpeded free individual speed for different impairments (Jiang et al., 2012).

Movement participation group	Horizontal Walking Speed (m/s)
No-aid	1.274
Single-crutch	0.873
Double-crutches	0.779
Healthy	1.549

Sørensen and Dederichs (2013a) investigated the free walking speed of PWD with varying degrees of visual impairment. The participants were sorted according to the Danish visual impairment categories, A, B, C and D based on the best-corrected visual acuity in the better eye. People with a visual acuity of 0.3 measured in the better eye is considered visually impaired (category A), and people with a visual acuity of 0.1 measured in the better eye is considered legally blind. The legally blind group are subdivided into three further categories consisting of social blindness (B, ≤ 0.1 ≥ 0.01), practical blindness (C, ≤ 0.01, ≥ 0.001), and total blindness (D, ≤ 0.001) (Buch et al., 2001).

The participants were asked to walk along a corridor and their movement was recorded using video cameras. Analysis was then done to determine the average walking speed for each category. Generally, the results in Table 2.3 show that the mean free walking speed decreases with increasing visual impairment.

Table 2.3: Mean free walking speed on horizontal planes for each Danish visual impairment category (Sørensen and Dederichs, 2013a).

<table>
<tr><th colspan="2">Designation</th><th>Category</th><th>Mean Free Walking Speed (m/s)</th></tr>
<tr><td colspan="2">Visually Impaired</td><td>A (n=2)*</td><td>-</td></tr>
<tr><td rowspan="3">Legally Blind</td><td>Social Blindness</td><td>B (n=8)</td><td>1.18</td></tr>
<tr><td>Practical Blindness</td><td>C (n=8)</td><td>0.95</td></tr>
<tr><td>Total Blindness</td><td>D (n=6)</td><td>0.75</td></tr>
</table>

*Only two data points available. Results are left out.

In another study, Sørensen and Dederichs (2014) conducted a full-scale evacuation experiment in a train coach to investigate the effects of heterogeneity on evacuation time. The train had a capacity of 46 passengers. During the evacuation experiment, four different scenarios were applied. The reference scenario consists of only normal passengers whereas the other three setups exclude mobility impaired passengers, visually impaired passengers and children, respectively. Video cameras were installed along corridors to record the movement of the pedestrians in each scenario. From the video recording, the free walking speeds on a horizontal plane of each pedestrian and hence subpopulation were determined. The results are presented in Table 2.4.

The results in Table 2.4 indicate that children and hearing impaired people had faster walking speeds than normal passengers, while passengers with reduced mobility had the slowest walking speed. However, the walking speeds found in this study were higher than those found in guidelines and literature due to the small test group and varying degree of disability displayed by the participants, evident from the large difference between the maximum and minimum walking speeds.

Table 2.4: Speed distribution of different subpopulations (Sørensen and Dederichs, 2014).

Subpopulation	Mean (m/s)	Min (m/s)	Max (m/s)
Able-bodied (n=58)	1.69	1.59	1.80
Elderly (n=12)	1.43	1.20	1.66
Children (n=16)	1.89	1.70	2.08
Hearing impaired (n=3)	1.81	1.28	2.33
Cognitive impaired (n=4)	1.55	0.35	2.76
Visually impaired (n=3)	1.53	0.89	2.16
Reduced mobility (n=3)	1.02	0.89	1.15

Meanwhile, the walking speed of people with visual impairments and wheelchair users in different walking environments such as a passageway, oblique angle, right angle, bottleneck and stairs in a controlled, indoor experiment was determined by Sharifi et al. (2016). The mean speeds for each pedestrian group in different walking facilities are shown in Table 2.5.

The results highlighted that complex facilities such as oblique angle turn, right angle turn, bottleneck and stairs, reduced the walking speed of all pedestrians. It is also apparent that motorised wheelchair users have the lowest speed among all groups in all facilities except the right angle due to the speed constrains of the motorised wheelchair. The findings also indicate that individuals with visual impairments were more restricted than mobility impairments in the stairs facility.

Table 2.5: Mean walking speed of different population groups in various indoor walking environments (Sharifi et al., 2016).

Type	Mean Walking Speed in Each Facility (m/s)				
	Passageway	Oblique Angle	Right Angle	Bottleneck	Stair
Visual impairment	0.83	0.76	0.67	0.69	0.39
Nonmotorised wheelchair	0.83	0.76	0.64	0.70	0.43
Motorised wheelchair	0.69	0.67	0.65	0.56	-
Individuals without disabilities	0.94	0.86	0.77	0.73	0.48

The buildingEXODUS Application Guide by Galea et al. (2017b) suggests a set of travel speed attribute values for people with movement disabilities. The data was generated from a study done by Shields et al. (1996) on the mobility capabilities of disabled people. The study involved participants with a wide range of disabilities and was conducted in a day care centre. The participants were asked to walk unassisted along a horizontal path measuring 50 m. The mean walking speed of each category was then determined. The values obtained are listed in Table 2.6 and show that normal people had the fastest walking speed (1.24 m/s), while those using rollators had the slowest walking speed (0.51 m/s).

Table 2.6: Mean travel speed of people with movement disabilities (Galea et al., 2017b; Shields et al., 1996).

Movement Aid	No. of Subjects	Mean Travel Speed (m/s)
Electric Wheelchair	2	0.89
Manual Wheelchair	12	0.69
Crutches	6	0.94
Walking Stick	33	0.81
Walking Frame	5	0.51
Rollator	5	0.61
No Aid	52	0.93
No Disability	19	1.24

As a summary, Table 2.7 shows the mean walking speeds of people with disabilities (PWD) presented in literature. Across the board, the PWD with visual impairment and wheelchair users were found to have a slower waling speed compared to normal people, except in the case of the manual wheelchair that is assisted by normal people. Meanwhile, between the five categories of PWD, the unassisted electrical wheelchair users had the slowest walking speeds, followed by unassisted manual wheelchair users and the visually impaired.

Table 2.7: Summary of the mean walking speed on level plane of selected categories of people with disabilities.

Category	Walking Speed (m/s)						
	Boyce et al. (1999b)	Tsuchiya et al. (2007)	Jiang et al. (2012)	Sørensen and Dederichs (2013a)	Sørensen and Dederichs (2014)	Sharifi et al. (2016)	Galea et al. (2017b); Shields et al. (1996)
Able-bodied	1.25	1.31	1.549	-	1.69	0.94	1.24
Visually Impaired	-	-	-	0.96*	1.53	0.83	-
Unassisted Manual Wheelchair	0.89	1.06	-	-	-	0.83	0.69
Unassisted Electrical Wheelchair	0.69	-	-	-	-	0.69	0.89
Assisted Manual Wheelchair	1.30	-	-	-	-	-	-
Mobility Impaired	0.95	-	1.274	-	1.02	-	0.93

*Averaged value

2.5 Characteristics of People with Disabilities (PWD)

People with disabilities have distinct mobility characteristics that distinguish them from normal pedestrians. These distinctions are presented in the following subtopics in terms of gender differences, effects of density, familiarity, exit door choice and capacity, orientation, and group dynamics.

2.5.1 Gender Differences

Tsuchiya et al. (2007) measured the individual walking velocity of 272 wheelchair users in a study on evacuation characteristics of wheelchair users. The study found that both male and female wheelchair users had similar average walking speed of 1.06 m/s. However, for normal pedestrians, the average walking speed was 1.33 m/s for males and 1.27 m/s for females. A t-test found that there was no difference in the walking speeds of male and female wheelchair users at 5% significance level, but comparing between normal male and females, a significant difference was found. This shows that gender does not have a significant impact towards the speed of wheelchair users, compared to normal people.

2.5.2 Effects of Density

The study by Sørensen and Dederich (2013a) found that the increase in pedestrian density would not affect the walking speed of the visually impaired to the same extent as normal people. Samoshin and Istratov (2014) also states that the value of threshold density (i.e. density that does not affect the speed of movement of people) of the visually impaired is higher compared with healthy people. In some cases, the movement of visually impaired people is faster in denser flow.

2.5.3 Familiarity

For PWD with visual impairments, familiarity with the environment significantly influences walking speed and egress time (Proulx, 2002; Samoshin and Istratov, 2014). In a study by Samoshin and Istratov (2014), blind and visually impaired people were asked to evacuate a building through a familiar and unfamiliar route. The walking speed was then determined by reviewing the video recording. The results in Table 2.8 found that the walking speed on familiar routes was almost two times faster than that of unfamiliar routes regardless of the route type.

Table 2.8: Velocity of blind and visually impaired people in familiar and unfamiliar routes by the type of route (Samoshin and Istratov, 2014).

Route Familiarity	Velocity (m/s) by Type of Route			
	Horizontal	Doorway	Stairs Up	Stairs Down
Familiar Route	0.83	0.54	0.67	0.57
Unfamiliar Route	0.44	0.36	0.36	0.30

2.5.4 Exit Door Choice and Capacity

With regards to the exit door choice, individuals with disabilities tend to follow other individuals with disabilities' choice of exit. This dependence can be attributed to the trust individuals with disabilities have on each other. In contrast, the presence of individuals with disabilities at an exit discouraged individuals without disabilities to select it, due to the perception that PWD will impede their exit from the room (Gaire, 2017).

Moreover, the presence of disabled people such as wheelchair users decreased the capacity or flow coefficient of doors, measured in people/m/sec. This effect was demonstrated by Shimada and Naoi (2006) in their experimental study on evacuation flow of a crowd involving wheelchair users. As the mixing rate of wheelchair users increased, the flow coefficient of the exit decreased regardless of crowd density and exit width. Meanwhile, Daamen and Hoogendoorn (2010) studied the relation between the capacity of emergency doors with population composition, doorway width and stress level. The study reported that emergency door capacity tends to decrease significantly with the presence of people with disabilities in wheelchairs and blind people in the pedestrian flow as opposed to other population compositions as shown in Figure 2.1. The population composition that includes 5% of disabled people had a door capacity below the minimum of 2.25 p/m/s stipulated by Dutch National Building Codes.

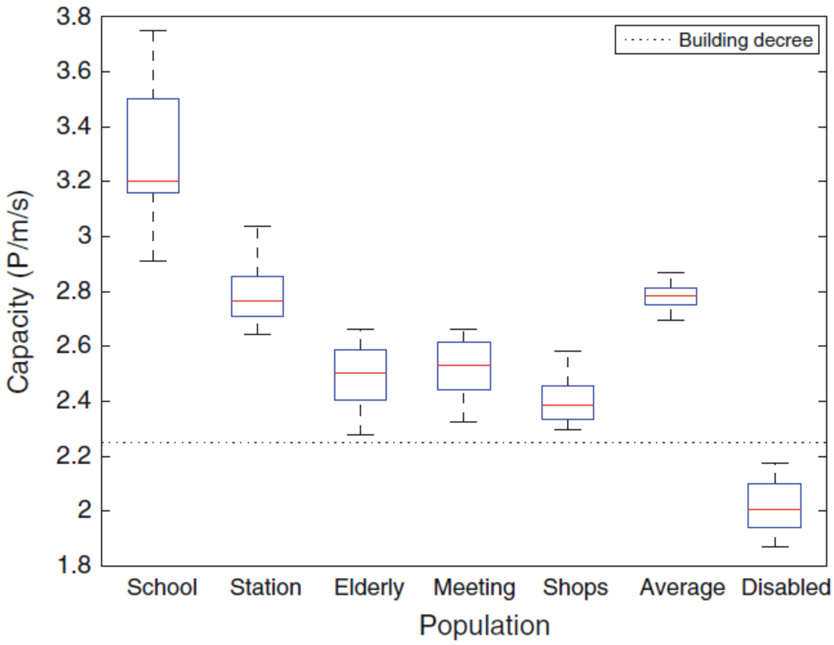

Figure 2.1: Capacity of emergency doors as a function of population at the doorway of 85cm, a light intensity of 200 lux and no open door (Daamen and Hoogendoorn, 2010).

2.5.5 Orientation

Visually impaired people typically use white canes when using public transport to navigate and orient themselves, in conjunction with tactile paving. Tactile paving is a system of textured surface indicators that guide visually impaired people to distinguish directions, identify hazards and reach expected destinations (Lu et al., 2009).

Visually impaired people also tend to orientate themselves by using the walls of the surroundings and handrails when using stairs (Sørensen and Dederich, 2013a). Samoshin and Istratov (2014) observed the same trend, calling it tactile contact with enclosing structures which include walls and railings, illustrated in Figure 2.2 (Page 19).

2.5.6 Group Dynamics

Group dynamics is an important factor in the study of pedestrian egress behaviour (Collins et al., 2014). In a crowd, up to 70% of people in a crowd were actually moving in a group (Moussaïd et al., 2010). Müller et al. (2014) found that when moving in a group, individuals formed a bond, acting more like a large particle, rather than individual particles. This led to decreased evacuation times and clogging effects. Heliövaara et al. (2012) discovered that grouping or herding behaviour had a negative effect on evacuation time. Faster evacuation times were observed when individuals egressed independently rather than cooperation with others. Groups of people also tend to wait for each other, slowing down the overall crowd movement (Reuter et al., 2014).

On the contrary, Hofinger et al. (2014) stated that affiliation among group members provided supportive behaviour that enabled the evacuation to be done smoothly and unharmed. An empirical study involving youths by von Krüchten and Schadschneider (2017) also found that evacuation times may possibly decrease for large groups due to self-ordering effects and cooperation behaviour.

These effects are important as people with visual disabilities exhibited strong grouping and assistive behaviour among themselves (Sørensen and Dederich, 2013a). Samoshin and Istratov (2014) observed that actions, like holding hands and exiting in groups, were more probable for people with visual impairments regardless of gender, as depicted in Figure 2.2.

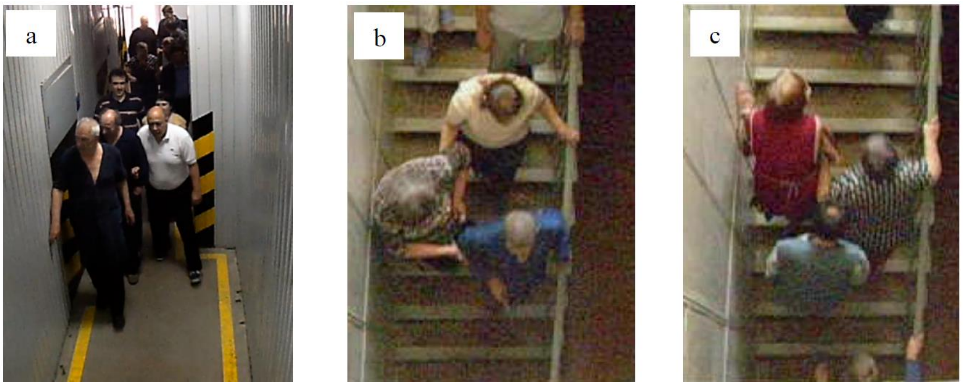

Figure 2.2: Behaviours of visually impaired and blind people: tactile contact with enclosing structures and distinct group movement (Samoshin and Istratov, 2014).

Individuals with disabilities, have a profound impact on crowd speed despite being a minority in the pedestrian stream. Individuals with disabilities are much slower and have a larger space requirement than the general population. Hence, disabled people in the pedestrian flow may act as a constraint, resulting in clogging and congestion within different walking facilities which was especially pronounced for complex geometries like stairs (Christensen et al., 2006; Sharifi et al., 2015). People with sensory and mobility-related disabilities may not only need assistance to safely exit via terrains that are difficult to negotiate by themselves such as stairs and obstacles but may also block the evacuation of others (Koo et al., 2012). Tsuchiya et al. (2007) found that groups with wheelchair users decreased the crowd walking velocity compared to groups with only normal people. However, the width of the walkway had a positive relationship with the crowd walking velocity as normal people were able to overtake wheelchair users in wider walkways.

The effects of disregarding disabled people in an evacuation were explored by Sørensen and Dederichs (2013b). The train carriage evacuation involved children, able-bodied, elderly, people with mobility impairments and people with other impairments. Four configurations were studied, each without one category of disabled people as shown in Table 2.9. The study found that the egress time for mixed groups was up to twice of that with only able-bodied people.

Table 2.9: Total evacuation time of four configurations (Sørensen and Dederichs, 2013b).

Setup	Configuration	Total Evacuation Time, (s)
1	Without Mobility Impaired	88.69
2	Without Visually Impaired	103.08
3	Without Children	108.53
4	Only Able-bodied	50.15

2.6 Pedestrian Simulation Models

Pedestrian simulation models are becoming invaluable tools for engineers to assess key aspects of a building's safety. Simulation models allow an individual's interactions with other individuals, the environment, building conditions such as fire and smoke, and the decision-making process of individuals to be taken into account. Hence, the multifaceted behaviours and interactions of PWD discussed can be simulated. This is a great departure from the assumptions of traditional hand calculations and standards of the past (Kuligowski et al., 2010).

According to Manley and Kim (2012), there were three general approaches to simulating pedestrian behaviour, macroscopic, microscopic and mesoscopic. Macroscopic models were defined as a top-down approach in which collective pedestrian dynamics such as spatial density or average velocity were related to model parameters. In this approach, occupants were not represented individually. Rather, an analogy to fluid flow was used (Ronchi and Nilsson, 2016). Microscopic models were characterised as a bottom-up approach and each pedestrian was modelled as an entity with individual attributes (Manley and Kim, 2012). Examples of microscopic models given by Liu et al. (2017) include the cellular automata, social force, velocity based, discrete choice and lattice gas models. buildingEXODUS is a microscopic model (Gwynne et al., 2005), which is the most common modelling approach today according to Manley and Kim (2012). Mesoscopic models were a combination of both modelling approaches.

2.6.1 buildingEXODUS Simulation Model

buildingEXODUS was developed by the Fire Safety Engineering Group at the University of Greenwich. It can be used for both evacuation simulation and pedestrian dynamics/circulation analysis, with the ability to consider people-people, people-fire and people-structure interactions (Fire Safety Engineering Group, n.d.; Galea et al., 2017a). buildingEXODUS was designed to simulate the evacuation of large number of individuals from a multi-story building. The model is a microscopic simulation model, hence it is able to track the trajectory of each individual as they find their way out of the building or are overcome by fire hazards (Gwynne et al., 2005).

The geometry within buildingEXODUS is represented in two-dimensional grids. The grid can be constructed manually within the software or imported from CAD software in DXF format. Each location on the grid is called a node and is linked by a system of arcs. Nodes are spaced at 0.5 m intervals. Each node represents a region of space typically occupied by a single occupant. An example of a model is shown in Figure 2.3.

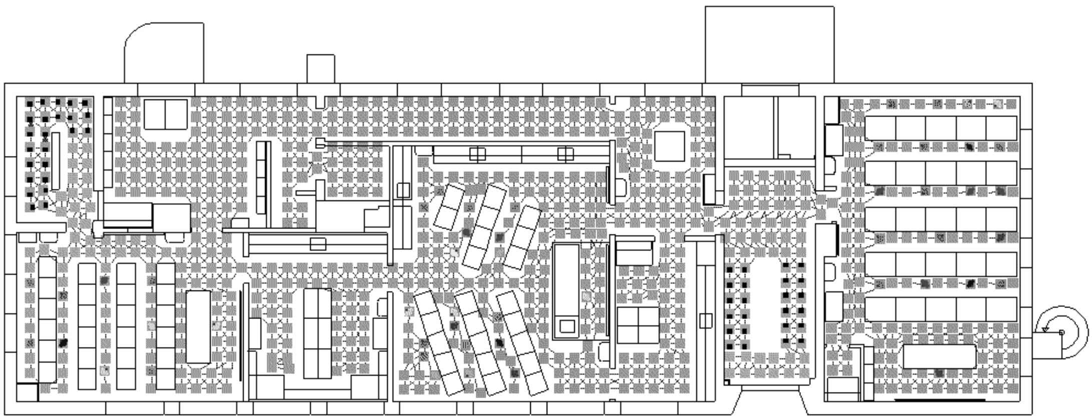

Figure 2.3: Typical outline of a building layout with nodes and arcs (Galea et al., 2017a).

The buildingEXODUS model comprised of five core interacting sub-models, namely the occupant, movement, behaviour, toxicity and hazard sub-models, illustrated in Figure 2.4.

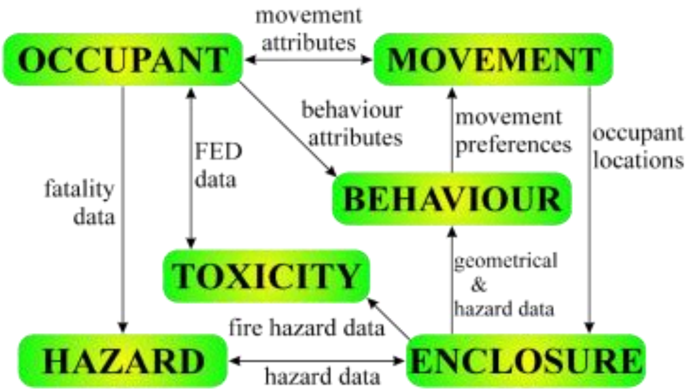

Figure 2.4: Interaction of EXODUS modules (Galea et al., 2017a).

The **occupant sub-model** defines an individual as a collection of attributes which broadly falls into four categories, physical (such as age, gender, agility, etc), psychological (such as patience, drive etc), experiential (such as distance, PET etc.) and hazard effects. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other sub-models.

The **movement sub-model** controls the physical movement of individual occupants from their current position to the most suitable neighbouring location or supervises the waiting period if one does not exist. The movement may involve behaviours such as overtaking, side-stepping, or other evasive actions.

The **hazard sub-model** controls the development of the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, smoke and toxic products throughout the atmosphere and controls the opening and closing of exits and the availability of exits.

The **toxicity sub-model** determines the effects on an individual exposed to toxic products distributed by the hazard sub-model. These effects are communicated to the behaviour sub-model which, in turn, feeds through to the movement of the individual.

The **behaviour sub-model**, which operates on the global and local levels, determines an occupant's response to the evacuation scenario. The global behaviour provides an overall escape strategy for the occupants while the local behaviour governs the occupants' responses to their current situation. This may include behaviours such as exit via the nearest serviceable exit or exit via the most familiar exit.

More details regarding the theory and application of buildingEXODUS can be found in the buildingEXODUS Manuals by Galea et al. (2017a, 2017b).

2.6.2 Pedestrian Simulation of Heterogeneous Populations

Pedestrian simulation models can be used to plan for the safe evacuation of a building, whilst taking into account the presence of vulnerable people groups such as the disabled and elderly.

Christensen et al. (2013) and Koo et al. (2012), studied the effect of individuals with disabilities in the evacuations of a four-story office building and 24-story high-rise building, respectively using BUMMPEE (Bottom-Up Modelling of Mass Pedestrian flows—implications for the Effective Egress of individuals with disabilities), an agent-based microsimulation model first presented by Christensen and Sasaki (2008).

The results from both studies showed a significant difference in evacuation time of homogeneous and heterogeneous populations. Figures 2.5 and 2.6 show that an increase in population size led to a larger difference between evacuation times. This was due to clogging at bottleneck areas of the building and blocking at evacuation routes by residents with disabilities that had larger space requirement and slower speed. The simulation result was used to determine the maximum number of residents that can be evacuated within a certain evacuation time or time needed to evacuate a certain number of residents.

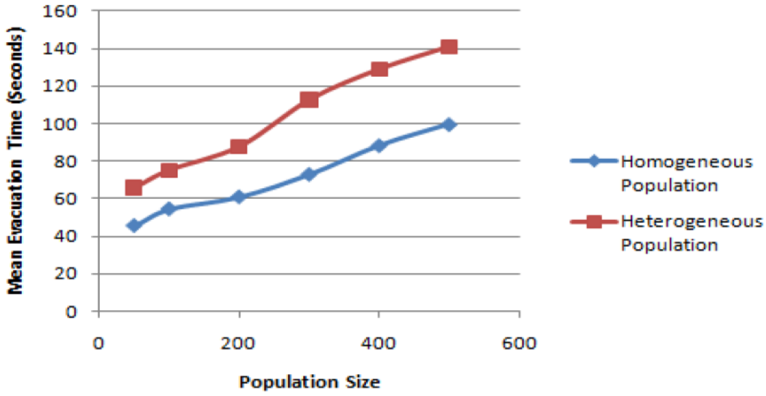

Figure 2.5: Effect of population size on the mean evacuation time of homogeneous and heterogenous population groups (Christensen et al., 2013).

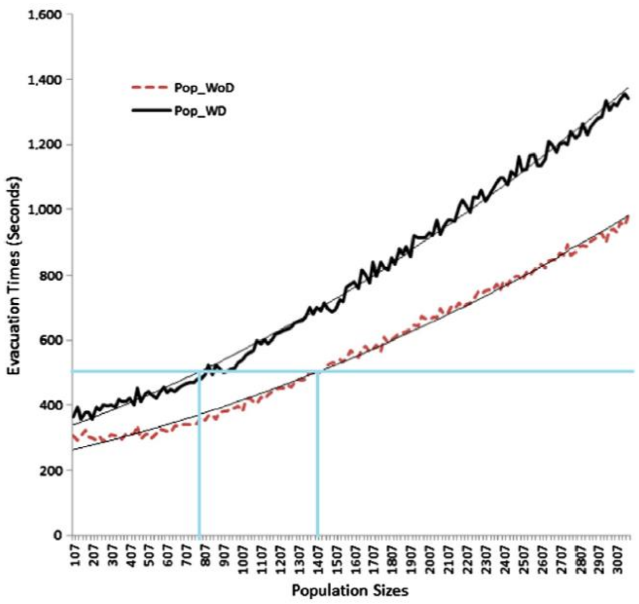

Figure 2.6: Relationship between population sizes and evacuation time (Koo et al., 2012).

Similarly, simulation-based optimisation method was utilised by Noh et al. (2016) to devise an evacuation strategy for a 24-story office building with the consideration of people with disabilities in BUMMPEE. The strategy involved dedicated routes for people with and without disabilities and was able to reduce the average evacuation time by 10%.