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The Evacuation Simulation of Wheelchair Users in a Building Fire: An Initial Dynamic Characterization of Structural Egress Components

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ABSTRACT

People with disabilities are one of the most vulnerable groups involved in building fires. According to the U.S. Fire Administration, in the United States alone, an estimated 700 home fires involve people with physical disabilities each year while over 1700 involve those with mental health disorders. Despite this, the current body of literature shows few studies focused on the evacuation of disabled people. This is a direct result of past and present social injustice on people with disabilities and has resulted in high injury and death rates during fires. To combat this, enrich the literature, and improve their experiences in the built environment, this thesis marks the inaugural study of an ongoing project that aims to include all forms of disability in building fire research. This is initiated through the identification of four general disability categories involved in evacuation: *functional independence, sensory perception, medical health,* and *social cognition*. By far the most abundant category, *functional independence* (physical disabilities) provides a starting point for future reference. Therefore, this thesis experiment involves the simulation of 1-3 wheelchair users in a building population of 80 occupants. Two iterations of simulations were completed for a low-rise university apartment building using the evacuation software Pathfinder, and the resulting 327 simulations were analyzed for potential structural aids and barriers to the evacuation process. As a byproduct of this research, a dynamic structural ranking system of egress components is proposed for wheelchair users. Overall, the goal of this research is to provide a connection between people with disabilities and engineers and officials in the structural fire field—therefore increasing awareness among the non-disabled community and improving access and egress in the built environment. Additionally, suggestions for structural modifications are provided to improve egressibility of the simulated building. Finally, the limitations and challenges of the research are identified, and plans for future research are provided.

DEDICATION

To those who have suffered due to inaccessible structures, media, and legislation: you are not alone, and you are not forgotten.

DISCLAIMER

This thesis includes the use of color-coding to identify minute structural differences and categorizations. The author acknowledges that some readers may not be able to visualize color differences and has provided alternative identification where possible.

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1. INTRODUCTION

Chapter 1 introduces the topic of disability in fire by noting significant hardships faced by people with disabilities in everyday life. The motivation for this research is provided in **Section 1.1** with further objectives detailed in **Section 1.3**. In **Section 1.4** we briefly discuss the contents of the remaining chapters of this thesis.

1.1 Motivation

Evacuation from building structures is a complex phenomenon that involves the dynamic interaction of fire, building occupants, and structural systems. While much information is known about material and structural system behavior [1–18] as well as fire behavior [19–24], the study of building occupants in fire is still a largely under-developed area, as it has only begun to gain ground in the past few decades (mainly following the 9/11 attacks on the World Trade Centers). This is a significant issue for building occupants, fire safety officials (FSO), and engineers as the main method of data collection on building egress and fire is through reconnaissance missions post-disaster [25–28].

In addition to the lack of research available on building occupants in fire, the behavior of evacuees themselves are complex. For example, human behavior is a large factor in occupant evacuation as it involves the interaction between evacuees and their environment. Constantly changing fire dynamics and situational information make an occupant's behavior fluid with decisions changing as more information about the fire event is revealed. Such behavior is also a function of an evacuee's inherent demographics (height, weight, age, gender, etc.). But while these characteristics are easy to quantify [29–31]., occupant interactions such as decision-making and thought processes are not as straightforward. This has resulted in a lack of research focused on human behavior in fire [26,32].

Even less established than the field of human behavior in fire is that of people with disabilities (PWD) in fire. More than 15% of the world's population identifies with some form of disability (approximately 1 billion people). However, a continued lack of understanding among engineers, FSOs, and disaster researchers has resulted in a limited body of evacuation research [33]. Furthermore, existing studies are heavily geared toward physical disabilities, which present most closely to that of the non-disabled population, are the most identifiable, and the easiest to quantify. According to the *Centers for Disease Control and Injury Prevention* (CDC), physical disabilities (mobility impairments) represent only one-half of those with disabilities in the United States (US). Thus, the other 50% of PWD are effectively ignored among evacuation experts.

Overlooking PWD in the built environment is not new. Structures, transportation services, and functional aids are still largely inaccessible, despite a concerted effort to improve accessibility through legislation such as the *Americans with Disabilities Act*. This, combined with a lack of understanding of PWD by the general public, has placed an unintentional safety burden on the disabled population. To further illustrate this issue, the *United States Fire Administration* (USFA) estimates that 700 residential fires involve people with physical disabilities each year (~2 fires/day) while 1700 involve people with mental health disorders (4 fires/day). In addition, the *National Fire Protection Association* (NFPA) estimates that physical disability was a factor in over 400 (15% of US fatal fires) fire deaths per year from 2007-2011. With most accessible egress components left unavailable in case of fire (i.e. elevators), it seems clear that many fire deaths among those with disabilities are a direct result of inaccessible and "inegressible" buildings [34–36].

Studying PWD in fire is integral to identifying key barriers and aids to the evacuation process. However, real-time evacuations involving fire are not feasible; they are costly, unethical, and pose challenges in regard to collecting data at the time of the event. Thus, evacuation simulation and modelling has gained significant attention in recent years. Unfortunately, this field lacks a standardized model, and therefore, there are large variations in accepted data and inclusion criteria. This is especially true for people with disabilities. By 2010, there were 26 models recognized by the *National Institute of Standards and Technology's* (NIST) Fire Research Division, with many more independent models in the works [37]. None of the models identified by NIST focused solely on people with disabilities, and very few included any disabilities. Improving evacuation models to include the entire disabled population is critical to overcoming the challenges of accessibility, egressibility, and safety gaps that PWD have experienced for centuries.

Based on the small breadth of current evacuation research for the disabled population, this thesis has four primary goals: 1) identify gaps in disability research and segment significant categories similarly affected by fire, 2) model a low-rise apartment building and categorize evacuation routes by types of structural components (stairs, ramps, etc.), 3) simulate the evacuation of the building population including various amounts of wheelchair users and 4) collect data on evacuation times to verify critical structural components that aid or hinder in the safe egress of the wheelchair users.

1.2 Background

To fully grasp the disparity between the disabled and non-disabled communities in today's society, it is first necessary to understand how we have arrived at this point. **Section 1.2** first dives into the history of disability rights and legislation around the world. Next, discrepancies between published definitions of disability are highlighted. Finally, **Subsection 1.2.4** provides a deeper look into PWD's experiences in the built environment with an emphasis on disaster response.

1.2.1 A Brief Look into Disability Rights History

Beginning with classical philosophers such as Aristotle labeling impairments as "abnormalities" and evolving into 19th century scientific thinking of *survival of the fittest*, people with disabilities have been marginalized for centuries [38,39]. It was not until the 20th century that people with functional limitations[1] became more interested in advocating for equal rights. In the United States, the Disability Rights Movement transformed treatments and perceptions of disability starting in the mid-1900s [40]. Organizations for people with disabilities existed well before the movement began, but it was not until the Great Depression that they gained significant popularity. In the 1930s, the *League of Physically Handicapped* was created to fight for equal employment [40]. The 1940s through 1960s saw an increase in organizations for people with mental health conditions and cognitive impairments with *We Are Not Alone* and the *National Association for Retarded Children.* Also, during this time, President Harry Truman formed the *National Institute of Mental Health* (NIMH), now the leading federal agency for research on mental health disorders in America [40,41]. In Europe and elsewhere, disability advocacy is more recent and mainly focused only on the last few decades [42]. In 1996, the *European Disability Forum* (EDF) was founded to represent the 50 million disabled people in the European Union [43]. Just three years later, the *International Disability Alliance* (IDA) was established as a network of global and regional disability organizations and was essential in the development of the *International Disability Caucus* (IDC), now a key negotiator of the *United Nations Convention on the Rights of Persons with Disabilities* (UN CRPD) [44]. In India, the Decade of Disabled Persons (1983-1992) marked one of the first shifts in advocacy for PWD [45]. Much like the Disability Rights Movement in the United States,

[1] Functional limitation is defined as "the restriction or lack of ability to perform an action or activity in the manner or within the range considered normal that results from impairment" [223].

this period saw an explosion of interest and development of local, national, and international non-governmental organizations (NGOs) related to disability.

Nearly all disability rights movements worldwide began with a push for social justice and an end to classical views, oppression, and traditional cultural ideas of disability. In the west, the root of this push was the emergence of the social model of the disability first introduced by the *Union of Physically Impaired Against Segregation* (UPIAS) in the 1970s [46]. According to their policy statement, the goal of the organization was to adapt inaccessible facilities so that PWD could fully participate in society and live and work independently. This was perhaps the first connection to disability and the built environment. By the social model's viewpoint, impairment and disability are not individual deficits, nor do they need to be cured by medical intervention. Instead, a modified society and environment can reduce the burden of disability.

The development and acceptance of the social model of disability were, in many ways, a form of liberation for disabled people. It no longer placed a burden on the individual and their impairment but instead transferred the responsibility to society to produce a change in accessibility and perceptions of disability. Additionally, the social model rejected the medical model of disability at its most fundamental level. This approach understands disability as an inherent quality of the individual, assuming that an impairment is a physiological issue rather than caused by societal views or expectations [47]. The medical model approach also characterizes PWD as requiring assistance in the form of rehabilitation or medical effort and treatment to overcome the impairment. Thus, disabilities are purely individual, and society retains no responsibility for the disadvantages they may cause. While scholars today rarely defend this model due to its suggestion that disability rights are "special", it continues to be the prominent paradigm of disability across much of western culture [47]. This has resulted in public perceptions of disability based on media and local culture, which largely misrepresent both the number of people with disabilities and the extent to which someone's disability is affected by daily life.

1.2.2 Disability Legislation and Accessibility

While certain aspects of the medical model remain important, its narrow focus means that many issues concerning disabled people are overlooked or ignored [48]. Clearly, one's impairment is an important aspect of their daily life; but encounters with societal barriers—whether physical, institutional, or attitudinal—only further prevent full participation in society [47] For this reason, scholarly and professional adoption of the social model of disability has been fundamental in advancing equal rights legislation for people with disabilities.

In Europe, this began just 20-25 years ago, when not a single state had national protections against disability discrimination. Statutes emerged quickly in the regions where the social model of the disability first took hold. For example, the United Kingdom (UK) *Disability Discrimination Act* was passed in 1995 and was the location where UPIAS first introduced the social model. Other initial disability statutes included the *Hungarian Equalization Opportunity Law* (1998) and the *Cypriot People with Disabilities Law* (2000), both related to employment discrimination [42]. Later, legislation emerged in Latvia, Denmark, Luxembourg, Poland, and FYR Macedonia. Now, more than thirty countries have some form of anti-discrimination law, and the European Union (EU) has signed and ratified the United Nations CRPD [42].

In the United States, more than 50 laws on civil rights and disability were passed between the years 1960 and 1990. The *1973 Rehabilitation Act* addressed items ranging from disability discrimination in the federal workplace to equal access to technological information. The *1975 Education for All Handicapped Children Act* guaranteed children with disabilities the right to a public-school education. Before this, the *1968 Architectural Barriers Act* became the first federal accessibility law in the world [49]. In 1990, the movement's greatest legal achievement—the Americans with Disabilities Act (ADA)—was passed nationally, prohibiting the discrimination of disabled people in many aspects of daily life [40]. This marked a clear transition away from the medical model in America by highlighting the social dimension of disability. However, continued adherence to viewing impairments through the medical lens created several interpretive issues with the legislation. The key component of the ADA was to provide equal accommodations for people with disabilities (in terms of public access, employment opportunity, and much more); however, its failure to clearly define disability has resulted in several Supreme Court decisions labeling individuals as either "too disabled" or "not disabled" enough [47]. Without clear definitions and requirements, accommodations under the ADA have had mixed results, sometimes not properly benefitting those who need them. Additionally, resistance among designers and construction professionals has resulted in more negative attitudes toward people with disabilities.

In other countries, anti-discrimination laws for PWD came later. 1993-2002 was declared the Asian and Pacific Decade of Disabled Persons [50]. In Hong Kong, this was heralded by one of the most far-reaching anti-discrimination laws for disabled people: the *Disability Discrimination Ordinance of 1995*. This is only one of three pieces of anti-discrimination legislation in the region but covers both the public and private sectors in a variety of areas ranging from education to housing to sports. In India, the *Persons with Disability Act* was passed in 1995 [45]. This law was strengthened by the initiation of the *National Centre for Promotion of Employment for Disabled People* (NCPEDP) in 2000, a national campaign that collaborated with NGOs, local governments, and other advocacy groups to form the National Disability Network. In South Africa, disability legislation came with the political transformation of the country in the early 1990s. The *Disability Programme* and the *White Paper on Integrated National Disability Strategy* were developed in

1997 [51]. This paper aimed to create equal opportunities and an enabling environment for PWD. The Office of the Status of Disabled Persons also worked to integrate disability resolutions into the changing government at the local, regional, and national levels [51].

1.2.3 The Complexity of the Disability Definition

Disability has yet to be consistently defined [52]. In the United States, most of the inconsistencies in creating a single disability definition have been focused on the vague definition created by the original Americans with Disabilities Act. The Act presented disability as a "*physical or mental impairment that substantially limits one or more of the major life activities of such individuals"* [53]. With many disagreements over the Act's range of applicability in its first 20 years of existence, one scholar noted that the "overarching disagreement…can rightly be characterized as a 'clash of perspectives' about the meaning of disability" [47]. In 2008, the development of the ADA Amendments Act aimed to fix this issue by emphasizing that the definition of disability be extended to include a larger range of individuals with impairments and reduce the amount of scrutiny placed on the decision of whether someone is disabled or not [53]. While this reduced the burden on PWD to prove their "disabled-ness," it only created another new definition with room for interpretation.

As seen with the ADA and its Amendments Act, any attempt to create a single, universal definition is met with conceptual issues of applicability and vagueness as well as backlash from both public and scholarly communities. This is partly due to the transition away from the medical model and toward the social model of disability, as definitions must also transition away from descriptions of impairments and toward social discrimination and components of restriction. This is a compounding issue among scholars and researchers, many of whom have already accepted the social model of disability because their definition must also appeal to their own field and the public. With much of the public still entrenched in the medical viewpoint, many researchers and organizations have resulted in creating their own definitions for personal application. For example, criteria from the *American Psychiatric Association's* (APA) Diagnostic and Statistical Manual are often adopted among mental health researchers [54].

Other organizations have attempted to define disability from a more inclusive standpoint. In the United States, the *Federal Emergency Management Agency* (FEMA) adopted the functional needs approach as a way to define disability in relation to the disaster. Published in both their Comprehensive Preparedness Guide 101 in 2010 and their National Response Framework (2019), this definition does not create a single description of disability but instead specifies five areas of potential need in the event of a disaster: *communication, medical health, functional independence, supervision,* and *transportation* [54–56]. Internationally, the most widely recognized definition of disability is the *World Health Organization's* (WHO) *International Classification of Functioning, Disability, and Health* (ICF). Written in 2001, it considers disability as "*neither purely a biological nor a social construct, but the result of interactions between health conditions and environmental and personal factors"* [57]. More generally, under WHO, disability is defined as an umbrella term that covers impairments, activity limitations, and participation restrictions [58]. It is a complex entity resulting from interactions between one's own self and their environment. Other international organizational definitions can be found in [59].

Disability cannot and will not remain the same over cultures and time. Not only does it represent a wide range of physical, mental, sensory, and medical impairments, it can also include a combination of them and a broad range of effects. Additionally, the acceptance of disability as a social construct means that it will also change with developing environments as well as communities, generations, and politics. With the emergence of disability studies as a working field, the continued presence of disability rights activism, and the push for cross-cultural information exchange through research and technological advances, the creation of a universally accepted disability definition is all too important in order to shape the changing world landscape and policy [51].

1.2.4 Disability, Disaster, and the Built Environment

More than 15% of the world's population is estimated to live with a disability today, and this number is only expected to grow due to the aging population, obesity epidemic, and push for equality [33,60,61]. However, despite the increasing number of PWD and actions taken during disability rights movements around the world, many disabilities continue to be thought of as abnormal, limiting, and different. Perhaps one of the most significant limiting factors in the push for equality for people with disabilities is accessibility in the built environment. Often defined as all buildings, spaces, and products created or modified by people, the built environment has recently been the focus of a growing body of research related to disability and public health [62–64]. For example, in a recent study conducted in England [65], people with disabilities were asked to describe their experience in public spaces. Almost all participants noted that it was easier for them to remain at home than to attempt to venture into public. Broken sidewalks, poor lighting, narrow doorways, a lack of ramps and elevators, and inaccessible bathrooms were all items that consistently prevented disabled people from entering or using buildings [65]. According to studies [66–69], the proper design of these features has been associated with preventing mobility disability, encouraging independence in those with underlying health conditions, and increasing physical activity.

Other related studies show similar results and highlight the inefficiency of functional accommodations for PWD, especially those with mental health conditions or cognitive impairments. Several forms of legislation have aimed to improve this in public environments, but they continue to show a lack of concern and awareness among designers and policymakers toward disabled people. For example, the amended *1968 Architectural Barriers Act* (ABA) specified that all buildings financed by the federal government in the US, intended for use by the public or which may be a home or workplace for physically handicapped persons, be designed and continuously inspected for accessibility barriers [47]. However, the legislation describes only minimums that must be taken by engineers and architects as they design and retrofit structures. With this mindset, few designers work toward truly accessible design; aesthetics, budgets, and timelines are often deemed more important.

The inaccessible design of structures, transportation services, and functional aids (ramps, handrails, etc.) is not the only problem people with disabilities experience in the built environment. People with disabilities are also disproportionately affected by disasters [70–72]. For example, people in wheelchairs cannot take refuge under desks or tables during earthquakes. They also cannot quickly descend stairs in the event of a fire, as seen in the 9/11 attacks on the World Trade Center (WTC) buildings. Several accounts of the event point to coworkers attempting to carry wheelchair users down flights of stairs that were only 44 inches wide—enough for two non-disabled people side by side [73]. Few used the over 100 “stair chairs” purchased following the 1993 bombing of the towers [73]. Those with visual or hearing impairments may not hear or see evacuation cues, warnings, or other indicators of disaster either, and people with learning difficulties or mental health conditions may not be able to interpret social or physical cues of dangerous events. Additionally, PWD who rely on electricity to treat or assist with medical conditions (dialysis, ventilators, communication devices) may not have access to these following disasters. After the 2008 Sichuan earthquake in China, people with disabilities were reported to search for their radios among the debris for information [70].

Unfortunately, this type of discrimination among disaster relief services and practices is all too common. The University of Kansas *Nobody Left Behind* project attempted to identify what disaster managers know and understand about people with disabilities during natural and human-influenced disasters. From a survey of 30 randomly selected FEMA disaster sites between the years 1998 and 2003, it was found that 66% of counties did not plan on updating their disaster management plans to better include those with disabilities because of costs, limited staffing, lack of awareness, and other demands [74]. In their study on natural hazards and human vulnerability, Hemingway and Priestley [75] also noted a lack of inclusion of people with disabilities in disaster planning and management. For example, the *Tsunami Evaluation Coalition* (TEC), created in response to the December 2004 Asian earthquake and tsunamis, was a collaboration of over 50 agencies [76]. These included members of the United Nations, Red Cross, and NGOs. Yet in the eleven broad evaluation reports published immediately following the disasters, only two referenced those with disabilities. Additionally, they only mentioned accessible restrooms in shelters and more generally stated that they had “not taken this (disability) onboard” [75].

1.3 Research Objectives

This research involves the simulation of building populations including wheelchair users post-fire alarm (i.e. only the evacuation movement phase). Then, simulations are analyzed, and a structural ranking system is proposed based on results and perceived ease of egress for people with physical disabilities. The objectives are as follows:

1. Review the breadth of available research focused on the disabled population in building fires and categorize results by type of disability as well as related structural egress components.
2. Develop a building model capable of supporting heterogenous populations of non-disabled occupants and wheelchair users.
3. Simulate the evacuation movement phase of building populations with 1, 2 and 3 wheelchair users based on an assigned evacuation route.
4. Analyze results and modify the simulation system as necessary to reduce discrepancies.
5. Identify egress components of the developed building model and propose a ranking system of “most egressible” to “least egressible” structural components.

1.4 Outline

Chapter 1 presents an overview of this thesis by providing a brief look into disability rights, legislation, and disaster. Next, research objectives are presented in **Section 1.3.** In the present section, we look forward toward the remaining chapters in this work.

Chapter 2 provides a comprehensive review of the open literature focused on building fire evacuation. More specifically, we look at the available information on the non-disabled population as well as the disabled population to draw parallels and deviations between the research areas. Finally, an overview of professional definitions of disability are provided and built upon for use in this work.

Chapter 3 includes the research methods used in this thesis as well as descriptions of the simulation environment, building model, and occupant characteristics.

Chapter 4 presents experimental results from two sets of simulations of heterogenous populations of non-disabled occupants and wheelchair users during the evacuation movement phase. Here, we report results based on a proposed structural ranking system as well as number of wheelchair users.

Chapter 5 focuses on research challenges and limitations. We also present suggestions for future work on this topic and plans for related research.

Chapter 6 presents final conclusions and inferences of the thesis.

2. LITERATURE REVIEW

This chapter starts by providing and overview of the inclusion criteria for a thorough literature review of people with disabilities in fire scenarios. A categorization of disability is also provided, which addresses key questions related to an individual's disability in evacuation. Next **Sections 2.2** and **2.3** review evacuation research focused on the non-disabled and disabled communities, respectively. Finally, an overview of key findings is provided, and a comprehensive definition of disability is developed based on findings of **Chapter 1** and **Chapter 2.**

2.1 Methodology

The first section of this review has focused on the past and present inequalities regarding people with disabilities. After reviewing this information, it became clear that one of the most persistent issues for PWD is accessibility in the built environment. While efforts have been made to reduce this burden through legislation and equality movements, there is still a lack of information regarding the safe *egress* of people with disabilities from public buildings. Inherently related to building design, physical accessibility, and disaster management, the ability of people with disabilities to safely egress and evacuate from a structure has only loosely been explored. Thus, a categorization of disability from a fire evacuation perspective was developed in order to identify research gaps. Presented in **Figure 1,** the *Disability Evacuation Framework* facilitated in the retrieval of articles and other reviews by identifying key components of the evacuation process for various types of disabilities. The questions and categories facilitated in the identification of the following keywords and phrases for the retrieval of existing articles and reviews on evacuation for PWD: "disability evacuation", "fire evacuation", "fire safety for people with disabilities", "functional independence", "evacuation assistance", "visual impairment with evacuation", "smoke effects on evacuation", "behavioral effect on evacuation." Papers were selected from the Elsevier and Science Direct Databases over a period of six months (January 2021 through June 2021), with additional searches for new work from July 2021 through December 2021.

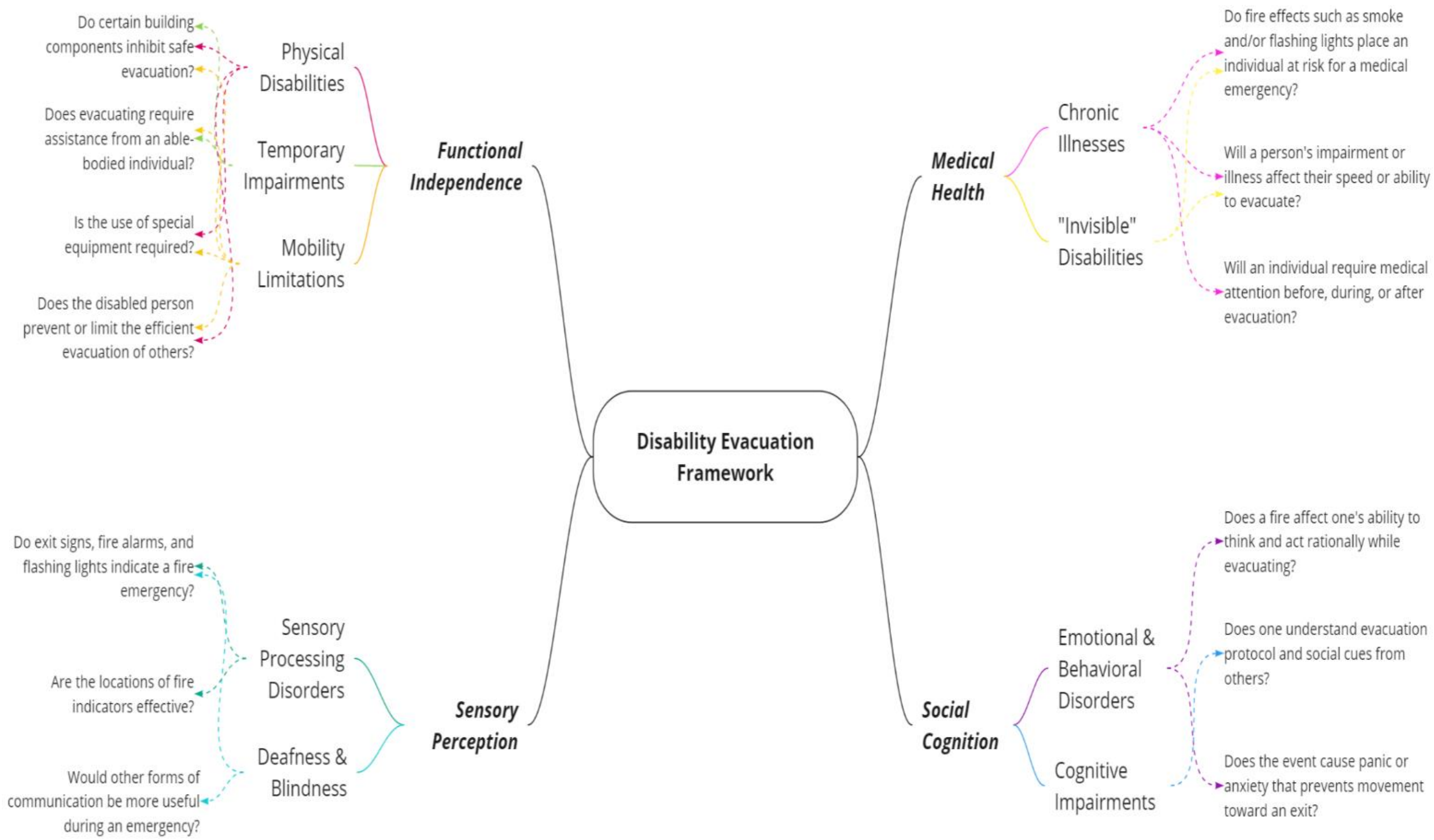


Figure 1: Disability Evacuation Framework

For papers to be included in this study, they had to address fire evacuation from buildings (public or private) and refer to people with functional limitations or diagnosed disabilities. Note that studies including non-disabled building occupants were also included in the following section in order to address the contrast between available research for both population segments. Both journal articles and reviews were included with an emphasis on evacuation studies and experiments—either real or simulated. Papers were excluded if they only focused on policy or legislation relating to fire safety, modelling development and methods, or buildings where assisted evacuation is expected (hospitals, nursing homes, etc.). The main focus of this study is on buildings where self-evacuation is expected, although papers were included if they mentioned help from otherwise "untrained" but non-disabled evacuees (i.e., coworkers assisting a wheelchair user downstairs). After gathering papers, information was extracted and sorted based on the four main categories in **Figure 1:** *functional independence, sensory perception, medical health, and social cognition.* Linking each paper to a category resulted in the identification of research gaps for certain disabilities and the identification of a baseline disability definition for fire evacuation.

2.2 Non-Disabled

Although the focus of this research is on those with disabilities, it is necessary to address the vast number of studies that have been completed for those without impairments. Following the terrorist attacks on the World Trade Centers (New York, USA) in 2001, researchers across the world became increasingly aware of the complex nature of building evacuations, especially high-rise evacuations. In fact, in the two decades following the event, over 15,000 studies, reviews, and experiments have been completed, according to the search engine Google Scholar. One of the most prominent studies produced during this time frame was the multi-year investigation into 9/11 performed by NIST [77]. While it mainly focused on structural reasons for the towers' collapse, the organization also produced a 298-page report on occupant egress, behavior, and emergency communication.

The NIST investigation made it clear that occupant survival was a direct result of both efficient structural design and social and environmental cues. For example, each affected tower (WTC1 and WTC2) had three interior stairwells: two of width 44 inches and one of width 56 inches [77]. These stairwells combined for a total of 6.5 units[2] of exit width—just enough to meet the minimum requirements of the New York City (NYC) Building Code under office occupancy [78]. Additionally, impending changes to the NYC code in 1965 resulted in the elimination and/or reduction of several egresses aids in the final design of both WTC1 and WTC2. Fire towers[3] were eliminated, reducing the total number of stairwells from 6 to 3, the size of exit doors was reduced by eight inches, and elevator and stair shafts were changed from a three-hour fire rating to a two-hour rating [77]. These changes, although they met code requirements from NYC and the International Building Code (IBC), undoubtedly resulted in several issues during the evacuation effort on September 11.

Social and environmental cues also played a large role in the evacuation of both towers on 9/11. The overall size of the buildings (110 stories) made it difficult for occupants located more than a few stories from the impact regions to understand the gravity of the situation; smoke, fire, and other emergency cues were undetectable. Thus, emergency communication was of the utmost importance for efficient evacuation. Unfortunately, this was an issue in both WTC1 and 2. In the North Tower (WTC1), NIST found no evidence that evacuation announcements were heard or understood by building occupants, despite several attempts by the lobby fire command station. In

[2] One unit is equal to 22 inches of exit width (approximately 56 centimeters) per the 1968 NYC Building Code [77]
[3] Fire towers are exterior fire-rated stairwells that terminate at ground level and are designed to ensure that smoke and fire conditions from the building do not infiltrate the tower [78]

the South Tower (WTC2), there were 16 minutes after the attack on the first tower but before the attack on the second tower. Before the second impact, occupants of WTC2 were instructed to return to their offices. However, just a few moments later, another announcement was made to evacuate. Both created issues in situational awareness that resulted in the deaths of approximately 100 people [77].

The NIST investigation wasn't the only study produced on the World Trade Center following 9/11. Several others aimed to study the evacuation from a variety of fronts. The first analysis of the event came from a collection of first-person accounts published either in the media or online [79]. While the over 700 accounts collected do not provide the same opportunity for analysis as other scientific studies, they did provide insight into occupant experiences, emotions, and behaviors that explained the complexity of human interactions and reactions to the event. Another study of 9/11 was performed by the Mailman School of Public Health at Columbia University under a grant from the CDC [28]. This study was performed from an epidemiological perspective, and it aimed to identify risk factors and to facilitate factors in evacuation time. Using a Participatory Action Research (PAR) framework and qualitative survey, the evacuation study found that factors associated with effective evacuation included disaster preparedness training, building familiarity, physical conditions, medical health status, footwear, and occupant behavior (social and sensory cues) [80]. The final 9/11 study was international—a collaboration between the Universities of Greenwich, Ulster, and Liverpool in the United Kingdom called Project HEED, or the High-rise Evacuation Evaluation Database. Its goal was to create a database of information on the towers and their evacuation on September 11 by tying occupant experiences to specific times and locations, thus allowing other researchers to estimate information such as response and evacuation times. Interviews with 271 WTC survivors gave an average travel speed of 0.29 m/s with the lowest recorded speed of 0.17 m/s, likely resulting from high levels of congestion and not physical ability [27]. Additionally, the study produced a large amount of data on response times and observed that Body Mass Index (BMI) and fitness do not appear to significantly affect the need for rest time or slower travel speeds [27].

The diverse and alarming findings from each of the 9/11 evacuation studies resulted in a large influx of evacuation studies focused on high-rise buildings, human behavior, structural components, crowding tendencies, and much more. Perhaps most prominent are those focused on high-rise buildings [81–94] as a recent study showed that vertical evacuation could take up to 70% of the total evacuation time in large structures [95]. Recent real-time experiments for tall buildings have focused on parameters such as downward/upward movement speed [83,87,89–92], crowd density or bottlenecking [83,93,96,97], the effect of visibility conditions [30,98–102], and combined elevator/stairwell evacuation times [90,94,103], all of which aim to quantify values for determination of efficient evacuation strategies. Another category of evacuation experiments is focused on evacuee characteristics, including gender [29,30,104], age [31,84], and weight/BMI [29]. Of these studies, none mentioned building occupants with disabilities or impairments.

The studies mentioned previously all represent the leading edge of real-time research related to fire evacuation of buildings. They surfaced mainly due to the diverse issues discovered following 9/11, but they are far from the first studies on fire evacuation. Prior to the World Trade Center attacks, evacuation studies were mainly performed in response to other fire incidents. For example, an analysis of behavioral cues was performed following a hotel fire that occurred in Tokyo, Japan, on February 8, 1982. The study gathered information on guests' recognition of emergency exits as well as their pre-evacuation behavior and found that people were mainly concerned with finding information about the severity of the fire threat before evacuating. Guests also evacuated quicker if they sought out emergency exits prior to the fire [32]. Similarly, an analysis of human behavior in the MGM Grand Fire (1980) also found information-seeking behavior among evacuees. Individuals were found to congregate together in refuge areas to gather information and communicate, resulting in as many as 35 people in a single room at once [26]. These groups, called “convergence clusters” by the authors, were documented on as many as 17 floors of the hotel. Other behavioral studies were common prior to 9/11 as well. Sources [105–107] studied reactions to various fire alarms and/or exit choice, finding that evacuees tend to choose the most familiar exit (usually the main exit), regardless of the time it takes to get there. They also found that people react the most quickly to spoken alarms rather than simple sounds or bells.

It is clear from the discussion above that evacuation research is diverse in topic and scope. Studies have been performed on human behavior, evacuee characteristics, building components, and much more. However, studying fire evacuation is difficult and sometimes unattainable. Real fires cannot be used in experiments because they present hazards to participants. Additionally, it can be hard to obtain people willing to participate in research studies, especially those requiring diverse populations (studies related to age, gender, people with disabilities, etc.). They can also be expensive, and selected building types and components may not be available (investigated high-rise buildings in rural locations, tunnel studies in locations without metro or subway systems, etc.). For these reasons, recent research has moved toward studying evacuation through simulation and modeling. This has created an entirely new realm of information and data on fire evacuation. Beginning around 1980, simulation modeling was introduced as a viable option for dealing with complex issues in the fields of safety and health [108]. In 1987, one of the first reviews on available computer models for evacuation analysis was published on network models[4] and algorithms using an early form of EVACNET+ as an example [109]. By 2010, there were 26 models recognized by NIST's Fire Research Division, all containing a vast number of special features [37]. More recently, independent models have been created to explore special problems usually not capable of being analyzed by those available for public use. For example, very few models can simulate the interaction between a building environment, occupants, and combustion materials. Since environmental conditions and smoke distributions can significantly influence human behavior and capabilities during fires, Chinese researchers Tang and Ren [110] developed a GIS-based model to incorporate all essential interacting variables using rule-based behavioral modeling and dynamic fire features. Other recent independent models have focused on combining several complex dynamic phenomena associated with building fires, thus working toward more realistic simulations. Nguyen, Ho, and Zucker [111] integrated smoke effect and blind evacuation strategies within their model, confirming that a reduction in vision has a significant impact on the number of casualties in a fire. Filippidis et. al. [112] introduced occupant interaction with signage systems in their evacuation model, thus incorporating physical obstructions and some behavioral concepts. Sources [110,113–122] also incorporated human behavior in their evacuation models, studying everything from stress variation to decision making and group effects.

Evacuation research has progressed significantly in recent decades. From simple experiments to quantify walking speeds and evacuation times to current simulation and modelling practices that include complex decision-making capabilities and occupant characteristics, researchers are all in agreement that evacuation is a complex phenomenon including a wide variety of dynamic

[4] Network models are graphic representations of paths or routes by which objects or energy may move from one point to another [109].

interactions between people and their environment. However, people with disabilities are still neglected. Nguyen, Ho, and Zucker studied reduced visibility due to smoke, but they did not incorporate blindness or those with other disabilities. The simulation and modelling studies incorporating human behavior are wide in scope, and all agree that occupant behavior plays a large role in how, when, and why someone chooses to evacuate, but they fail to include heterogeneous populations and those who make decisions differently than the neurotypical population. Similarly, case studies and investigations do not typically recognize those with disabilities and their evacuation strategies. The exception to this is the NIST 9/11 investigation, which recognized the roughly 1,000 people with mobility impairments that evacuated from the towers during the event. This mention was only in passing, however, as NIST explained that over one-half of people interviewed from WTC1 and one-third of those from WTC2 reported injured and/or disabled occupants as a constraint to their own evacuation in the stairwells [77]. As the number of impaired and disabled people continues to grow due to an aging population, the obesity epidemic, and the push for equality, a more concerted effort needs to be made to include them in evacuation studies and experiments.

2.3 Disability

The wide number of evacuation studies focused on homogenous populations of non-disabled occupants suggests a significant push to improve fire safety and knowledge regarding building fires. But while there have been many studies focused on quantifying evacuation times, studying human behavior and decision-making, and the effects of smoke or low visibility for those without impairments, there is still a lack of research focused on those with disabilities. This is surprising for a number of reasons. First, PWD accounts for over 15% of the world's population (over one billion people) [123]. Additionally, 2-4% of those with disabilities experience significant difficulties functioning; and the number of PWD will only continue to grow due to population aging, the rapid spread of chronic illnesses, and improvements in medical care [123]. Second, the push for equality (both during the Disability Rights Movements and today) means an increased number of people with disabilities are working to reclaim their freedom in society. More PWD in all building types directly results in a more diverse building population with more complicated needs during disasters. Finally, researchers have already shown increased interest in human behavior during fire, proving that decision-making and development of inclusive evacuation procedures for the neurotypical and non-disabled population is difficult. With these reasons, as well as examples such as the NIST 9/11 study citing people with disabilities as a constraint to evacuation due to lack of inclusive evacuation procedures, an increased effort needs to be made to introduce those with impairments into fire research.

Despite the underdeveloped field of evacuation research for those with disabilities, several researchers have made an effort to include PWD in their reviews. Boyce et. al. [124] considered mixed populations as they reviewed design provisions and historical fires, noting that design guidance (mostly on exit and stair widths) is determined almost exclusively from largely non-disabled populations. Additionally, the authors stated that there is no international requirement to provide lifts as a means of evacuation despite being the preferred method in the UK [125]. Narrow stair and exit widths combined with a lack of evacuation lifts can lead to congestion, blockages, and much more. Additionally, those who cannot evacuate via stairs are left waiting for help from colleagues or emergency personnel rather than evacuating on their own. Another recent study has focused on existing egress datasets with the goal of updating them based on changing demographics [126]. The authors explain that existing datasets (for walking speeds, evacuation times, etc.) are outdated and based mainly on limited populations. Changing demographics and heterogeneous populations make the evacuation process more complex by changing rescue requirements for emergency personnel, increasing social pressures for help and assistance among other building occupants, changing overall evacuation performance, and producing a discrepancy between the required safe egress time (RSET) and available safe egress time (ASET) [126]. In a final recent review, authors Bukvic et. al. [127] highlights the lack of research for those with cognitive impairments through a categorization of evacuation actions. Using a variety of case studies and experiments, common evacuation activities and procedures were identified (walking downstairs, crawling, information-seeking) and paired with a classification from the ICF, thus creating a database of evacuation activities and evacuee behavior.

The majority of evacuation research, including PWD is focused on physical impairments and easily quantifiable data, as shown from the previously mentioned reviews. However, those pertaining to wheelchair users are the most abundant. Studies [128–132] performed evacuation experiments to determine how flow rates change as the number of wheelchair users increases. They each noted a significant decrease in flow coefficient as the number of wheelchair users increased, thus showing a clear difference between homogeneous and heterogeneous population dynamics in a fire. Other studies using wheelchairs are mostly based in hospitals in order to isolate as many physically disabled occupants as possible [133–135]. Still, others have focused on disaster preparedness and guidance for more efficient evacuation strategies [134,136–138]. Overall, experiments and simulations with wheelchair users at the forefront claim that they present the most challenges and barriers to safe evacuation for all because they take up more space, move slower on average than those without disabilities, and cannot navigate some building components.

Other studies, including people with physical disabilities, typically refer to one's limitation as a *mobility impairment*. They focus more on building components than the type of disability. For example, there are many experiments and simulations that study stair evacuation [136,139–145]. Several have gathered local movement speeds with average values ranging between 0.30-0.50 m/s, although individual speeds vary tremendously due to surface changes, congestion, aid or lack thereof, and assistance. Additional structural components studied include elevators or lifts. Occupant emergency elevators (OEEs) have long been suggested to benefit evacuation for all populations, as they were first introduced by NIST in 1914 [146]. Now proven to aid in the evacuation of mobility-impaired occupants by allowing them to self-evacuate, studies using OEEs have shown a significant reduction in evacuation time as well as fatigue and exhaustion [136,147–154]. Additionally, they reduce the problems that arise with stair evacuations and devices. For example, when an evacuee is transferred to a stair chair, they give up their own independence and the ability to use their mobility aids. Furthermore, they must rely on other individuals to keep them safe. In much the same way, waiting for help in refuge areas also forces disabled occupants to relinquish their independence. One study found that people were uncomfortable with waiting for moderate periods of time for fear of being forgotten or isolated [155]. Others have noted factors such as crowding, under-utilization, and a lack of understanding of refuge areas [156]. Source [157] studied several combinations of structural components to determine the optimal number of stairwells, OEEs, and refuge floors. Using simulation, results showed that providing one refuge floor in combination with six OEEs and three stairwells allowed for 25% more people to evacuate. However, increasing the number of refuge floors resulted in congestion and long queues in the refuge area. Despite the clear disadvantages, refuge areas have been commonly implemented in the design of ultra high-rise buildings. In Hong Kong, they have been in use since 1996 [157]. In the United States, the IBC requires all new construction to include an area of refuge unless the building is single-story, has a supervised automated sprinkler system, and has a wheelchairfriendly route out of the building [158]. Elsewhere, refuge areas may be required every seven floors [159]. This is because they can provide a temporary resting area for those with low stamina, act as a place of assembly for all occupants, and provide a safe waiting area for those requiring assistance to navigate stairs [124].

Apart from physical disabilities, there has been some interest in sensory disabilities among evacuation researchers. This includes the blind and deaf communities as well as those with sensory processing disorders. For the blind and visually impaired, walking speeds both horizontally and downstairs were explored by authors Sorensen and Dederichs in 2013 [160]. Their evacuation drill included 40 participants with different degrees of vision loss and found that recommended horizontal walking speeds present in the literature are typically much higher than results showed for the visually impaired (1.19-1.34 m/s compared to 0.75-1.18 m/s) [160]. Experiments and case studies [161–166] also explored occupants with visual impairments. Many of them noted that orientation (familiarity) and surrounding sounds are the most significant factors of evacuation. Loud fire alarms can prevent visually impaired evacuees from hearing ambient noise, thus depriving them of necessary cues to orient themselves [163,167,168]. Auditory disabilities are wide in range and scope and can impede perceptions of fire alarms and other hearing emergency cues [163]. For example, at a Russian boarding school for deaf children in 2003, 28 were killed, and 17 more were injured in a fire because auditory alarms were not heard [169,170]. In another instance, a deaf teacher and her students were left in a classroom during a fire drill because the school issued only audible alarms [169]. Thus, the ability to alert the deaf community of an emergency has been of great concern among researchers, and several studies have focused on alerting devices such as shaker beds and visual alarms [171–174]. In research study [171], a new vibratory device to wake sleeping occupants was proven to be up to 93% for the hard of hearing. Additional studies discussed in [173] show similar effectiveness for shaker beds.

Chronic medical health disorders and cognitive impairments or mental health disorders are by far the least studied forms of disability in evacuation research. This is likely because these disabilities are largely considered "invisible" and hard to quantify. However, one study evaluating evacuation performance of a variety of occupants (elderly, visually/hearing impaired, cognitively impaired, etc.) found that those with cognitive or intellectual disabilities required the longest time to make evacuation decisions, but their response (movement) time was the shortest [175]. Another study suggests that long-term training and reminders seem to be the best approach to evacuating people with mental impairments [163]. However, many trials are needed, and training must be repeated at regular intervals to ensure building occupants do not forget evacuation procedures. For people with chronic health conditions, evacuation can be challenging for a number of reasons. First, this group is diverse and complex, ranging from people with asthma to those with heart disease, cancer, or diabetes. Additionally, people with medical health disorders may require additional equipment, some of which must be powered by electricity. Finally, as mentioned, people in this group are hard to easily identify. All of these factors make it hard for researchers to study anonymously or without knowing individual characteristics. Thus, an unannounced evacuation drill or a non-biased experiment toward building occupants may be nearly impossible to achieve. No experiments or case studies for fire evacuation were found among those with chronic health disorders during this literature review. Studies primarily focused on disaster preparedness and the needs or development of impairments following disasters.

Simulation and modelling is also an important aspect of evacuation research for people with disabilities. However, to current knowledge, there has only been one model developed with the initial goal of studying PWD. The BUMMPEE model: *Bottom-Up Modeling of Mass Pedestrian flows—implications for Effective Egress of individuals with disabilities* was developed as a “platform for evaluating the environmental characteristics and population criteria used to include the diversity and prevalence of disabilities in the population” [176]. BUMMPEE can incorporate the blind and deaf communities, the physically disabled, and some cognitive disabilities. Additionally, modified environmental characteristics such as routes, exits, and obstacles are included as they have been shown to have behavioral effects on disabled populations [176]. While this model is a step in the right direction for the safe evacuation of people with all forms of disability, most, if not all, features can be simulated in other evacuation software such as Pathfinder [177], which do not have the main goal of simulating people with disabilities.

2.4 Overview of Key Findings

Throughout history, people with disabilities have generally been overlooked in the social, economic, and legislative realms. This has only recently changed with disability rights movements around the world; and a push for equality in the public environment has created the need for updated building components and accessibility requirements. Legislation such as the ADA in the United States, the *Disability Discrimination Ordinance of 1995* in Hong Kong, and many more have allowed PWD to re-enter society and gain much of the freedom they lacked for so long. However, their needs are still often neglected in disasters. This is clear from the comprehensive review of existing literature for fire evacuation presented herein. Research is abundant for homogeneous populations of non-disabled building occupants, focusing on everything from high-rise buildings to human behavior and even boat or aircraft evacuation. For disabled occupants, much less information is available. Additionally, evacuation research for PWD is primarily focused on physical disabilities. There are few studies focused on cognitive impairments or chronic health conditions.

The unbalanced number of studies available between the disabled and non-disabled communities has identified a clear set of issues. First, many people with disabilities are neglected or altogether forgotten about in the fire. From the unwillingness of the non-disabled to assist those with impairments during the evacuation of the World Trade Center towers during 9/11 to the lack of studies focused on all forms of disability in disaster, those who need the most help are usually unable to get it. This includes those with chronic health conditions such as asthma, cystic fibrosis, or cancer. No studies devoted to these impairments were identified in the literature, despite several focused on smoke and toxic gases for the non-disabled. Of those for the non-disabled population, many have identified problems with smoke impairing vision and creating breathing issues that hinder safe evacuation. In fact, smoke inhalation has been considered as the number one cause of fire fatalities for many years [178,179]. From this, one can only assume that for those with respiratory health conditions, the effects would be compounded.

Similar to chronic health conditions, mental health disorders are also rarely found in the literature. This is surprising due to the recent push among evacuation researchers to study human behavior in fire, as it can vary greatly among different people and populations. In the non-disabled population, for example, significant information-seeking behavior has been identified. People regularly look for signs of danger (smoke, other people evacuating, etc.) before attempting to evacuate. This leads to increased evacuation times and alterations in route choice, stairwell use, and other choices during the evacuation process. People have also been found to evacuate in groups, often called convergence clusters in the literature. While these groups may reduce stress for evacuees because they bond over shared experiences, they only increase queuing and congestion in buildings. These behaviors among evacuees are consistent and easy to identify. However, they continue to be difficult to quantify, especially for the disabled population. This may be why there are few studies focused on those with cognitive disabilities. Neurodiverse populations make decisions and find information differently than those without disabilities. However, because there are a limited number of current studies, it is unclear if they are consistent in their evacuation behaviors, choose exit routes in the same way as non-disabled populations, or even evacuate in the same time frame. Thus, it is all too important to begin studying those with cognitive impairments in fire.

This work also brought to light the need to identify structural aids and barriers to evacuation for all populations. For those without disabilities, stairs and elevators have widely been considered to assist in the evacuation. However, there are significant issues with overcrowding in stairwells, bottlenecks around corners and within doorways, and long waiting times for elevators. Additionally, fire signals such as alarms and lights have been proven to save lives during nighttime fires. However, they do not work for all populations. Those with sensory impairments require unique fire signals so that the visually impaired are not disoriented, and those with auditory impairments are alerted to the issue. Correct alarms may also ease decision-making issues for the sensory impaired by leading them to the most efficient exit rather than the most familiar exit. These issues have shown that the need for self-evacuation among PWD is imperative. Researchers have published several accounts of evacuees struggling to find help downstairs or afraid to wait in refuge areas for fear of being forgotten. If structural components can be tied to various categories of building populations, designers and fire safety engineers may be better able to plan for a variety of fire scenarios. This may also be better tackled if PWD are included in the building planning and construction phases. All too often, legislation and planning focused on helping people with disabilities is finished without ever consulting someone with a disability. This results in building designs that aim to reduce the difficulty of PWD to traverse public buildings but actually fail to provide an environment that benefits impaired occupants.

Finally, evacuation modeling and simulation have been consistently shown as one of the most effective ways to study and improve life safety in the built environment. Low cost, study efficiency, and ease of use are attractive features of most models, and they reduce the need for willing participants and desirable locations. Researching the evacuation of people with disabilities is a challenge in any fashion, but evacuation models give the ability to incorporate a wide range of impairments without seeking a study group in real life. With the introduction of virtual reality and artificial intelligence, using simulations to study evacuation has become even easier. Serious gaming has been implemented in several evacuation studies recently [121,150,180,181]. These give researchers the ability to study human behavior with real evacuees but without the possible danger associated with a fire evacuation. Additionally, they present a more accurate representation of building fires for study participants, which in turn gives better results compared to real-time experiments that cannot use fire or simulations that only estimate behavior. Currently, many evacuation models do not incorporate the complexity of all human behavior in a fire scenario. However, their continued development and the implementation of virtual reality results may improve these significantly in the near future. Including heterogenous populations in these studies will only further improve evacuation models, allowing the research community to gain a better understanding of how to improve the future safety of everyone in the ever-evolving built environment.

2.5 Defining Disability

Also discussed in this review is the broad and long history of disability. Centuries of overlooked disabled populations and their societal needs have created a world in which many people do not understand disability, and it has ultimately resulted in the lack of a comprehensive definition of the term. This is apparent by the wide range of definitions adopted by organizations around the world. For example, FEMA's functional needs approach attempts to define the needs of people with disabilities following a disaster. The World Health Organization has also defined disability through the ICF by recognizing it as a complex entity resulting from both society and the environment. While these definitions provide an inclusive and overarching view of impairments for the general population, they fail to identify qualities that affect their safety in a fire. Thus, it is imperative that a new definition be introduced from an engineering and evacuation background. Divided into four parts, the following definition of disability was produced based on the available research for disabled populations in a fire as well as historical categorizations of disability (see **Figure 1**). Disability in relation to evacuation is therefore defined as follows:

1. *Functional Independence*: Related to the physical ability of one to evacuate a structure and inherently includes a building's organization and design components (stairwells, hallways, elevators, etc.) This part also encompasses any assistive technology required by an evacuee and in their daily life.
2. *Sensory Perception:* Related to the detection, interpretation, and response of an individual to environmental stimuli. This section of the framework involves the ability of one to understand and respond to exit signs, fire alarms, smoke, and other protective fire components and can be interpreted by an individual's requirement of alternative communication.

3. *Medical Health:* Related to an individual's personal medical needs and how they change due to a fire. This section includes the effects of smoke, flashing lights, and the evacuation process on someone's health.

4. *Social Cognition:* Related to rational thinking and the ability of one to make proper decisions during an emergency. The part includes mental health disorders and the interaction between building occupants.

None of the four items specify "applicable" forms of disability, leaving room for researcher interpretation. However, each can be generally applied to a group of disabilities if desired. The review of existing literature clearly identified physical disabilities as the most widely studied among evacuation researchers. Thus, *functional independence* loosely refers to physical and mobility impairments. This includes wheelchair-bound individuals, those with other gait irregularities, and those requiring assistive technology (oxygen, service animals, canes, etc.). The second most frequently studied were sensory impairments. *Sensory perception* refers to the deaf and blind communities but can include any sensory difficulties previously acquired or obtained during a fire event. Third, the *medical health* category can be applied to those with chronic illnesses and "invisible" disabilities such as seizure disorders or multiple sclerosis. Finally, *social cognition* is applicable to many mental health and cognitive disorders. Each section requires different actions during an emergency, but there is room for overlap as well. Many people with disabilities who require assistance evacuating may also need medical intervention during a fire event. Just as each individual's impairment or disability is unique, so is their safe evacuation path and procedure. Furthermore, each is inherently associated with structural components that restrict movement during emergencies. Identifying each part in future studies will allow engineers to extract the main element preventing an individual's safe evacuation.

The hope behind introducing a new definition of disability is for researchers and non-disabled occupants to be able to effectively categorize the needs of various disabilities in fire. If building components and evacuation aids can be placed alongside each section of disability, one can easily pair disability with the most effective method of evacuation. This may result in a more efficient evacuation for all populations, even when some are uneducated on disability needs in the built environment. This can also be extended to building designers and fire safety professionals. As mentioned, people with disabilities are rarely consulted in design processes. Referencing this definition (and a future tie to structural components) will help ensure the proper facilities are included in each new building. Finally, the ultimate goal of this research on PWD in fire is to allow everyone to self-evacuate during an emergency rather than waiting for help, which may never arrive. Providing the most beneficial structural evacuation aids for each person's disability is key to achieving this, and a new definition is just the beginning for evacuation researchers and professionals.

3. METHODOLOGY AND SIMULATION

Chapter 3 provides the background and rationale necessary to complete the evacuation simulations in this thesis. **Section 3.1** first reviews the analysis methods used by evacuation researchers and provides an overview of the general capabilities of the chosen evacuation model. Then, the building model created for this research is described. **Section 3.2** dives further into the parameters used to analyze various evacuation cases and includes the development of the fire scenario, building population, and research assumptions.

3.1 Simulation Environment

As stated by Erica Kuligowski in the Society of Fire Protection Engineers' (SFPE) Handbook of Fire Protection Engineering, "an engineer performing a life safety analysis on a structure is presented with a number of alternative tools" to choose from to complete their analysis [182]. These techniques include empirical calculations, manual engineering calculations, and evacuation models. Empirical calculations form the basis of evacuation research and have been implemented since the 1950s [183]. This technique uses available egress datasets from which educated predictions are made about a similar structure. Manual engineering calculations involve the use of the previous technique, but at the component level (stairs, doors, etc.) rather than an occupant level. In this method, the performance of evacuees is predicted along pre-defined egress routes. Finally, evacuation models represent a wide variety of techniques and methods. Models may be simple and include empirical data or manual engineering methods (simply automating the process), or they may be sophisticated and involve automated agents moving seamlessly through three-dimensional space [182].

Empirical calculations, manual engineering calculations, and evacuation models are all supported methods that can be used to evaluate evacuation scenarios. However, there are clear advantages to using models over the manual methods. First, recent technological advancements have provided researchers with a wide variety of available evacuation models to choose from. As previously mentioned, there were 26 building evacuation models recognized by NIST's fire safety division in 2010, and many more have been independently introduced since then. This allows researchers to select a model that best fits their project requirements. Technological advancements have also allowed for the development of flexible techniques and complex building design implementation—items that generally cannot be tackled through hand calculations. For instance, computer evacuation models can evaluate results from a variety of structures (buildings, tunnels, aircraft, cities, marine vessels, etc.) and a variety of scenarios (fires, bomb threats, weather events, riots, relocation, etc.) [182]. Models also decrease study time and costs. This gives researchers the ability to easily modify projects—thus producing a greater number and variety of results that others may refer to in the future.

Due to the inherent benefits of evacuation modelling, this method was chosen for the present thesis. Project requirements were considered in the choice of a suitable model and include available information, nature and scope, and time and cost. For this thesis, available information includes two-dimensional building floor plans of known area, author-defined building occupants, and a theoretical fire scenario. These requirements allow great flexibility in the choice of an evacuation model because the general scope is flexible. However, a building model interface (one in which a building can be created within the software without requirement of imported three-dimensional drawings) and the ability to incorporate people with disabilities (wheelchair users specifically) were required. The pre-evacuation phase and fire dynamics are not investigated in this thesis and were not required components of the selected evacuation model. While the nature and scope of the thesis is small (involving the simulation of wheelchair users and non-disabled occupants in a low-rise building), future works aim to include a larger variety of PWD and alternate building types. It was significant to select a model with flexible features of structural design and human behavior. Furthermore, both the timeline and budget of this thesis are small. It was necessary to choose a model that is widely available to the public for a reduced cost. For the reasons described herein, as well as the information provided in NIST’s Review of Building Evacuation Models [37], Pathfinder was selected for this thesis [177].

3.1.1 Pathfinder Evacuation Software

Pathfinder is an agent-based egress and human movement simulator released by Thunderhead Engineering Consultants, Inc. in 2009. Its production was funded by a Small Business Innovative Research (SBIR) grant supported by the United States National Science Foundation (NSF) from 2005-2007 [184]. Initially, Rolf Jensen and Associates (RJA), a worldwide leading protection consulting firm specializing in fire safety and security, completed the testing that assisted in Pathfinder’s development. Now, user feedback through Thunderhead’s support forum guides further development and improvements, and approximately four major updates are released per year. For this thesis Pathfinder versions 2021.4 and 2022.1 (released in December 2021 and April 2022, respectively) were used.

Pathfinder includes three tools to represent building models and simulation results. First, a graphical user interface (GUI) creates and runs simulation models. An example of this interface is provided in **Figure 2.** Next, a three-dimensional (3D) results program is included for high-performance visualization of simulation time history. Finally, a two-dimensional (2D) plotting program graphically represents time histories. Examples of the results interfaces are shown in **Figure 3.**

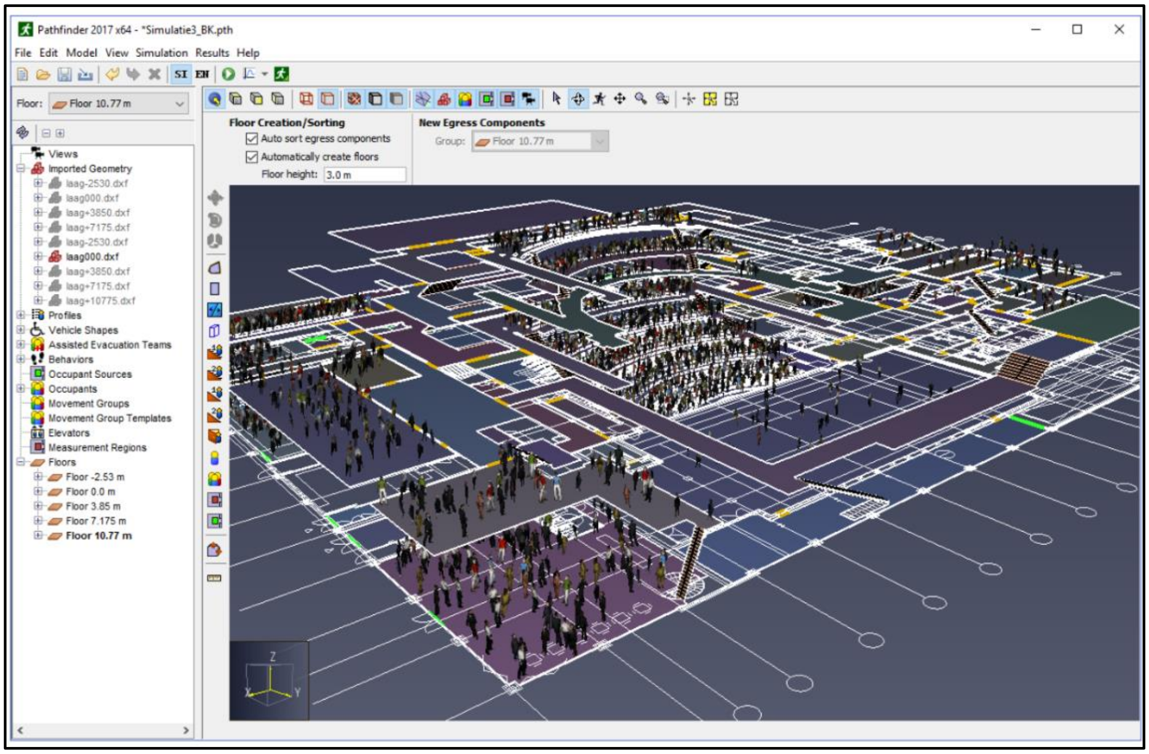
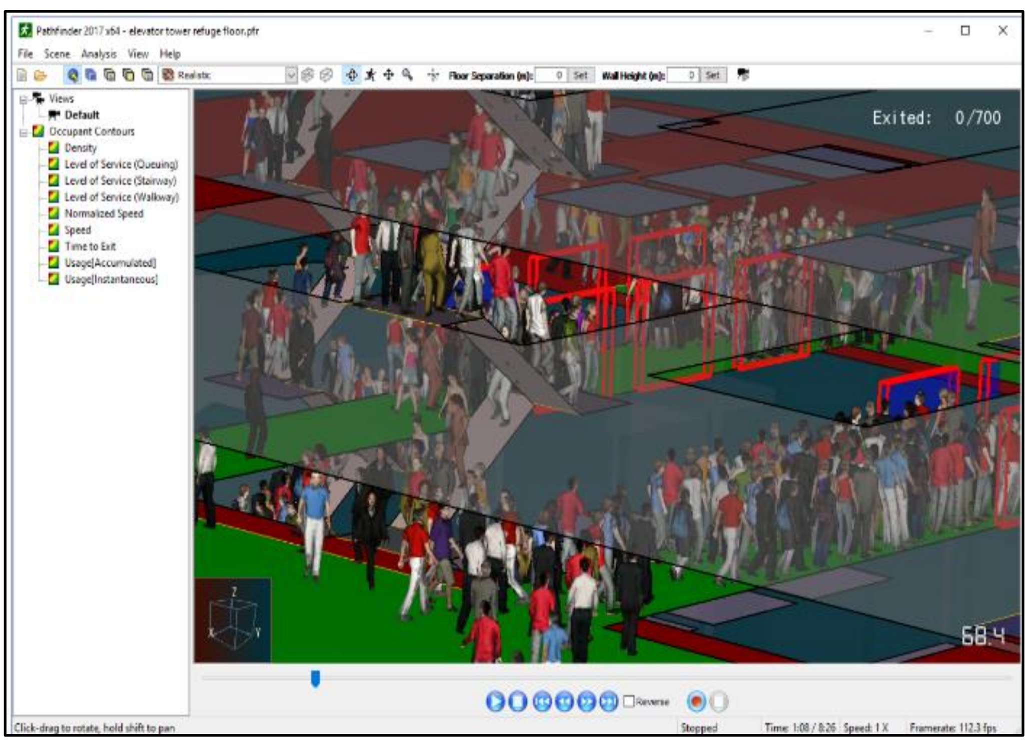
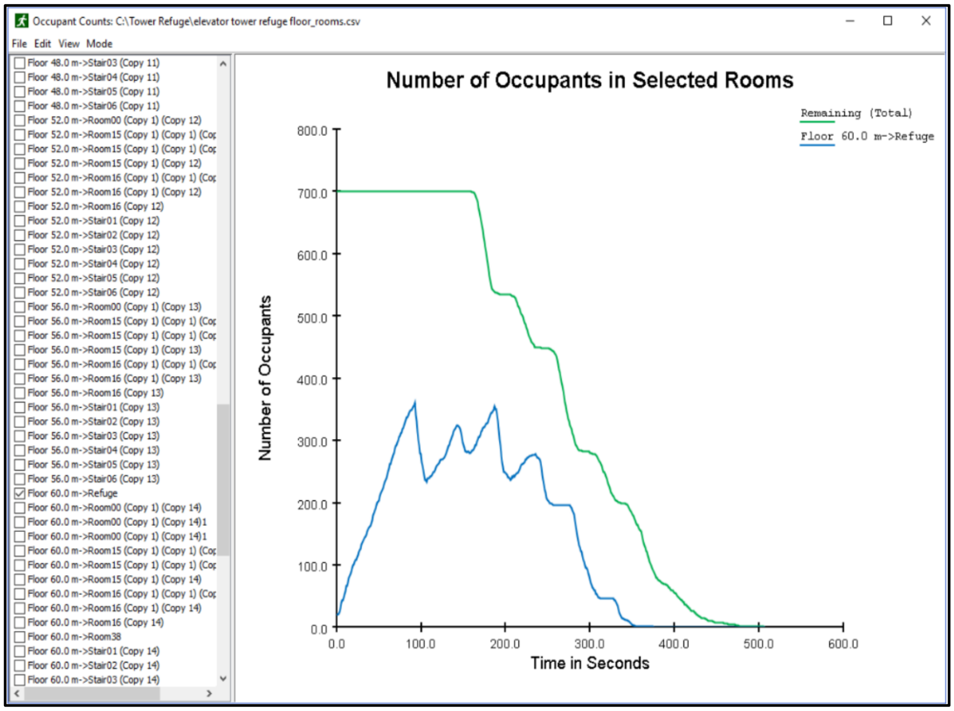


Figure 2: Pathfinder Graphical User Interface Example (Model of the Theater de Vest created by Van Hooft Adviesburo) [184]



a) Three-Dimensional Results Visualization



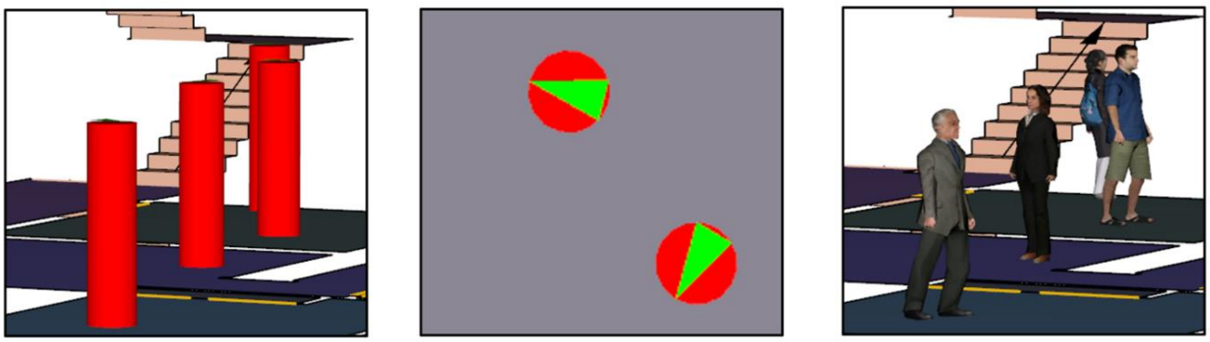
b) Two-Dimensional Time History Plot

Figure 3: Pathfinder Results Interface Examples

Each of the aforementioned tools is designed to visualize the movement environment (a 3D triangulated mesh) and match real building dimensions. This space is called the navigation geometry and includes egress components defined as doors, rooms, stairs/ramps, and elevators. In Pathfinder, rooms are polygonal shapes that must not overlap on the same level (x- or y-direction). Doors are thick or thin elements that connect two rooms on the same level (z), stairs and ramps connect rooms on different levels, and elevators may travel in any direction. Floors provide group assignments for the navigation geometry and are defined by their vertical (z) locations. They also control the drawing plane in the graphical user interface and provide information about area, number of people, and density of people on the floor. Non-egress components such as walls and permanent obstacles are simply included as gaps in a building model. These are implicit representations of such geometry, as they are not run through the simulator and occupants cannot move through them. Navigation geometry can be defined manually or extracted from 3D building plans (.dwg files or similar). For this thesis, a real building was selected for simulation (see **Subsection 3.1.2)**, but 3D drawings were unavailable. Thus, the building model was created manually. More information about the drawing process and model are described in **Subsection 3.1.3.**

Once a building model is complete, occupants can be added to the GUI. In Pathfinder, occupants are defined by two main characteristics: profile and behavior. Profile defines fixed characteristics such as avatar, color, speed, and size. In this section, visual appearances can be assigned, and occupants can be seen as cylinders, disks, or 3D models (see **Figure 4).** This is useful for results visualization, where it may be difficult to identify occupants of interest. Wheelchairs and hospital beds may also be defined here, and movement restrictions can be added. For example, during a health care facility evacuation, occupants in hospital beds require assistance to move. Restrictions allow the user to specify this unique quality, and the occupant is flagged for a required assisted evacuation. Wheelchairs and beds are added using the "Vehicle Shapes" function, where the number of assistants, location of assistants, and size of vehicle is defined. This dialog is shown in **Figure 5** for a default wheelchair user with one assistant. The user may also specify exit preference, door choice, and advanced speed properties (constant, uniform, normal, log-normal, or user-defined) under occupant profiles. After profiles are defined, behaviors can be added for individuals or groups to represent a sequence of actions they will go through during the simulation. Once an occupant has completed all assigned actions, they are removed from the interface. By default, Pathfinder assigns all occupants to the "Goto Any Exit" behavior [184]. This tells occupants to find the nearest exit from their starting position and is the simplest behavior possible.

Occupants can also be told to go to points of interest, rooms, refuge areas, or queues. Additionally, they can be told to wait, assist other occupants, or wait for assistance; and multiple actions can be assigned to create unique behaviors in the simulation. Each of the available actions in Pathfinder are provided in **Table 1.** More information about unique occupant parameters for this thesis are described in **Subsection 3.2.3.**



a) Cylinders b) Disks c) 3D Models

Figure 4: Pathfinder Occupant Appearance Options

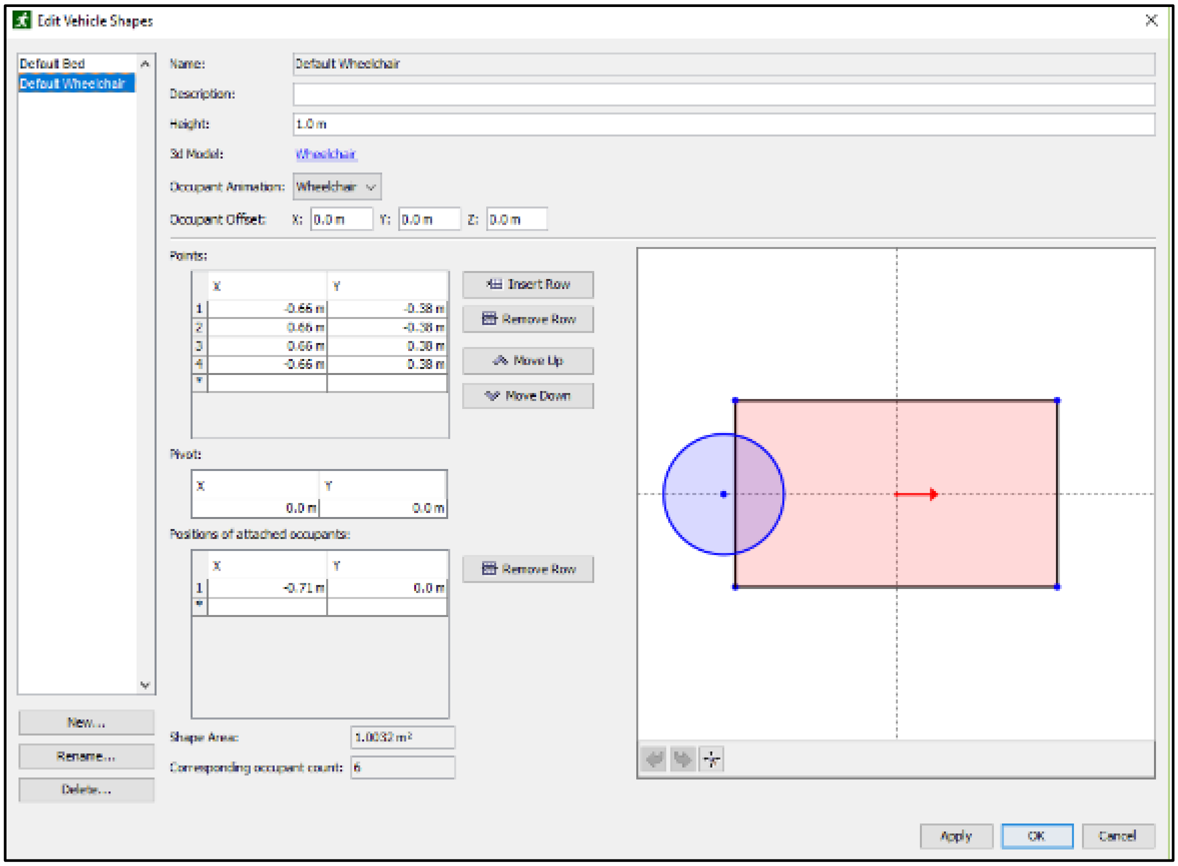


Figure 5: Pathfinder Vehicle Shape Dialog Box

Table 1: Behavioral Actions in Pathfinder [184]

Action	Description
Goto Waypoint	Specifies that an occupant should go toward a specific point on the navigation mesh.
Goto Rooms	Specifies that an occupant must select a room out of a set and go to it.
Goto Elevators	Tells an occupant to use evacuation elevators.
Goto Queue	Specifies that an occupant should join a designated queue.
Goto Occupant Targets	Tells an occupant to reserve an Occupant Target out of a set and travel to the target.
Abandon Occupant Targets	Tells an occupant to abandon Occupant Targets they have previously reserved.
Wait	Tells an occupant to wait in their current location for a specified amount of time.
Wait Until	Instructs an occupant to delay their movement until a specified simulation time passes.
Change Behavior	Instructs an occupant to change a behavior to a new behavior picked randomly from a behavior distribution.

Change Profile	Instructs an occupant to change to a different profile picked randomly from a behavior distribution.
Assist Occupants	Instructs the occupant to join an assisted evacuation team and begin assisting occupants who request assistance from that team.
Wait for Assistance	Indicates that the occupant should wait for assistance from other occupants.
Detach from Assistants	Detaches a client from their assistants, allowing the assistants to continue helping other clients.
Resume Prior Behavior	Instructs the occupant to continue using the behavior prior to the current behavior.
Remove Occupant	The occupant will be removed from the simulation.
Wait Until Simulation End	The occupant will wait in their current location until the end of the simulation.
Goto Refuge Rooms	Instructs the occupant to go to one of a set of rooms marked as *refuge areas.*
Goto Exits	Instructs an occupant to take the fastest route to a set of exits.

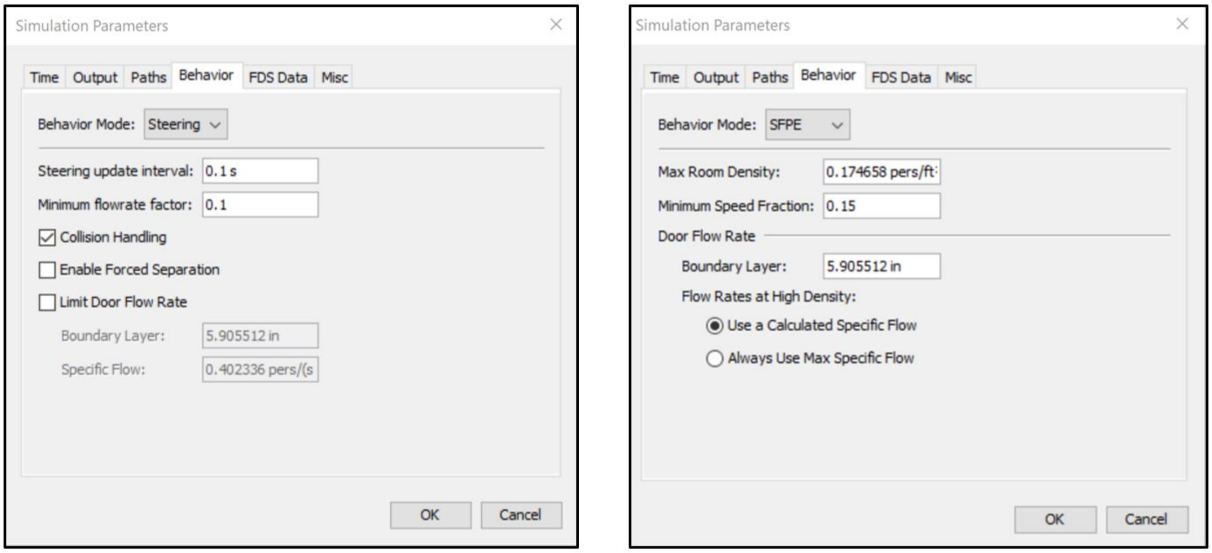
Profiles and behaviors help describe what a Pathfinder evacuee looks like and how they move through a simulation. However, for those with disabilities that require help, additional steps must be taken to assign assistants and exit routes. These are completed through the "Assisted Evacuation" dialog, which is particularly useful for hospital evacuations and scenarios where a disabled occupant cannot reach an exit on their own. In this section, those who require help are called *clients,* those who provide help are *assistants,* and a group of assistants is called a *team* [184]. Assistants can help clients in a variety of ways. First, they may provide assistance throughout the duration of an evacuation. This allows the client to visit multiple intermediate waypoints or rooms all while being assisted. Next, they may help a client for only part of an evacuation. This is useful for wheelchair users who can travel on their own, but require help to ascend or descend stairs along their route. Finally, assistants may provide help in stages. For example, some evacuation teams may provide help for part of a journey and then transfer assistance to another team at a certain waypoint. This is generally used for large structures such as high-rise buildings to prevent exhaustion. In order to assign the proper help for a client, occupants are first told to assist them through Pathfinder's behaviors. Then, an evacuation team is created from the defined assistants, and a client is assigned to a team (typically by distance from each other). Within behaviors, clients and assistants can then be assigned to exit routes and paths that allow for the safe evacuation of the disabled occupant.

A building model and user-defined occupants are the two main requirements in Pathfinder. If no errors in either parameter exist, simulations can be completed. There are two primary simulaiton modes in Pathfinder: SFPE and Steering. SFPE mode is based on the assumptions and equations presented in the *Engineering Guide to Human Behavior* (2019) [184]. It uses a simple set of parameters (maximum room density, floor rate, and speed fraction), and returns results similar to hand calculations produced using the SFPE Guide. In SFPE mode, the simulation mechanism is the door queue, which may be more useful for larger bodies of occupants and buildings. In Steering mode, the mechanisms of simulation control are collision avoidance and occupant interaction. This often produces results closer to experimental data and with faster evacuation times than given from SFPE mode. Steering mode supports the options provided in **Table 2,** and the dialog boxes from both modes are provided in **Figure 6.** In this thesis, Steering mode is used to create a more realistic evacuation.

Table 2: Pathfinder Steering Mode Parameters

Option	Description
Steering Update Interval	Specifies how often to update the simulation. This is also considered to be an occupant's cognitive response time. The higher the number, the faster the simulation, but the poorer the decision-making skills of the occupant.
Minimum Flowrate Factor	This is used when occupants are deciding which doors to use when there are queues. The factor is multiplied by the door's nominal flowrate to determine a minimum observed flowrate.
Collision Handling	Controls whether occupants avoid one another and can collide with each other

Enable Forced Separation	When enabled, this will cause occupants to attempt to maintain a set personal distance.
Limit Door Flow Rate	This imposes a maximum flow rate on doors. In steering mode, this is calculated from the boundary layer and specific flow (similar to SFPE) but does not allow flow rates to be based on room density.



a) Steering Mode b) SFPE Mode

Figure 6: Pathfinder Simulation Modes

3.1.2 Building Description

The literature review presented in **Chapter 2** brings to light a shortage of evacuation studies focused on low-rise[5] buildings, especially residential structures[6]. This is largely due to the assumption that people will have little trouble evacuating from smaller buildings [136]. However, congestion, exhaustion, bottlenecking, and many other difficulties can still arise during a low-rise

[5] The American Society of Civil Engineers (ASCE) *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* version 7-16 defines low-rise buildings as enclosed or partially enclosed structures that have a mean roof height of less than 59.1 ft (18 m) and mean roof height that does not exceed the least horizontal dimension [224].

[6] According to the US Code of Federal Regulations (CFR), a low-rise residential building is any building three stories or less in height above grade that includes sleeping accommodations where the occupants are primarily permanent in nature [225].

evacuation. Thus, it is necessary to explore all fire possibilities in order to reach maximum safety for building populations.

For this thesis, a complex of three-story apartment buildings on the campus of Clemson University (Clemson, South Carolina, USA) was chosen to represent the fire scenario. Opened in the fall of 1991, the apartment community features 10 similar buildings (shown in **Figure 7)** with a total of 474 occupant spaces (combined) and a separate commons building [185,186] The construction type is common to this area of United States and is comprised of light-frame wood with exterior steel-frame hallways, stairwells, and ramps. A brick façade completes the design for aesthetic purposes. Interior renovations were completed in phases from 2015-2020 but the exteriors remain original, as shown in **Figures 8** and **9** [187]**.** With rising enrollment, the university hopes to add an additional 151,000 square feet (approximately 14,000 square meters) and 430 spaces of similar design to the complex in the near future [186].

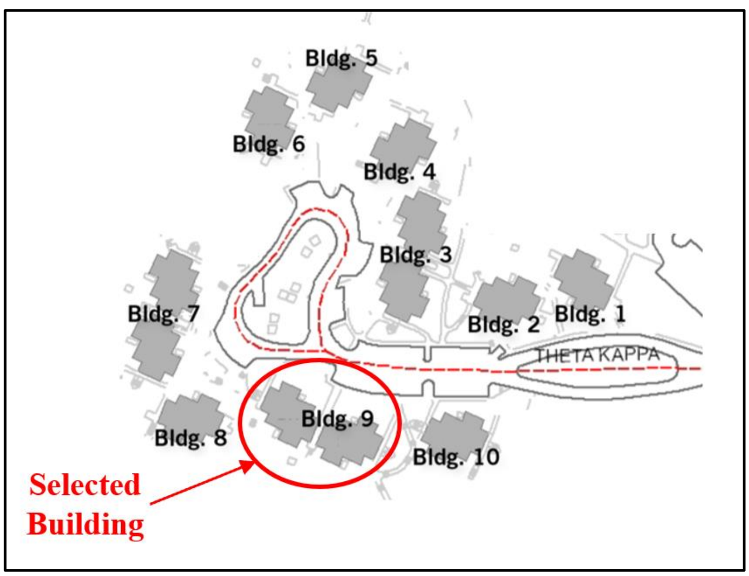


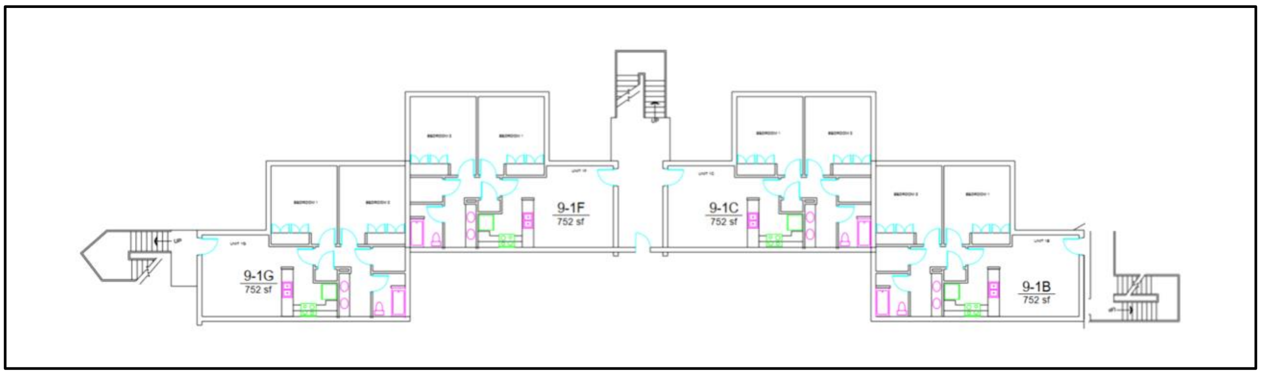
Figure 7: Community Layout [185]

Figure 8: Apartment Complex Exteriors [185]

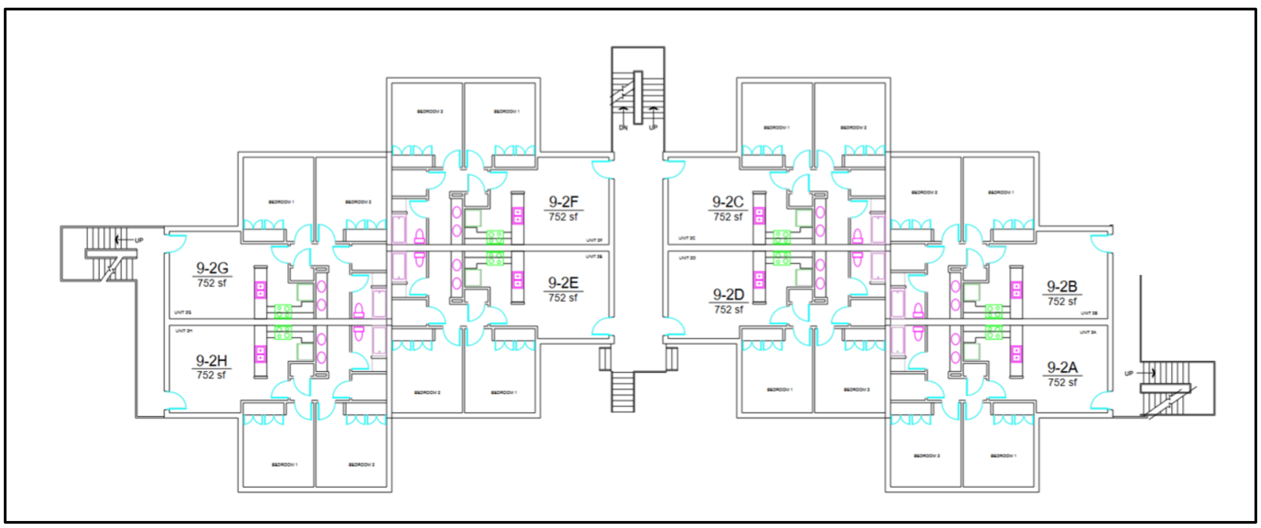
Figure 9: Apartment Complex Interiors [185]

Due to the similarity in design throughout the complex, a single building on the property was chosen for use in this thesis. As numbered by the university, this is building 9 (shown in **Figure**

7). Building 9 is one of the largest in the complex and houses a maximum of 80 students in 20 apartments. The building layout per floor is provided by the two-dimensional plans in **Figure 10.** As shown, there are four apartments on Floor 1 and 8 on each Floors 2 and 3. Each apartment is labelled first by the building number followed by the floor number and unit letter. For example, 9-3A is Apartment A on the third floor of building 9. Since this thesis only features the units in building 9, the 9 is omitted in this manuscript for simplicity. Apartments are fully furnished according to **Table 3** and feature four closets (one per bedroom and two in the common area), a living room, a kitchen, and one bathroom (see **Figure 11).** Structural dimensions of each room are provided in **Table 4.** Individual apartments are approximately 752 ft^2 (70 m^2) in living space for a total of 15,040 ft^2 (1397 m^2) in the building [185].



a) Floor 1



a) Floors 2 and 3

Figure 10: Building 9 Floor Plans [188]

Table 3: Apartment Furnishings

Room	Furniture
Bedroom (2)	Twin XL Bed (2), Desk (2), Chairs (2), Chest of Drawers (2)
Kitchen	Stove, Refrigerator, Microwave, Bar Chairs (2)
Living Room	Sofa, Loveseat, Coffee Table, Side Table, Mounted TV
Bathroom	Full Bath, Double Vanity

Figure 11: Apartment Floor Plan [185]

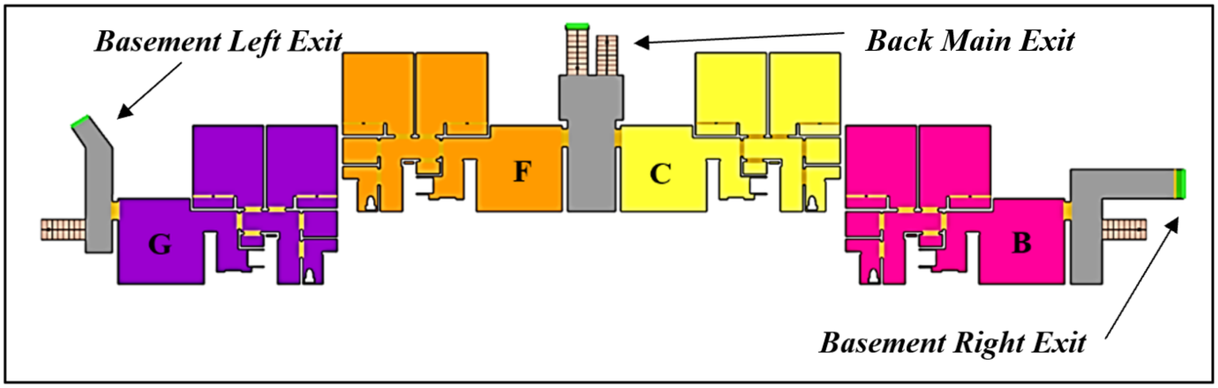
Table 4: Apartment Dimensions [185]

Room	Dimensions
Bedroom (2)	12 ft x12 ft (3.66 m x 3.66 m)
Kitchen	*Information not Available*
Living Room	12 ft x14 ft (3.66 m x 4.27 m)
Bathroom	*Information not Available*
Bedroom Window	36 in x70 in (91 cm x 178 cm)
Living Room Window	36 in x70 in (91 cm x 178 cm)
Closet (4)	24 in x78 in (61 cm x 198 cm)

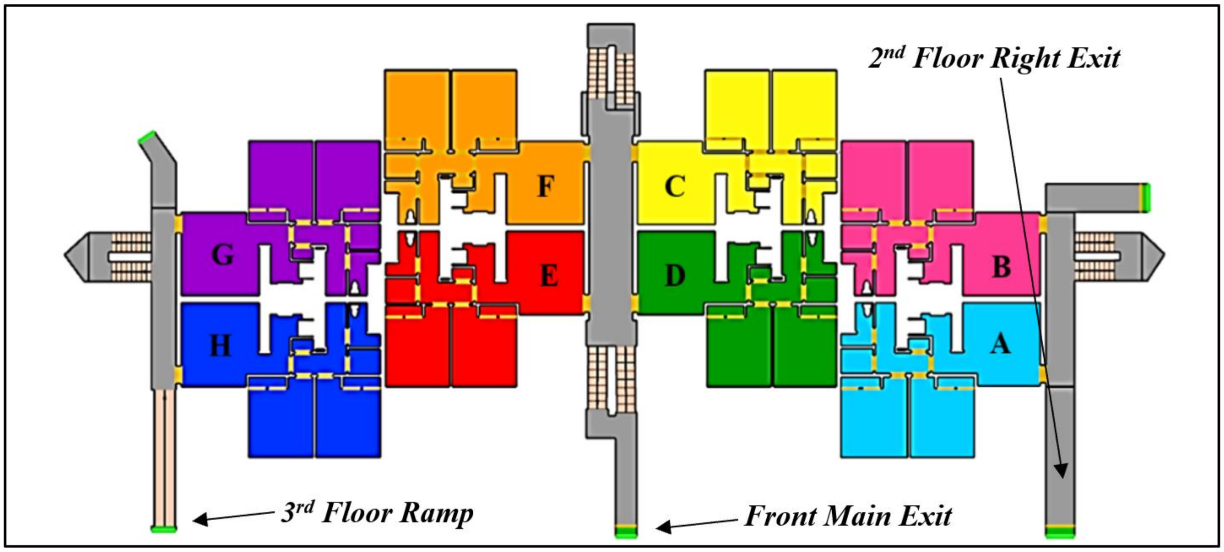
As mentioned, the ramps, hallways ("flat exits" of 0% incline), and stairwells are exterior to the building and are thus not included in the provided living space. These comprise the six exit routes of the building, each of which is uniquely associated with nearby apartments. For example, in the provided structural layouts of each floor (**Figure 10),** units G and H may only be accessed from the leftmost stairwell and third floor ramp (not shown). There is no internal route that allows access to the centermost or rightmost exits from these apartments. All apartments have two exit options which are described in greater detail in **Subsection 3.1.3.**

3.1.3 Pathfinder Building Model

Pathfinder requires a user-designed building model to run evacuation simulations. This can be completed directly in the GUI, but ideally, a three-dimensional building model is imported into the software from a drawing file (.dwg). Then, the user can then define a length unit, extract the imported geometry (floors and rooms), define doors and exits, and add occupants. Unfortunately, three-dimensional models are not always available, as was the case for the chosen apartment building. Thunderhead Engineering recognizes this issue and supports the importation of two-dimensional background images (.jpg or similar file extension), from which the user can sketch a model to scale. Floor plan and elevation views of the completed model are shown below (**Figures 12** and **13**). Because only two-dimensional plans were available for use in this research, the building height was unknown. An educated estimate of 10 ft (3 m) floors was used in this model. Apartments are color-coded and labelled by unit (A-H) for visual clarity. The author recognizes the limitations of labelling such items through color (readers with color-blindness may not be able to identify subtle differences). However, Pathfinder can only label features through color or material texture (concrete, brick, etc.). A color key is provided herein to combat this limitation.



a) First Floor

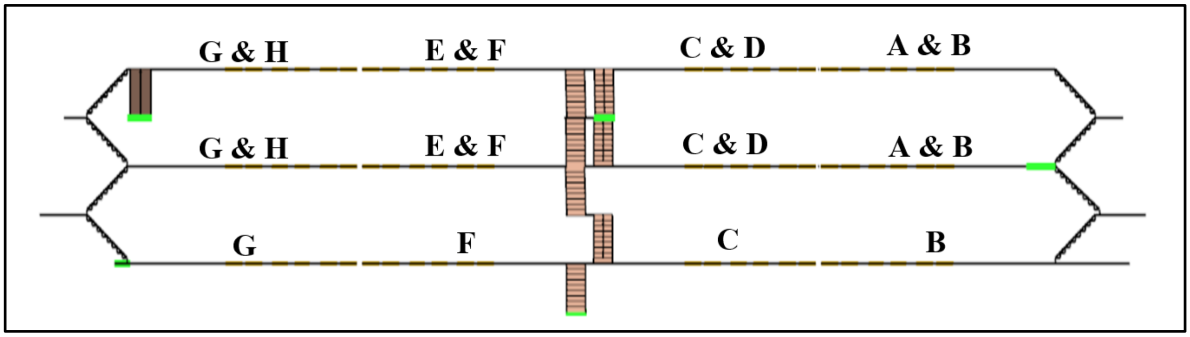


b) Second/Third Floors

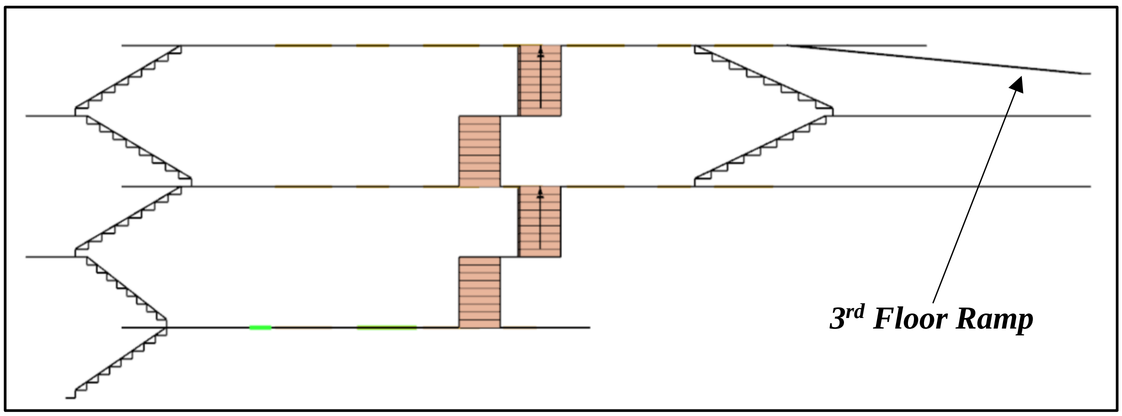
Key

Feature	Color
Apartment A	
Apartment B	
Apartment C	
Apartment D	
Apartment E	
Apartment F	
Apartment G	
Apartment H	
Hallways/Flat Exits (0% Incline)	
Stairwells and Ramps (Inclined)	
Doors	
Exits (representing safety)	

Figure 12: Pathfinder Building Model Floor Plans



a) Front



b) Left

Figure 13: Pathfinder Building Model Elevations

Six exits are defined in the building model and include stairs, ramps, and flat exits. When a building occupant navigates through one of the defined exits, it is classified as "safe" and disappears from view. The exits were defined according to their location in the building and are henceforth referred to by the labels shown in the Pathfinder building model floor plans. More information about each exit is given in **Table 5.** As previously mentioned, the unique layout of the building means that some exits are not accessible by distant apartments. While there are six in the building, occupants in each apartment only have the choice of two exits each. This has inherent positive and negative qualities. Students in apartments A, B, G, and H will experience less evacuation congestion than those in the centrally-located apartments (C-F). For example, only five apartments (20 occupants) will use the two leftmost exits (apartments G and H on all floors). Similarly, another 20 occupants will use the rightmost exits (from apartments A and B) on all floors. At maximum building capacity, this requires 10 apartments (40 people) to exit via the main exits at the front and back of the building.

Table 5: Exit Information

Exit	Main Structural Components	Accessible Apartments
Front Main	Stairwell	C, D, E, F (all floors)
Back Main	Stairwell	C, D, E F (all floors)
Basement Left	Stairwell, Flat Exit	G, H (all floors)
Basement Right	Stairwell, Flat Exit	A, B (all floors)
2nd Floor Right	Stairwell, Flat Exit	A, B (all floors)
3rd Floor Ramp	Ramp	G, H (all floors)

Included furnishings such as beds, sofas, and tables were determined to make a negligible difference in evacuation paths and exit times. Thus, they were not included in the building model or evacuation simulations. On the other hand, permanent fixtures such as refrigerators, bars, and vanities were extracted from the model in order to preserve the general structural layout of each apartment. This was of particular importance for the navigation of wheelchair users in each unit. Doors, stairwells, hallways, and ramps were not drawn to scale in the two-dimensional floor plans used to build the Pathfinder model, so standard or larger widths were used as provided below [77,189,190]. For doors, the interior width of 32 in (81.3 cm) meets the minimum wheelchair passage width as required by section 4.2.1 of the ADA [191]. The slope of the third-floor ramp is set at 1:12 (8.3%, 4.8°), and its length is 24 ft (7.31 m). This slope is the maximum allowable incline according to the ADA, and the length is less than the maximum of 30 ft (9.14 m) allowed before a rest platform is required [189]. Ramp and door accessibility requirements are provided in **Figure 14.** For hallways, the floor plan was used to estimate length and width (**see Table 6)**. Each flight of stairs is comprised of two "half flights" equally divided between floors (5 ft or 1.5 m in height) with a landing between each. All treads and risers are 7 in and 11 in (17.8 cm and 27.9 cm), respectively.

Table 6: Exit Geometry Widths

Feature	Width, in. (cm.)
Interior Door	32 (81.3)
Exterior Door	36 (91.4)
Stairwell	40 (102)
Ramp	44 (112)
Left Hallways	52 (132)
Right Hallways	61 (155)
Central Hallways	93 (236)

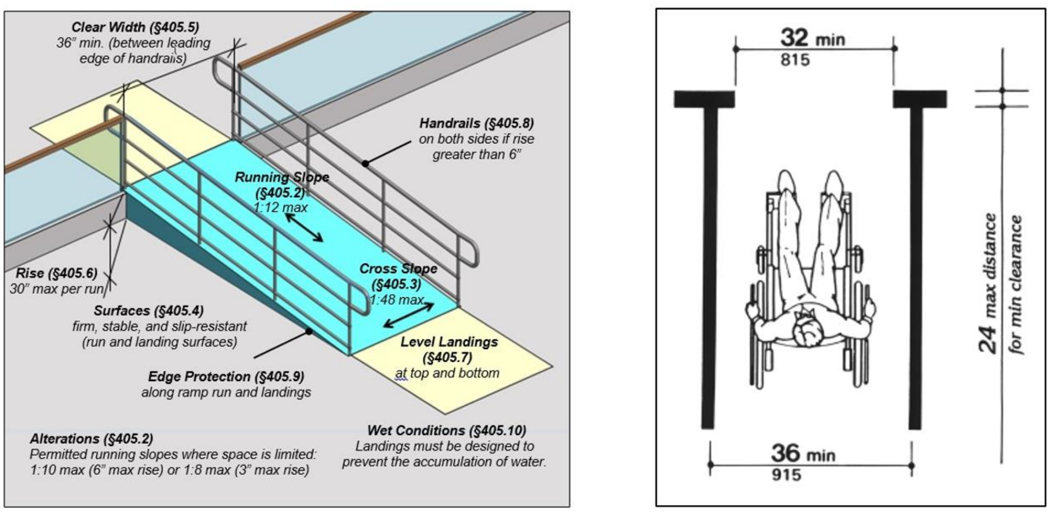


Figure 14: ADA Ramp and Door Accessibility Standards [192,193]

3.2 Study Parameters

Section 3.2 provides an in-depth description of the study criteria used in this thesis. First, an overview of the research topic and selected variables are provided. Then, the fire scenario, building occupants, and structural parameters are delineated. Finally, the main assumptions of this thesis are provided.

3.2.1 General

The evacuation framework and subsequent definition of disability presented in **Chapter 2** portray four broad categories of disability for evacuation research: physical impairments, sensory disorders, chronic health conditions, and mental or cognitive disabilities. While all disabilities are under-studied in this area, physical impairments are the most common and provide the basis for most legislation and evacuation procedures. Furthermore, physical disabilities are arguably the most straightforward (in terms of quantification) and are perceived to experience the most difficulty in traversing structural components such as stairs and ramps. This is confirmed with the wide variety of studies focused on people with functional limitations and their ability to perform evacuation tasks, while few are available for other disabilities[7]. They make evacuation decisions in the same way as the general public (unlike those with sensory disorders or cognitive disabilities), and existing published data on travel speeds allow for study comparison and confirmation. Additionally, wheelchair users and people confined to hospital beds are already included in Pathfinder. These reasons, combined with a focus on self-evacuation, led to the choice of wheelchair users (*functional independence)* as the disability of focus for this thesis[8].

The low-rise building selected for this thesis was also chosen due to its foundational qualities. With few structural parameters (floors and exit routes), many of the variables that effect evacuation (bottlenecking, queuing, exhaustion) are eliminated. This allows for greater focus on the building

[7] A recent list of evacuation studies focused on people with functional limitations is published in source [126]. Bukvic et. al.'s review also addresses the role of functional limitations on evacuation performance [127], and additional studies with quantifiable evacuation data are provided in **Chapter 2.**

[8] The author recognizes the need for all disabilities to be included in evacuation research. Thus, this thesis is only a preliminary study, furthermore called "Phase A". Future studies aim to progress this research by including additional structural components (elevators, sky bridges, stair chairs, etc.), building types, and the remaining three categories of disability. Physical impairments and low-rise buildings provide a starting point that can be validated with existing literature before increasing the study's complexity.

occupants with fewer discrepancies due to external variables. Furthermore, building 9 is the largest of the apartment complex. While all buildings in the complex are similar, it was necessary to choose a building that could give the most telling details of the evacuation. Larger buildings give larger evacuation times with more opportunities for disparities between populations (i.e. increasing time differences between disabled and non-disabled evacuees). Additionally, this building is seemingly the most accessible in the community. It contains unique ramps and flat exits, whereas the others only feature stairs. Therefore, it is the most likely building in the complex for wheelchair users to live in.

Apart from the building's implicit features, the apartment complex featured in this thesis is on the campus of a university. Unlike independent housing, university housing must be accessible for all prospective students, faculty, and staff—including people with disabilities. This right is protected under Titles II and III of the ADA as well as Section 504 of the *Rehabilitation Act of 1973*. According to many Department of Justice (DOJ) rulings on Titles II and III of the ADA, "no individual shall be discriminated against on the basis of disabilities in the full and equal enjoyment of the goods, services, facilities, privileges, advantages, or accommodations of any place of public accommodation" [53,193]. Similarly, Section 504 prohibits discrimination against PWD in programs that receive federal financial aid and from exclusion or unequal treatment in schools and the community [194]. These protections give credibility to inclusion of wheelchair users in the given building and highlight the prospective issues with stair evacuation for people with physical disabilities.

3.2.2 Fire Scenario

The evacuation completed for the building model and study parameters discussed in **Sections 3.1** and **3.2,** respectively, are based on a theoretical fire scenario. Statistics have shown that fires involving PWD occur most often in kitchens and cooking areas—comprising 38% of residential fires involving people with physical impairments [195]. Additionally, 65% of these fires are limited to the room of origin. This leaves individuals residing in the burning room with little time to evacuate (during the pre-movement phase), although others in the residential building are allotted additional time due to fire containment. For these reasons, a kitchen fire contained to a single apartment in the building represents the fire scenario in this thesis.

Fires contained to a single room of a building are often called *compartment fires.* Assuming a compartment fire has sufficient fuel and ventilation, it will progress through three stages: growth, flashover[9] and complete engulfment, and decay (see **Figure 15)**. In the growth phase, the fire remains small and localized with relatively low temperatures. Then, flashover results in a fully developed fire that involves all combustible items in the compartment, and flames fill the room. Once the combustibles (fuel) have been consumed, the fire begins to die, and the temperature falls below 80% of the maximum achieved during the second stage [196]. Anyone who has not escaped from the compartment before flashover is unlikely to survive, as high temperatures and volumes of toxic gases overwhelm the room.

[9] Flashover is a thermally-driven event that results in the complete engulfment of all combustibles in a compartment or enclosed space. It is characterized by a rapid increase in temperature with simultaneous ignition of nearby combustibles. Generally, flashover is said to occur when the upper compartment reaches a temperature of 1100 °F (593 °C) [226]

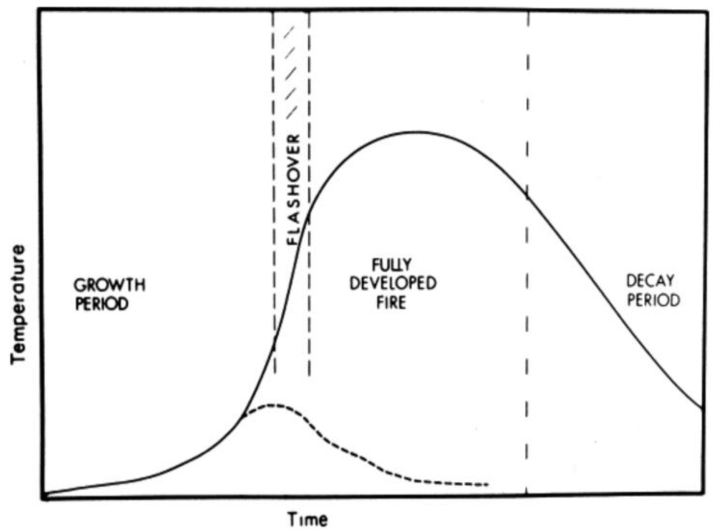


Figure 15: Phases of a Compartment Fire [196]

As stated in **Chapter 2,** evacuation is comprised of two distinct phases: pre-evacuation (also called pre-movement) and movement. In order to be considered "safe" from a fire, evacuees must complete both phases prior to total engulfment (flashover) and/or failure of a structure. While the goal of this thesis is to investigate the movement phase, it constitutes a significantly lower time frame than the pre-evacuation phase, and occupants must progress beyond the location of a compartment fire quickly to have a chance at survival. Thus, it is necessary to confirm that a wheelchair user's pre-movement time is less than the time it takes to reach flashover before this thesis can progress to the movement phase. **Figure 16** shows typical pre-movement phase times for various building occupancies. For residential buildings, the expanded database (leftmost residential column) time range is approximately 30 seconds to 10 minutes. The average of the database (4.94 minutes) is used as an estimate of the *pre*-movement phase of all building occupants in this thesis.

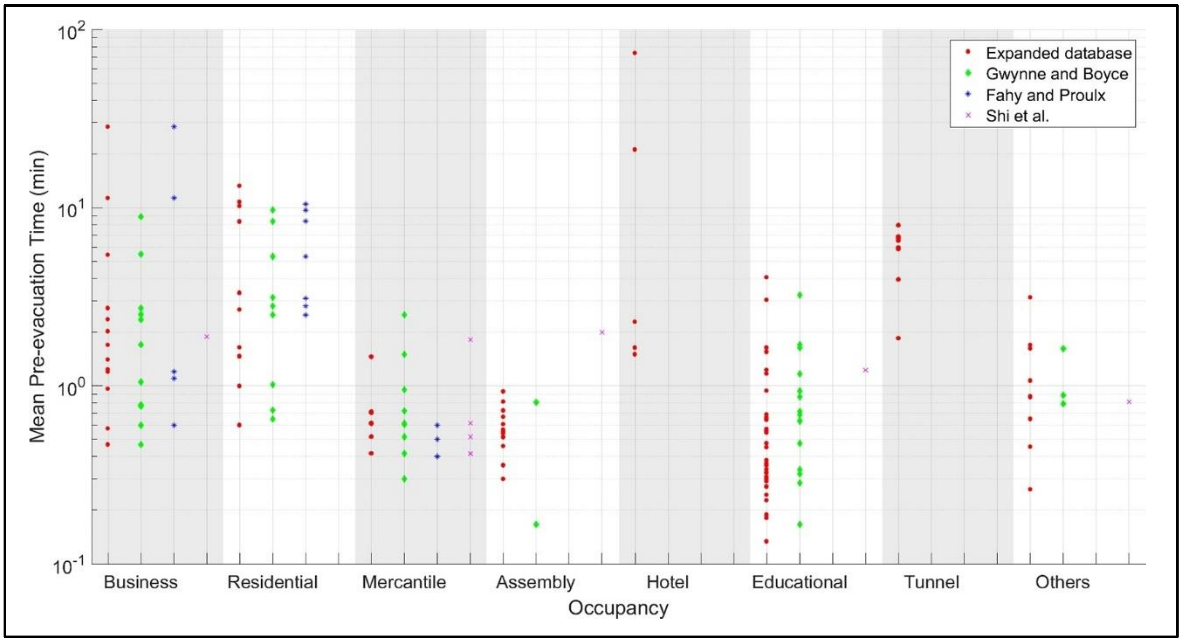


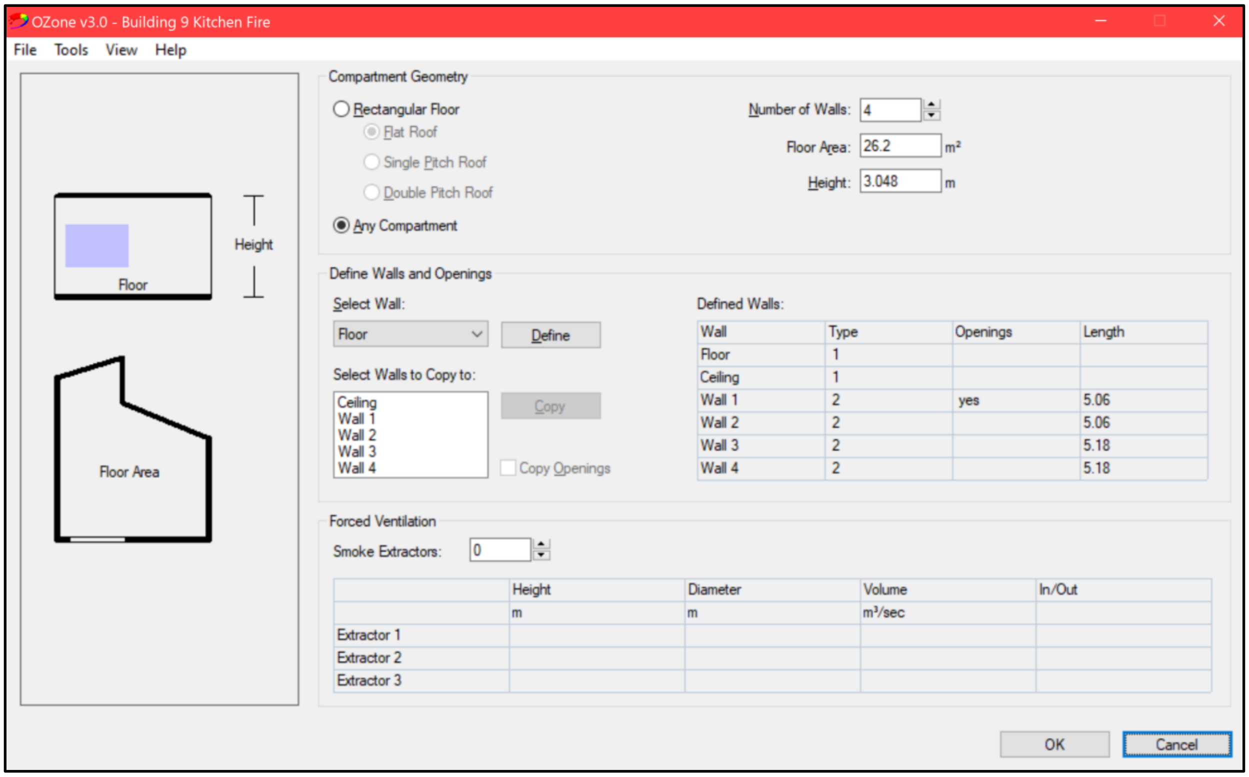
Figure 16: Pre-Movement Times of Various Building Occupancies [197]

To estimate the kitchen fire's progression, the fire modelling software OZone (version 3.0.4) was used. This software supports only standard compartment fires in rooms of known dimensions and materials. For building 9, the open concept kitchen and living area were modelled as a single compartment of 282 ft^2 (26.2 m^2). Note that while the actual building compartment contains more than four walls, OZone is not capable of modelling more, so the room was assumed to be a rectangle of the same square footage. Materials (studs, flooring, and finishings) and dimensions were estimated as shown in **Table 7.** Windows (openings) are assumed to be broken in order to model unlimited compartment ventilation. The room parameters were input into OZone as shown in the dialog boxes of **Figure 17.**

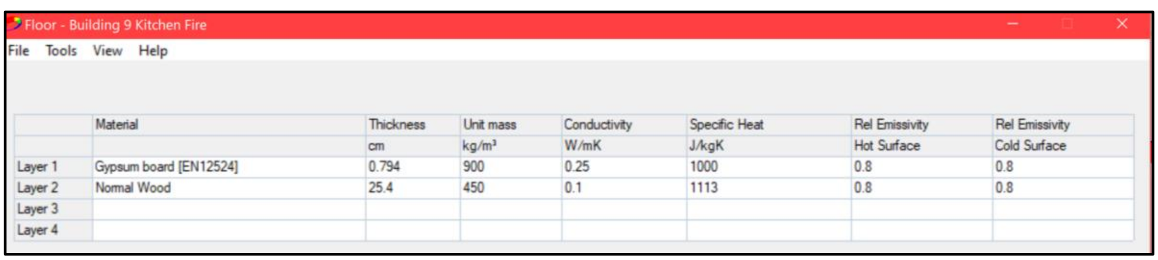
Table 7: Compartment Materials and Dimensions

Location	Materials	Dimensions, in (cm)
Floor	Beams/Diaphragm: Normal Wood	2x10 (5.08x25.4)
	Finish/Overlay: Gypsum Board	5/16" thick (0.794)
Ceiling	Beams/Diaphragm: Normal Wood	2x10 (5.08x25.4)
	Finish/Overlay: Gypsum Board	5/16 thick (0.794)

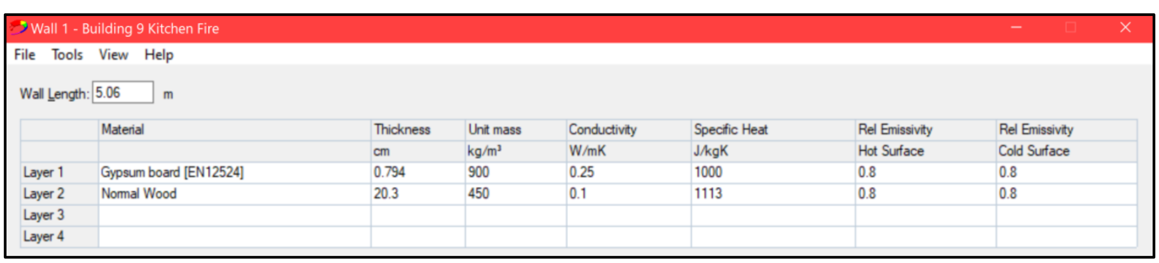
Walls	<u>Studs:</u> Normal Wood <u>Sheathing:</u> Gypsum Board	2x8 (5.08x20.3) 5/16 thick (0.794)



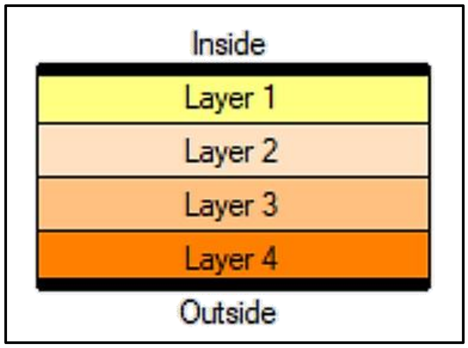
a) Compartment Dialog Box



b) Material Type I (Floor and Ceiling)



c) Material Type II (Walls)



d) Material Layer Definition

Figure 17: OZone Compartment Dialogs

Fires in OZone are typically modelled using the Eurocode EN 1991-1-2 standard fire. The user may also define a fire according to its time-temperature curve if available. For this thesis, the standard fire was used. As shown in the compartment fire dialog box in **Figure 18,** the defined fire for this scenario includes an automatic water extinguishing system with fire detection by heat as well as an automatic alarm to the fire brigade. These are typical features of the Clemson University housing facilities [198]. The fire growth rate was determined according to the building's occupancy type (dwelling) with a maximum fire area equal to that of the compartment area.

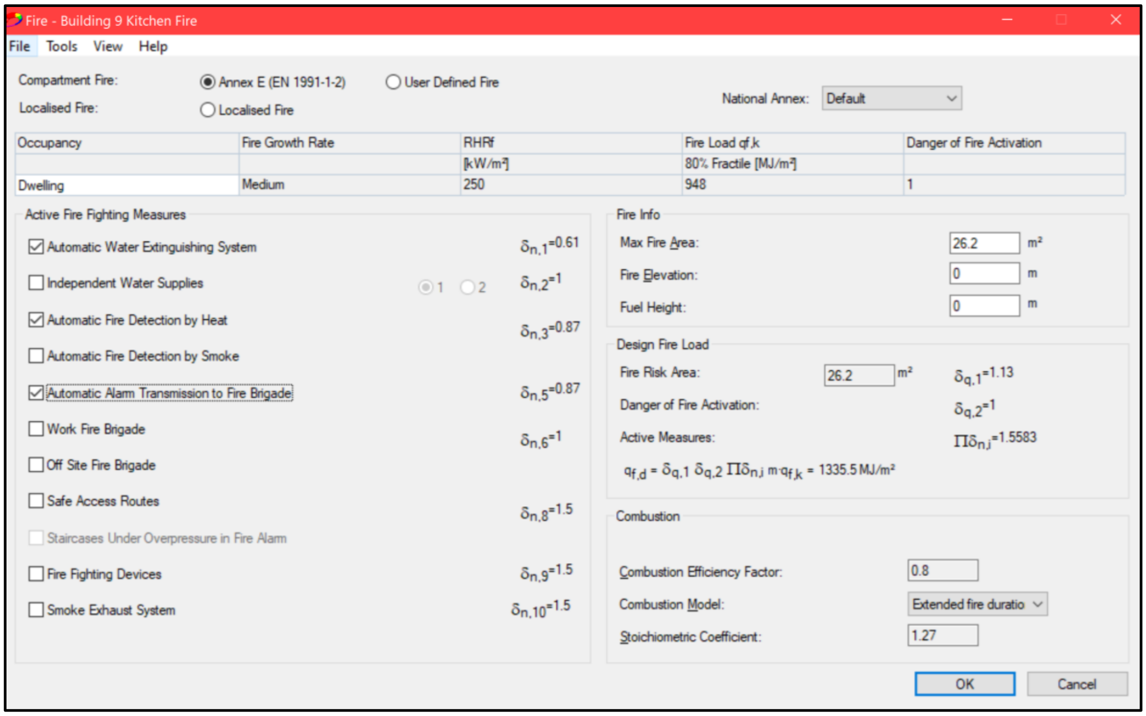


Figure 18: OZone Fire Dialog

Once the compartment and fire are defined in OZone, its time-temperature curve (similar to that of **Figure 15)** can be computed. This is shown in **Figure 19.** Flashover is the critical point in a fire for safe evacuation (pre-evacuation here) and occurs between 500°C and 600 °C. For the given fire and compartment, this temperature occurs at 9 minutes (using 600 °C). With an estimated pre-evacuation time of 4.94 minutes, occupants have a 5-minute leeway prior to engulfment, and should reach the exterior of the building safely. This is confirmed in combination with movement phase evacuation times in **Chapter 4.**

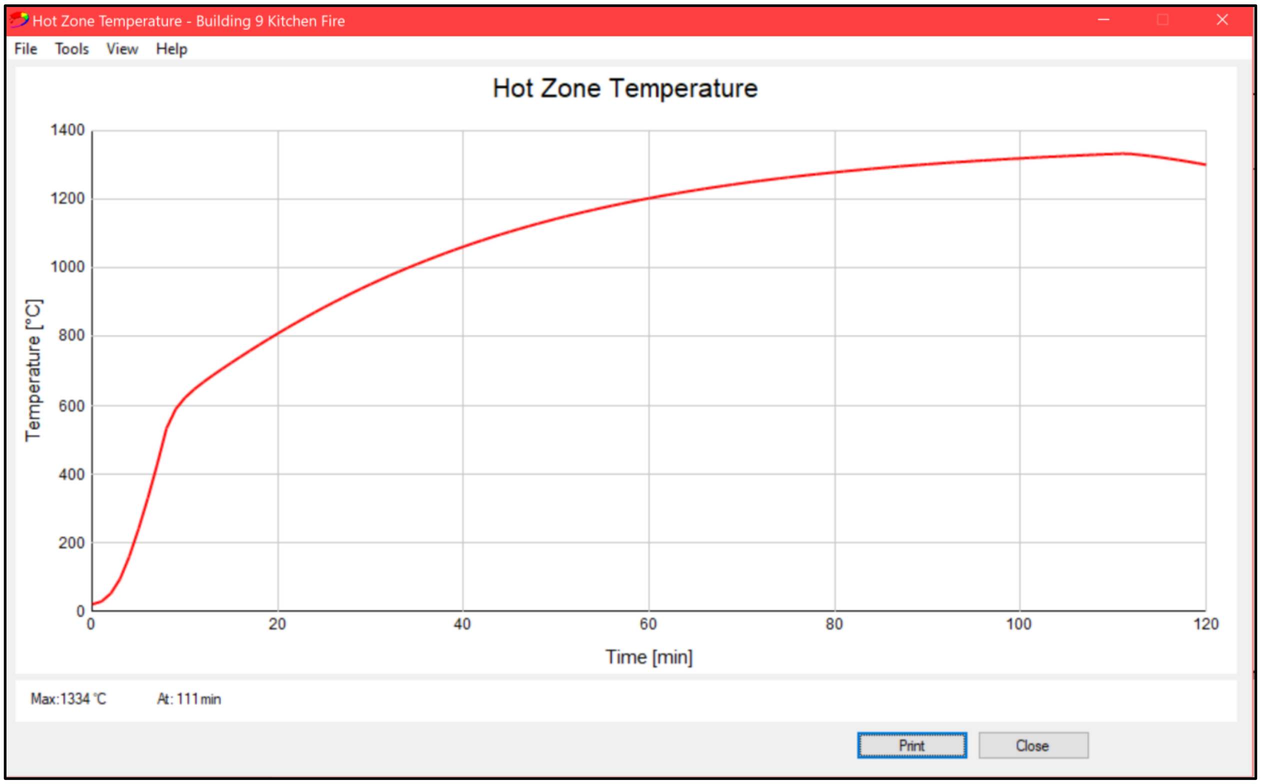


Figure 19: OZone Compartment Fire Time-Temperature Curve

3.2.3 Building Occupants

Occupants considered in this research are either non-disabled evacuees or wheelchair users. Individual parameters are first defined for each occupant via their profile. Since this thesis is not concerned with evacuation time of non-disabled occupants but rather their ability to help wheelchair users, they were given the default speed and shape parameters in Pathfinder and labelled "Default". According to the Pathfinder User Manual, the default shape (diameter/shoulder width) is based on the average body measurements provided in *Bodyspace: Anthropometry, Ergonomics, and the Design of Work*, by Stephen Pheasant and Cristine Haslegrave [184,199]. This shoulder width also results in movement that matches the SFPE fundamental diagrams, as shown in the Pathfinder Validation and Verification Manual [200]. The characteristics of the Default occupants are provided in **Table 8.** Non-disabled occupants may use any exit and begin the simulation at any orientation. If congestion is not an issue, they will maintain a personal distance of 0.262 ft (0.080 m), but this will reduce at high volumes and through narrow exits.

Table 8: Non-Disabled Occupant Profile

Item	Value
Speed	3.90 ft/s (1.19 m/s) *Constant*
Diameter	17.9 in (45.5 cm)
Height	6.00 ft (4.88 m)
Orientation	[0°-360°] *No Restriction*
Door or Exit Restrictions	*None*
Acceleration Time	1.1 s
Collision Response Time	1.5s
Maintained Personal Distance	0.262 ft (0.080 m)

The disabled occupant profile is similar to the non-disabled profile and labelled "Wheelchair (WC) User". Disabled evacuees are given the same door restrictions, acceleration and collision response times, and personal distance parameters as non-disabled evacuees. However, their speed and shape are different. First, the vehicle shape is based on a general rectangular wheelchair of area 10.8 ft^2 (1.00 m^2). Each wheelchair user is assigned two non-disabled people as assistants who "attach" to the sides of the wheelchair as shown in **Figure 20.** Assistants may attach and detach based on defined behaviors of the wheelchair user (requiring assistance on stairs vs. no assistance required on flat surfaces). Assuming a sense of urgency among wheelchair users during evacuation, the speed of the disabled occupants was determined using the results of a 2013 study of 20-minute exercise parameters among manual wheelchair users (see Source [201]). The objective of this study was to determine normative values of propulsion (velocity or speed) and distance travelled of tetraplegic and paraplegic spinal cord injury patients in the given time frame. Using the 50^{th} percentile results, a weighted average speed of 3.89 ft/s (1.19 m/s) was calculated for the given combination of male and female tetra- and paraplegic wheelchair users[10]. Additional data from this study is provided in the Appendix.

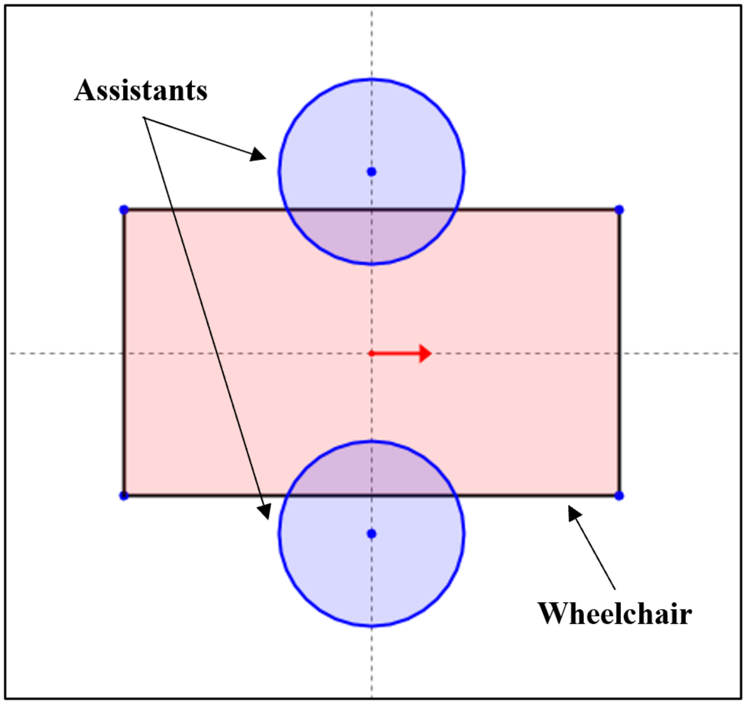


Figure 20: Defined Wheelchair Shape with Non-disabled Assistants

Once profiles were defined for the non-disabled and disabled building occupants, behaviors were assessed and input into Pathfinder. Behaviors of all evacuees were first based on the needs of WC users (clients) and their prospective locations within the building. Exit options were traced to each apartment in the building, and an egress route was mapped. If the exit route to an apartment involved egress components that wheelchair users cannot traverse independently, further

[10] The difference between disabled and non-disabled building occupants in this thesis is minute. The author recognizes that wheelchair users *leisurely* move at a much slower pace than that of non-disabled people (see Source [227] for published manual wheelchair speed data). However, this study is focused first on a group of wheelchair users in an emergency scenario. As stated by McConnell and Boyce [155], disabled occupants are uncomfortable with waiting for help (for fear of being isolated or forgotten) in a fire. Thus, the author implies a sense of urgency through the use of exercise speeds among the wheelchair users in this thesis. Next, this thesis features non-disabled college students, who may assume a fire in their apartment building is only a drill or non-serious situation. Non-disabled occupant speed is thus perceived to be a lower than a jog or urgent pace.

conditions were added to the path. For example, any WC user located in apartments 3C-3F was determined to use the Front Main exit. Since this requires the use of stairs, WC users in those apartments must be assigned assitants. The most likely assistants for disabled occupants in a university apartment building are friends located in the same apartment. Thus, two non-disabled assistants were defined for each apartment group. Then, portions of the exit path were analyzed for the requirement of assistance. For apartments 3C-3F, assistance is only needed for a small set of stairs. Thus, wheelchair users and assistants were assigned to wait in the hallway outside of the apartments, "attach" to one another and traverse the stairs, and then "detach" to complete the evacuation. This set of rules provides the quickest and most efficient travel scenario for all building occupants. The process is described visually for occupants in apartment 3E in **Figure 21**. The fourth apartment occupant's only rule is to leave the building via the assigned exit.

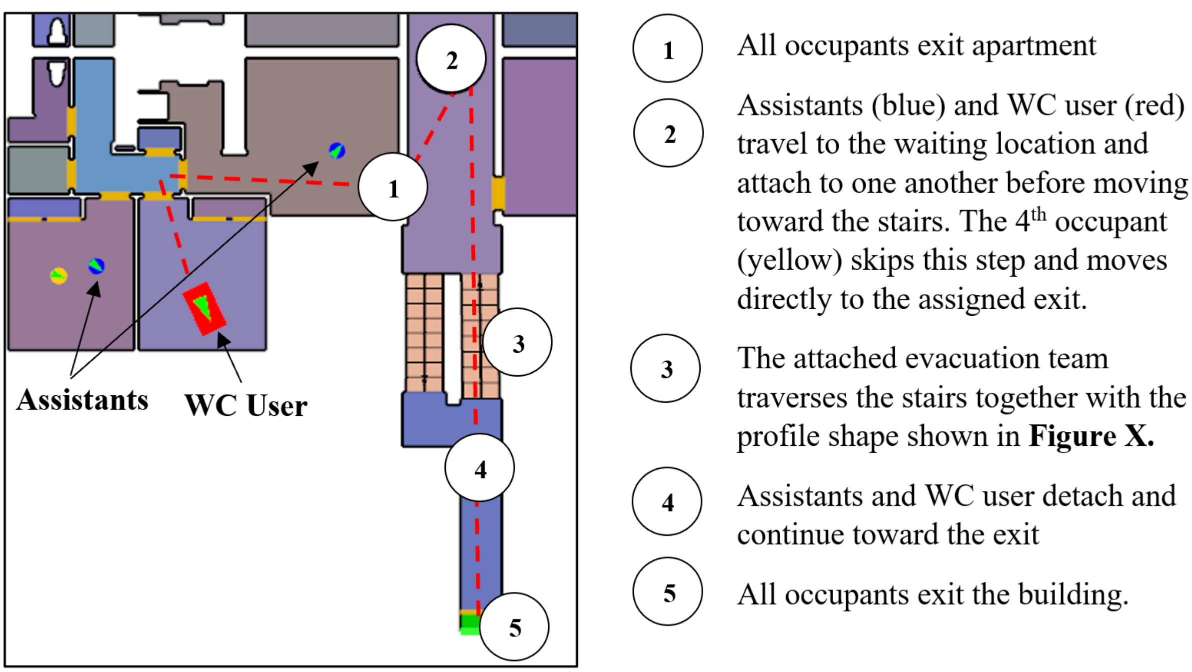


Figure 21: Sample Exit Path (Behavior Assignment), Apt. 3E

Since assistants are assigned from the same apartment as the wheelchair user, there is a maximum of one WC user per apartment (with four occupants per apartment, there are not enough assistants to help more than one WC user). Overall, there is a maximum potential of 20 WC users with 40 assistants and 20 additional non-disabled occupants (80 total). It is impractical to simulate 20 wheelchair users in the given apartment building, as there are a relatively small number of wheelchair user worldwide. In fact, wheelchair users comprise approximately 1.7 million people in the US [202]—just 0.5% of the population. Therefore one wheelchair user in building 9 represents over twice the percentage of wheelchair users in the United States (1.25% of the building population). However, it is recognized that more than one wheelchair user is likely to reside in the same place, especially given the small amount of accessible housing on a university campus. Thus, this thesis explores the evacuation of building populations with each one, two, and three wheelchair users (1.25%, 2.5%, and 3.75% of the building population). In each group of simulations, wheelchair users are located randomly in different apartments and have access to their own group of two assistants. Their egress routes may overlap, and they may use the same exits; but assistants cannot be assigned to more than one wheelchair user, and wheelchair users cannot be located in the same apartment as another wheelchair user.

3.2.4 Assumptions

Several assumptions about structural parameters, building occupants, and fire dynamics are admittedly and expectedly incorporated in this thesis. While determined not to significantly affect the research outcome, it is necessary to disclose the parameters for readers and researchers in the field. Future studies will also address many of the assumptions described below.

First, fire dynamics (heat and smoke) are assumed not to affect occupant evacuation. Based on the compartment fire scenario (see **Subsection 3.2.2)** a prospective apartment fire builds slowly and is contained within the apartment of origin. Since evacuation components are located on the exterior of the building, the imminent danger to evacuees is assumed to decrease drastically once they leave the building's interior. Given a maximum presumed pre-evacuation time of 4.94 minutes and a flashover time of 9 minutes, occupants are unlikely to be exposed to the fire long enough to warrant the inclusion of smoke inhalation or heat [203]. The fire is also assumed to occur away from apartment entrances and therefore does not block exit routes.

Next, building occupants are also based on a few minor assumptions. As shown in **Subsection 3.2.3,** the non-disabled occupants are given default dimensions and parameters for this thesis. Additionally, the wheelchair dimensions for each disabled occupant are the same for all users and simulations with a default area of 10.8 ft^2 (1.00 m^2). Default dimensions allow for a focus on variations in evacuation time without additional parameters that may affect movement through apartments or across exit routes. Default parameters also assume that non-disabled occupants experience no intrinsic limiting factors during their evacuation, while those of the wheelchair users are only based on their ability to traverse egress components. Additionally, we expect each wheelchair user to have two willing and able assistants so that we may investigate only evacuation times without including additional waiting time for helpers who may never arrive. The number of people in the building is also based on the premise of full occupancy (80 people). While this is unlikely to occur often, the safe evacuation of all building occupants is paramount. This is considered a high-risk scenario that takes into account the variability in the building population from day-to-day.

The final assumptions in this thesis are based on structural parameters and t ravel obstacles. First, structural failure is not considered during the evacuation time of the building occupants. For low-rise light-frame wood assemblies with gypsum wallboard finish, fire resistance ratings range from 30 to 120 minutes [204]. Given a small pre-evacuation time (less than 5 minutes), it is unlikely that structural failure will occur within the evacuation time frame (this is confirmed from the simulation results of this thesis in **Chapter 4**). Additionally, furniture and non-permanent obstacles were not considered. Trial runs including furniture in a single apartment of the Pathfinder building model were compared to those without furniture and determined to make a negligible difference in evacuation performance.

4. EXPERIMENTAL FINDINGS

In this thesis, groups of 1, 2, and 3 wheelchair users in building 9 are simulated and analyzed to evaluate their egress time in the selected building. WC users were placed randomly[11] within the building, but in separate apartments, and assistants to each WC user were assigned based on the nearest non-disabled occupants within the same apartment unit. Comparisons were drawn between a benchmark case of 0 wheelchair users, as well as between each of the wheelchair user groups. Additionally, evacuation times were computed for both the wheelchair users and the total building population by adding the pre-determined pre-evacuation time of 4.94 minutes. Based on these results, a structural ranking system of egress components is proposed by ease of wheelchair navigation (lower egress times).

4.1 Benchmark (Zero Wheelchair Users)

To determine the effect of wheelchair users on individual apartment and total building egress time, a benchmark case of only non-disabled occupants was simulated. This homogenous population is identical to each of the wheelchair cases (80 total occupants, 4 per apartment) and use the same exit routes (see **Table 9** below) as that of the wheelchair users just without any disabled occupants. Exit routes were determined as the most optimal based on accessible exits from each apartment as given in **Table 5.** The total building evacuation took 42.8 seconds (from simulation start to last to exit) and resulted in a total pre-evacuation plus movement time of 5.65 minutes (5 minutes and 39 seconds). This is about 62.7% of the time it takes for flashover to occur (9 minutes) and only 18.8%

[11] Wheelchair users can be randomly input into Pathfinder by assigning percent distributions of occupant profiles. For example, for two wheelchair users, 2.5% of the population was assigned to the WC user profile, while the remaining percentage remained Default. If wheelchair users for the two and three WC user scenarios appeared in the same apartment, they were randomized until they appeared in separate apartments. Scenarios were not repeated, as they result in the same egress times (results do not have stochastic outputs). For the one WC user cases, a single user was assigned to each of the 20 apartment units, resulting in 20 scenarios.

of the time allotment before structural failure (if the light frame wood assemblies are given the lowest fire resistance rating of 30 minutes).

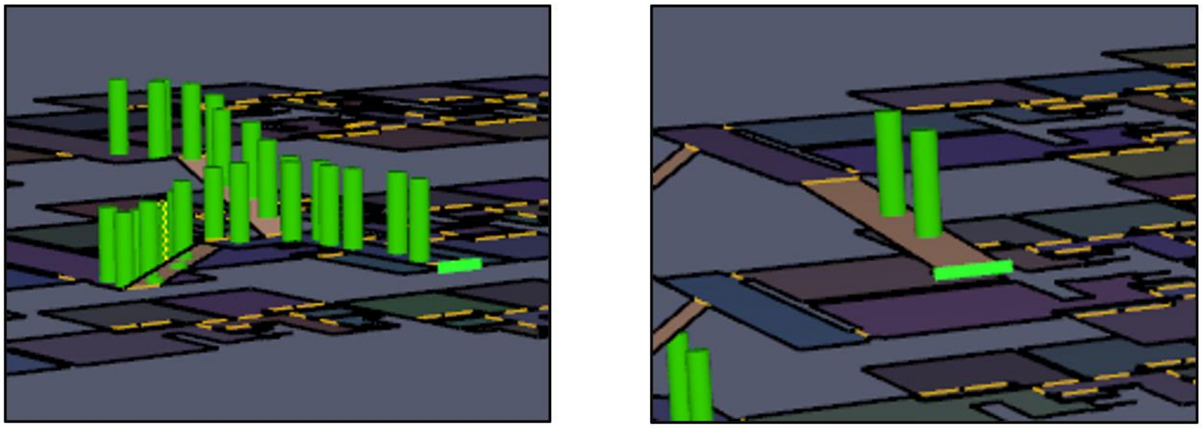
Table 9: Exit Assignments by Apartment

Apartment	Exit Assignment
1B	Basement Right
1C	Basement Main
1F	Basement Main
1G	Basement Left
2A	2nd Floor Right
2B	2nd Floor Right
2C	2nd Floor Main
2D	2nd Floor Main
2E	2nd Floor Main
2F	2nd Floor Main
2G	Basement Left
2H	Basement Left
3A	2nd Floor Right
3B	2nd Floor Right
3C	2nd Floor Main
3D	2nd Floor Main
3E	2nd Floor Main
3F	2nd Floor Main
3G	3rd Floor Ramp
3H	3rd Floor Ramp

Benchmark egress times for each apartment were determined using the last person to exit each unit. This allows for direct comparison between wheelchair users in each apartment in later simulations. Results are provided in **Table 10.** From the table, the minimum egress time was 15.6 seconds (Apartment 3H) while the maximum is the same as the total building egress time (42.8 seconds, Apartment 2C). The average exit time for the last non-disabled occupant in each apartment is 29.2 seconds. Time differences are likely due to the occupant's proximity to their assigned exit as well as exit congestion. For example, the occupant with the maximum exit time originates in Apartment 2C. The assigned exit is 2nd Floor Main (see **Figure 12)**—the most common exit. During the simulation, congestion occurs near the convergence of the stairs, resulting in slower movement. This does not occur during the egress of the occupant with the minimum time, as the exit (3rd floor ramp) is only assigned to 8 occupants. See **Figure 22** for comparisons in congestion near each of the mentioned exits at the 20 second mark in the simulation.

Table 10: Benchmark Exit Times by Apartment

Apartment	Egress Time, s	Total Evacuation Time, s (Pre-Movement plus Egress Time)
1B	16.1	312.5
1C	21.5	317.9
1F	19.8	316.2
1G	17.5	313.9
2A	17.8	314.2
2B	24.9	321.3
2C	42.8	339.0
2D	33.3	329.7
2E	36.7	333.1
2F	41.7	338.1
2G	26.6	323.0
2H	30.1	326.5
3A	40.1	336.5
3B	38.4	334.8
3C	40.9	337.3
3D	25.2	321.6
3E	34.1	330.5
3F	37.5	333.9
3G	23.8	320.2
3H	15.6	312.0



a) 2nd Floor Main Exit (Max. Egress Time) b) 3rd Floor Ramp (Min. Egress Time)

Figure 22: Benchmark Minimum and Maximum Egress Time Exit Congestion

4.2 Wheelchair Users

Once a benchmark was established, wheelchair users were added to the Pathfinder building model. First, individual simulations are run for a single wheelchair user in each of the 20 apartment units. Results for these simulations are provided in **Subsection 4.2.1.** Then, a second wheelchair user is added randomly to the building model, resulting in an additional 58 simulations, as shown in **Subsection 4.2.2.** Finally, three wheelchair users are added to the building population, and 96 more simulations were run (**Subsection 4.2.3).** Results for each group of simulations (1, 2, and 3 wheelchair users) are compared in **Subsection 4.2.4.**

4.2.1 One Wheelchair User

Egress times for each of the WC users in the 20 "single WC user" simulations are provided in **Table 11.** On average, egress times increased by 22.0 seconds (75.3% increase) when compared to the benchmark exit times per apartment, resulting in an overall average egress time of 51.2 seconds. When added to the pre-evacuation time of 4.94 minutes, the average total evacuation time of wheelchair users is 347.6 seconds (5 minutes and 48 seconds). This is 64.4% of the allotted time before flashover and just 19.3% of the time before possible structural failure. There were only two simulations that resulted in faster exit times for the wheelchair users than the benchmark: Apartments 2A and 3G. In each of these cases, the wheelchair users do not need help evacuating the building, as they use the 2nd floor right exit and the 3rd floor ramp. With very similar movement speeds, wheelchair users in these apartments are nearly identical to that of the non-disabled building occupants. Thus, it is likely that faster evacuations are simply due to closer exit proximity since the benchmark exit times are based on the last person to exit the apartment of interest (worst case scenario).

Table 11: Results for One Wheelchair User

Apartment	**WC User Egress Time, s**	**Deviation from Benchmark Egress Time, s (from** Table 10**)**	**Total Evacuation Time, s (Pre-Movement plus Egress Time)**
1B	21.4	+ 5.3	317.8
1C	31.6	+ 10.1	328.0
1F	44.7	+ 24.9	341.1
1G	26.9	+ 9.4	323.3
2A	13.1	- 4.7	309.5
2B	31.6	+ 6.7	328.0
2C	65.0	+ 22.2	361.4
2D	71.0	+ 37.7	367.4
2E	69.3	+ 32.6	365.7
2F	71.3	+ 29.6	367.7
2G	66.2	+ 39.6	362.6
2H	66.2	+ 36.1	362.6
3A	72.1	+ 32.0	368.5
3B	83.4	+ 45.0	379.8
3C	68.5	+ 27.6	364.9
3D	59.2	+ 33.7	355.6
3E	62.4	+ 28.3	358.8
3F	61.5	+ 24.0	357.9
3G	22.0	- 1.8	318.4
3H	16.8	+ 1.2	313.2

The 20 single wheelchair user simulations resulted in large variations in egress times as well. For example, the three shortest egress times were 13.1, 16.8, and 21.4 s (Apartments 2A, 3G, and 1B, respectively) while the three longest egress times were 71.3, 72.1, and 83.4 s (Apartments 2F, 3A, and 3B, respectively). Since each wheelchair user is identical, it is reasonable to assume that egress times rely heavily on the assigned egress route rather than individual capabilities. For each of the shortest egress times, no assistance was required to safely evacuate the building. On the other hand, those with the longest egress times must traverse stairs. Thus, they must first exit their apartment and wait for assistance before traveling toward the exit. Based on this information, Apartments 2A, 3G, and 1B are identified as possible optimal living quarters for wheelchair users, while 2F, 3A, and 3B are flagged as "at risk" for unsafe egress conditions.

The evacuation of the entire building population was also explored for the single wheelchair user scenarios. The total time for all occupants to exit the building is given in **Table 12** for each of the 20 simulations. In 7 scenarios, the total population egress time remained the same as that for the benchmark case (42.8 s). This indicates that the wheelchair user did not affect the evacuation of other building occupants, and they were not the last to exit the building. Likely, this is due to low congestion on the assigned exit routes and similar speeds of disabled and non-disabled evacuees. In 6 of these cases, the wheelchair user evacuated independently and did not require assistance. Only the evacuation from Apartment 1C required help (to traverse the back main stairwell). In the remaining 13 simulations, the egress time increased significantly. The wheelchair user and their assistants were the last people to exit the building in each of these cases, and all wheelchair users required help to evacuate safely.

Table 12: Building Population Egress Times (One WC User)

Apartment	Total Population Egress Time, s	Total Building Evacuation Time, s (Pre-Movement plus Egress Time)
1B	42.8	339.2
1C	42.8	339.2
1F	48.3	344.7

1G	42.8	339.2
2A	42.8	339.2
2B	42.8	339.2
2C	66.5	362.9
2D	72.5	368.9
2E	70.8	367.2
2F	74.3	370.7
2G	67.5	363.9
2H	67.5	363.9
3A	73.5	369.9
3B	85.0	381.4
3C	71.3	367.7
3D	65.3	361.7
3E	65.3	361.7
3F	64.5	360.9
3G	42.8	339.2
3H	42.8	339.2
AVERAGE	59.6	356.0

4.2.2 Two Wheelchair Users

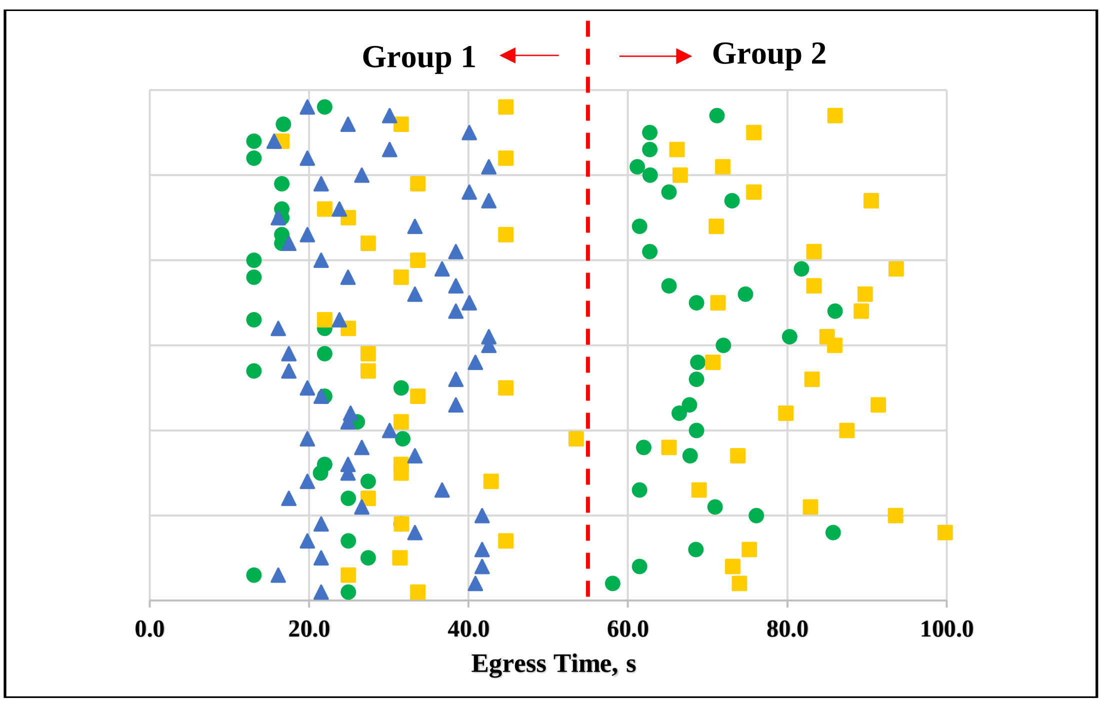
The randomization of wheelchair users throughout building 9 resulted in 58 unique simulations that include two wheelchair users. In each of these simulations, the egress times of both WC users were documented, and the average for the pair was found. These results can be found in **Table 13.** In each case, the apartment whose WC user exited first appears first (i.e. 1B/1C means the WC user originating in 1B reached safety before that of 1C). Overall averages across all simulations are also provided in the table. These results are more clearly shown in **Figure 23,** where the benchmark egress time for the apartment whose WC user exited last in each scenario is also shown. As shown in the figure, there are two distinct groups of simulations, each comprising approximately half of the 58 “two WC user” scenarios. Group 1 features exit times of the wheelchair users ranging from approximately 15-40 seconds, while Group 2 has a general time range of 60-90 seconds[12]. The most common apartments featured in both groups are 1B-1G, 2A-2B, and 3G-3H for Group 1 and 2C-2H and 3A-3F for Group 2.

Table 13: Results for Two Wheelchair Users

Apartments	First WC User Egress Time, s	Last WC User Egress Time, s	Average WC User Egress Time, s
1B/1C	24.9	33.6	29.3
1B/1F	24.9	44.7	34.8
1B/1G	24.9	27.4	26.2
2A/1B	13.1	24.9	19.0
1B/2B	21.4	31.6	26.5
3G/1B	22.0	24.9	23.5
3H/1B	16.6	24.9	20.8
1C/1F	31.8	53.5	42.6
1G/1C	27.4	31.4	29.4
2A/1C	13.1	33.6	23.4
2B/1C	31.6	31.6	31.6
3G/1C	22.0	33.6	27.8
3H/1C	16.6	33.6	25.1
1G/1F	27.4	42.9	35.1
2A/1F	13.1	44.7	28.9
2B/1F	31.6	44.7	38.1
3G/1F	22.0	44.7	33.3
3H/1F	16.6	44.7	30.6
2A/1G	13.1	27.4	20.3
1G/2B	26.1	31.6	28.8
3G/1G	22.0	27.4	24.7
3H/1G	16.6	27.4	22.0
2A/2B	13.1	31.6	22.3
2A/3G	13.1	22.0	17.5
2A/3H	13.1	16.6	14.8
3G/2B	22.0	31.6	26.8
3H/2B	16.8	31.6	24.2
3H/3G	16.6	22.0	19.3
2H/2G	71.0	82.9	76.9
2G/3A	65.2	75.8	70.5
2G/3B	65.2	83.4	74.3
3D/2G	62.8	66.6	64.7
3E/2G	62.0	65.2	63.6
3A/2H	71.2	86.0	78.6

[12] Speculations and possible reasons why the 20 second gap between the groups of simulations occurred will be visited in **Section 4.3.**

2H/3B	86.0	89.3	87.7
3D/2H	62.8	66.2	64.5
3E/2H	68.6	87.5	78.1
3A/3B	67.7	91.4	79.6
3D/3A	62.8	75.8	69.3
3E/3A	68.6	71.3	70.0
3D/3B	62.8	83.4	73.1
3E/3B	68.6	83.1	75.9
3E/3D	66.5	79.8	73.1
2D/2C	73.1	90.6	81.8
2E/2C	72.0	86.0	79.0
2C/2F	76.1	93.6	84.9
3C/2C	80.3	85.0	82.7
3F/2C	61.2	71.9	66.6
2E/2D	85.8	99.8	92.8
2F/2D	74.8	89.8	82.3
3C/2D	67.8	73.8	70.8
3F/2D	61.5	71.1	66.3
2F/2E	81.8	93.7	87.7
2E/3C	68.8	70.7	69.7
3F/2E	61.5	68.9	65.2
3C/2F	68.5	75.2	71.9
3F/2F	61.5	73.2	67.3
3F/3C	58.1	74.0	66.1
AVERAGE	45.5	57.3	51.4



KEY

● First WC User Egress Time

■ Last WC User Egress Time

▲ Benchmark

Figure 23: Results for Two WC Users

Overall, the Group 1 simulations resulted in similar egress times to the Benchmark. This means that wheelchair users in this group can exit the apartments without fear of being left behind or overtaken by the non-disabled population. However, wheelchair users that came from the apartments featured in the Group 2 simulations were severely disadvantaged. The time gap appears even for the faster wheelchair user in each case. Thus, even the *slowest* non-disabled evacuee (see the benchmark results in **Figure 23)** to exit each apartment reaches safety before the *fastest* wheelchair user. Similar to the single wheelchair user simulations, this is likely due to the egress route and structural components used to exit the building. It is unlikely that the small difference in movement speed (just 0.01 ft/s) resulted in nearly 40 second discrepancies between the benchmark/Group 1 simulations compared to Group 2. Furthermore, the wheelchair users in Group 2 were the last people to exit the building in every simulation. In a building population without assigned helpers, one can safely assume that the time for people with physical disabilities to evacuate from these apartments is compounded due to the time it takes for them to recruit assistance.

The total building population egress time was also recorded for each of the two wheelchair user simulations and is included in the Appendix. In 21 of the simulations (36.2%), the time did not increase from the benchmark. In the remaining 37 simulations (63.8%), the total building population egress time increased by an average of 20.8 seconds, resulting in a mean population egress time of 63.6 seconds. There were no simulations that resulted in faster egress times than their benchmark counterparts. However, there were increases of more than 50.0 seconds in 4 simulations. The largest egress time was 101.3 seconds, which resulted from wheelchair users in Apartments 2D and 2E. Since both apartments are located in the main interior of the building, they both use the same egress route (2^{nd} Floor Main). While the stairwells and walkways are wide enough to support the congestion of multiple non-disabled occupants, they cannot support two wheelchair users and their assistants placed side-by-side. Thus, one group must wait for the other to traverse the stairs before they can proceed. This was the case in each scenario where the wheelchair users used the same egress components. In fact, each of the four simulations with 50.0 second increases (116.8%) from the benchmark featured wheelchair users evacuating via the front main exit. Thus, not only did these occupants have to wait for the other WC user and their assistants, but they also had to navigate through the congestion of non-disabled evacuees. Perhaps a more efficient evacuation plan for building populations with two wheelchair users located in the center of this building is for non-disabled, non-assistants to navigate to the back stairwell, while the wheelchair users exit via the less-taxing front main exit.

4.2.3 Three Wheelchair Users

For a building population including 3 wheelchair users and 77 non-disabled evacuees, a total of 96 simulations were recorded. Results are provided in **Table 14** with apartments listed in the order by which wheelchair users were evacuated in each simulation. Wheelchair users displayed an overall average egress time of 47.0 seconds (across all simulations), while the minimum egress time was 13.1 seconds (WC user originating in Apartment 2A) and the maximum egress time was 121.9 seconds (WC user originating in Apartment 3B). In 25 simulations (26.0%), none of the wheelchair users or their helpers were the last to exit the building. In 21 simulations (21.9%), one out of three wheelchair groups were the last people to exit the building. The other two wheelchair users in these scenarios evacuated before some of the non-disabled building occupants. In the remaining 50 simulations (52.1%), all three wheelchair users and their assistants were the last people to exit building 9. These statistics result in 171/288 wheelchair users (59.4%) exiting last across 96 simulations. More than half of a three-wheelchair user population will exit building 9 behind the remaining 77 non-disabled evacuees (71 occupants not including WC user assistants) when attempting to leave this campus apartment building.

Table 14: Results for Three WC Users

Apartments	First WC User Egress Time, s	Second WC User Egress Time, s	Last WC User Egress Time, s	Average WC User Egress Time, s
1B/1C/1F	24.9	31.8	53.5	36.7
1B/1G/1C	24.9	27.4	31.4	27.9
2A/1B/1C	13.1	24.9	33.6	23.9
1B/2B/1C	21.4	31.6	31.6	28.2
3G/1B/1C	22.0	24.9	33.6	26.8
3H/1B/1C	16.6	24.9	33.6	25.0
1B/1G/1F	24.9	27.4	42.9	31.7
2A/1B/1F	13.1	24.9	44.7	27.6
1B/2B/1F	21.4	31.6	44.7	32.6
3G/1B/1F	22.0	24.9	44.7	30.5
3H/1B/1F	16.6	24.9	44.7	28.7
2A/1B/1G	13.1	24.9	27.4	21.8
1B/1G/2B	21.4	26.1	31.6	26.3
3G/1B/1G	22.0	24.9	27.4	24.8
3H/1B/1G	16.6	24.9	27.4	23.0
2A/1B/2B	13.1	21.4	31.6	22.0
2A/3G/1B	13.1	22.0	24.9	20.0
2A/3H/1B	13.1	16.6	24.9	18.2
1B/3G/2B	21.4	22.0	31.6	25.0
3H/1B/2B	16.8	21.4	31.6	23.3
3H/3G/1B	16.6	22.0	24.9	21.2
1C/1G/1F	13.6	30.0	56.0	33.2
2A/1C/1F	13.1	31.8	53.5	32.8
1C/2B/1F	30.8	31.6	43.9	35.4
3G/1C/1F	22.0	31.8	53.5	35.8
3H/1C/1F	16.6	31.8	53.5	34.0
2A/1G/1C	13.1	27.4	31.4	24.0

1G/2B/1C	26.1	31.6	31.6	29.7
3G/1G/1C	22.0	27.4	31.4	26.9
3H/1G/1C	16.6	27.4	31.4	25.1
2A/2B/1C	13.1	31.6	31.6	25.4
2A/3G/1C	13.1	22.0	33.6	22.9
2A/3H/1C	13.1	16.6	33.6	21.1
3G/2B/1C	22.0	31.6	31.6	28.4
3H/2B/1C	16.8	31.6	31.6	26.6
3H/3G/1C	16.6	22.0	33.6	24.1
2A/1G/1F	13.1	27.4	42.9	27.8
1G/2B/1F	26.1	31.6	44.7	34.1
3G/1G/1F	22.0	27.4	42.9	30.8
3H/1G/1F	16.6	27.4	42.9	29.0
2A/2B/1F	13.1	31.6	44.7	29.8
2A/3G/1F	13.1	22.0	44.7	26.6
2A/3H/1F	13.1	16.6	44.7	24.8
3G/2B/1F	22.0	31.6	44.7	32.7
3H/2B/1F	16.8	31.6	44.7	31.0
3H/3G/1F	16.6	22.0	44.7	27.7
2A/1G/2B	13.1	26.1	31.6	23.6
2A/3G/1G	13.1	22.0	27.4	20.8
2A/3H/1G	13.1	16.6	27.4	19.0
3G/1G/2B	22.0	26.1	31.6	26.5
3H/1G/2B	16.8	26.1	31.6	24.8
3H/3G/1G	16.6	22.0	27.4	22.0
2A/3G/2B	13.1	22.0	31.6	22.2
2A/3H/2B	13.1	16.8	31.6	20.5
2A/3H/3G	13.1	16.6	22.0	17.2
3H/3G/2B	16.8	22.0	31.6	23.4
2H/3A/2G	71.0	75.8	82.9	76.6
2H/2G/3B	71.0	82.9	83.4	79.1
3D/2H/2G	62.8	71.0	82.9	72.2
3E/2H/2G	62.0	71.0	82.9	72.0
2G/3A/3B	65.2	74.9	86.8	75.6
3D/2G/3A	62.8	65.2	75.8	67.9
3E/2G/3A	62.0	65.2	75.8	67.7
3D/2G/3B	62.8	65.2	83.4	70.4
3E/2G/3B	62.0	65.2	83.4	70.2
2G/3E/3D	65.2	66.5	79.8	70.5
3A/2H/3B	67.7	79.4	91.4	79.5
3D/2H/3A	62.8	66.2	75.8	68.2
3A/3E/2H	71.3	73.8	92.8	79.3
3D/2H/3B	62.8	66.2	83.4	70.8
3E/3B/2H	69.2	83.1	92.4	81.6
2H/3E/3D	66.2	66.5	79.8	70.8

3D/3A/3B	62.8	74.9	86.8	74.8
3A/3E/3B	67.7	68.6	91.4	75.9
3E/3A/3D	66.5	75.8	79.8	74.0
3E/3D/3B	66.5	79.8	83.4	76.5
2D/2E/2C	88.0	108.1	121.9	106.0
2D/2C/2F	73.9	88.2	99.9	87.3
3C/2D/2C	67.5	75.4	88.5	77.1
3F/2D/2C	61.5	73.1	85.7	73.4
2E/2C/2F	74.1	89.9	99.6	87.9
2E/3C/2C	71.4	76.5	86.4	78.1
3F/2E/2C	61.5	72.5	86.5	73.5
2C/3C/2F	70.6	77.6	83.7	77.3
2C/3F/2F	75.2	77.4	89.8	80.8
3F/2C/3C	58.1	74.1	79.5	70.6
2E/2F/2D	79.7	94.7	109.7	94.7
2D/3C/2E	75.1	76.8	89.2	80.4
3F/2D/2E	61.5	69.6	87.0	72.7
2D/3C/2F	67.3	69.7	82.4	73.1
3F/2D/2F	61.5	69.1	82.6	71.1
3F/2D/3C	60.6	72.7	74.4	69.2
2E/3C/2F	63.8	70.4	80.3	71.5
3F/2E/2F	61.3	68.8	82.6	70.9
3F/2E/3C	60.6	67.4	75.1	67.7
3F/3C/2F	60.6	73.0	78.3	70.6
AVERAGE	37.9	46.0	57.0	47.0

From the table above, the time intervals between the first, second, and third wheelchair users to exit building 9 in each scenario can also be compared. First, the fastest wheelchair user in each simulation exited the building in an average of 37.9 seconds. This is just 4.9 seconds faster than the full population egress time of the non-disabled benchmark simulation—an alarming number when considering the *fastest* wheelchair group to exit in the three WC user simulations. Next, the second WC group to reach safety in each simulation did so in an average time of 46.0 seconds. This is an 8.1 second increase from the fastest wheelchair user in each simulation and results in an average greater than the benchmark full population evacuation of 42.8 seconds. Finally, the average time for the slowest wheelchair user to safely exit is 11 seconds greater than the second wheelchair user and 19.1 seconds greater than the fastest wheelchair user. This results in a time of

57.0 seconds to egress the building on average. While some of the last wheelchair users to exit the building did so in under 30 seconds, others took more than 100. Since most non-disabled evacuees egress in under 40 seconds, it is unlikely that the wheelchair users who took the longest time to evacuate experienced extreme congestion to hinder their progress. Instead, it is most likely that inaccessible egress routes (stairs, narrow walkways/stairwells) slowed their evacuation.

The results for the three wheelchair user simulations are further compared in **Figure 24.** Similar to the two wheelchair user simulations, there are two distinct groups, each displaying the same characteristics as before. The first group of simulations has an egress time range of approximately 15 seconds to 55 seconds, while the second group ranges from 60 to 120 seconds. In the first group, most of the wheelchair users exit the building at the same time or before their benchmark counterparts. Again, this shows relatively few issues with the safe evacuation of wheelchair users originating from the apartments in this group. Unironically, these are the same apartments determined as Group 1 for the two wheelchair user simulations: 1B-1G, 2A-2B, and 3G-3H. However, wheelchair users evacuating from apartments 2C-2H and 3A-3F in Group 2 are again disadvantaged. They never evacuate before the last wheelchair user in each of the Group 1 simulations and are on average 50.0 seconds slower than Group 1. Additionally, they never reach safety before the last non-disabled occupant in the benchmark, meaning all three wheelchair users and their assistants were the last people to exit building 9 in every case. They all exit the building after the full population egress time determined from the benchmark simulation (42.8 s).

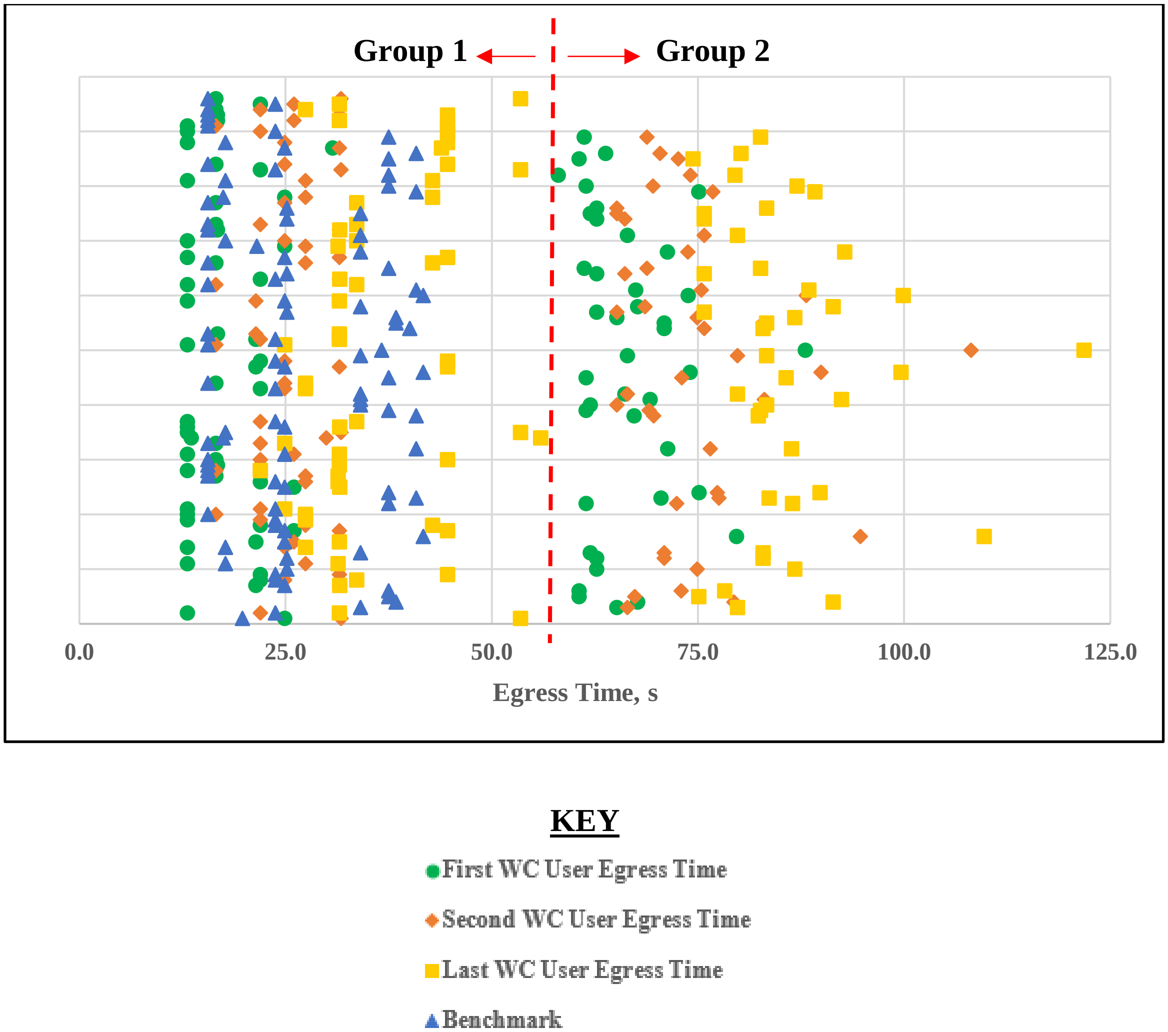
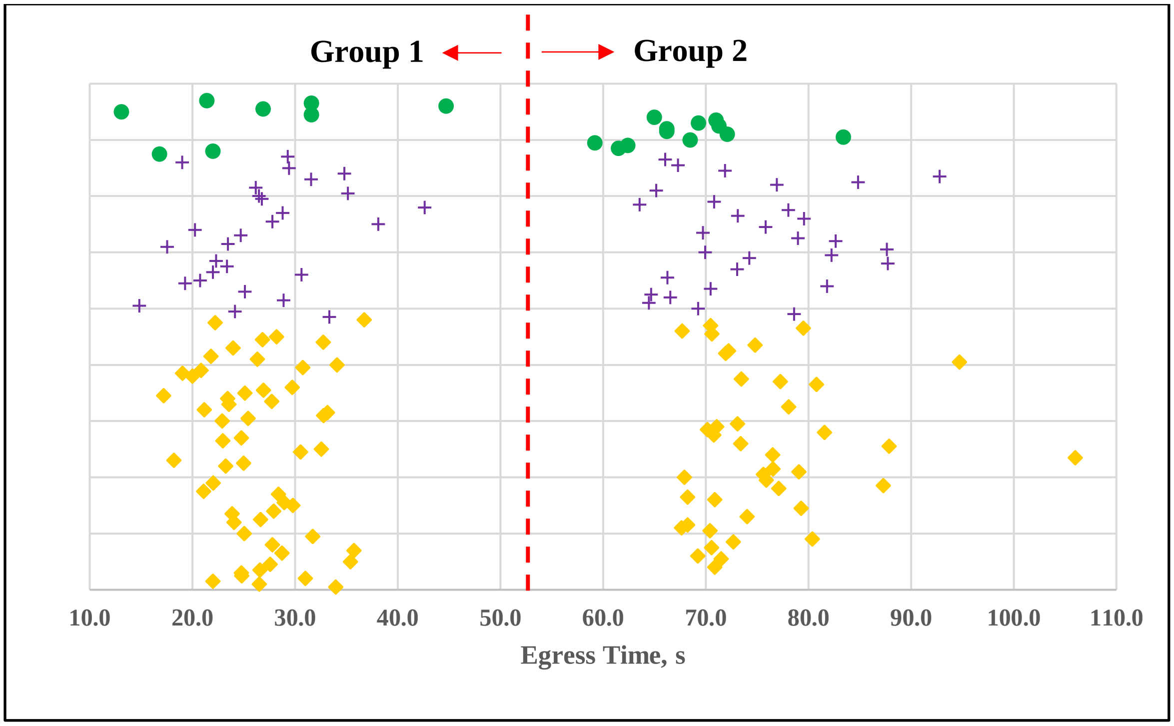


Figure 24: Results for Three WC Users

As with the simulations for one and two wheelchair users, the total building population egress time was also recorded for the three wheelchair user simulations. These results are shown in the *Additional Simulation Data* section of the Appendix. In 35 simulations (36.5%), the time for the entire population to exit the building remained the same as the benchmark. The remaining 61 simulations (63.5%) saw substantial increases in total population egress time, resulting in times greater than 120 seconds—a percent increase of 180.4% from the benchmark. This is over 80 seconds longer than the time it takes for all other non-disabled evacuees to exit the building. Since low visibility and breathing issues (due to smoke) can set in quickly, the longer evacuation times put wheelchair users and their helpers at a greater risk for injury than their non-disabled counterparts.

4.2.4 Simulation Case Comparisons

A total of 174 simulations were completed for 1, 2, and 3 wheelchair users in building 9. While each set gave striking results when placed next to the benchmark simulation of 0 wheelchair users, it is important to also compare the changes that occur as more disabled evacuees are added to the population. The average exit times for all 174 simulations are shown according to the number of wheelchair users in **Figure 25.** When using the average values, the distinction between Group 1 and Group 2 simulations is clear. Regardless of the number of wheelchair users, occupants using wheelchairs who originate in Apartments 2C-2H and 3A-3F (Group 2) will always take longer to evacuate than those in the remainder of the building (Group 1). When evaluating these apartments, it was determined that the components hindering evacuation progress in Group 2 are a combination of stairwells and exit congestion. Most wheelchair users originating in the Group 1 apartments can self-evacuate (via flat exit of 0% incline or ramp), and when stairs are required, only the back main exit is used (where there is little congestion).



KEY

●One WC User

+Two WC Users

◆Three WC Users

Figure 25: Average Egress Times by Number of WC Users

It is also interesting to note the consistent increase in the largest population egress times across the 1, 2, and 3 wheelchair user simulations. For one wheelchair user, this time was 85.0 seconds. For two and three wheelchair users, the largest population egress times were 101.3 seconds and 123.3 seconds, respectively. Thus, an increase of approximately 20 seconds is seen in each case. In each simulation, the wheelchair users required assistance to navigate stairs, and they originated from apartments 2C-2E and 3B (all Group 2 apartments). Additionally, they were the last people to exit the building in all three simulations. With this information, one would expect to see an increase in the average population egress time for each set of simulations as well. However, this was not the case. Instead, the average remained fairly consistent for the 1, 2, and 3 wheelchair user simulation groups (59.6, 63.6, and 63.0 s, respectively). Thus, the addition of more wheelchair users in the building are placing the other disabled people at a disadvantage, while the non-disabled occupants are not significantly affected.

Finally, it is important to note the exponential increase in egress times given just 1-3 wheelchair users in a population of 80 people (1.25-3.75%). The largest population egress times mentioned in the previous paragraph equate to a percent increase of 98.6%, 136.7%, and 188.1% from the benchmark population egress time of 42.8 seconds. Similarly, the average egress times result in significant percent increases when compared to the benchmark average for each set of simulations. These results are shown in **Figure 26.** While even the largest time (7 minutes including pre-evacuation) is well under the flashover point, it must not be overlooked. This does not include the potential for blocked exits, changes in egress routes, increases in pre-evacuation times, smoke inhalation, or delay due to fire alarms. Additionally, we assume that two assistants are willing and able to help each wheelchair user evacuate. In reality, two assistants may not be readily available. This gives WC users just two minutes to find help and begin their evacuation before smoke and flames engulf their apartment and the remainder of the building. Thus, for this building, it is likely that a fire with multiple wheelchair users in the population would result in injury to the wheelchair user and/or assistants (due to smoke, fire, etc.) if they do not experience an “ideal” scenario.

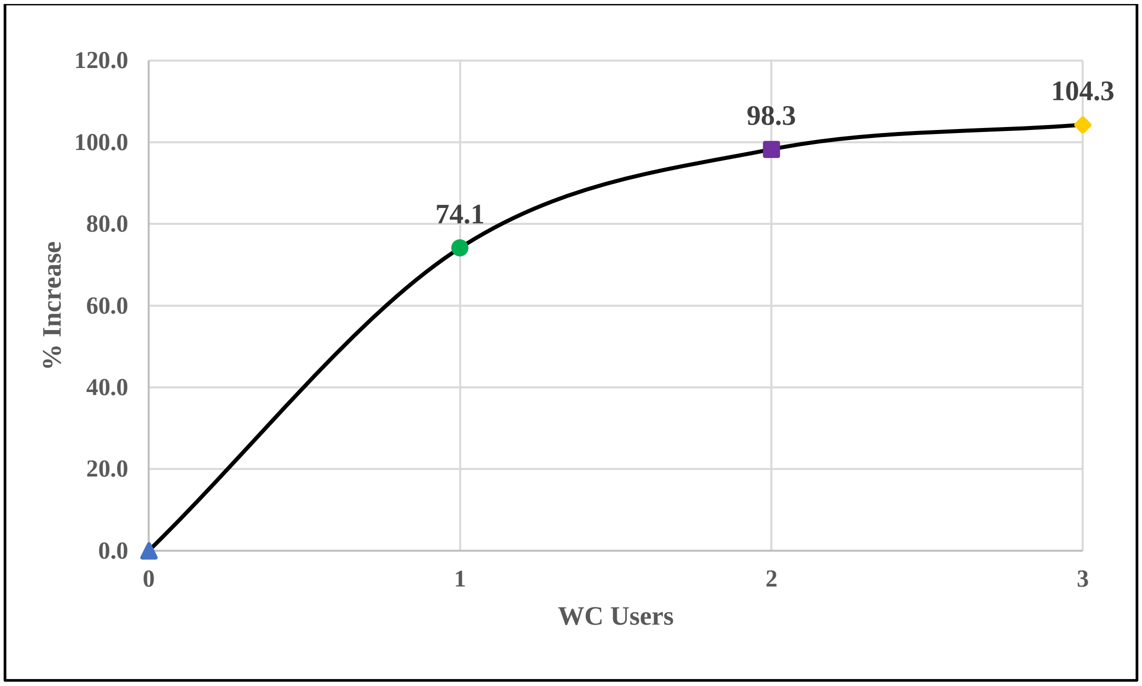


Figure 26: Average Percent Increase in WC User Egress Times

4.3 A Proposed Structural Ranking System

The discovery of two distinct sets of egress times (Groups 1 and 2) for each 1, 2, and 3 wheelchair users in the 174 Pathfinder simulations for the chosen building led to further investigation of the egress components related to each group. The apartments featured in the first group of simulations are 1B-1G, 2A-2B, and 3G-3H, while those featured in Group 2 are 2C-2H and 3A-3F. These remain the same regardless of number of wheelchair users in the simulation. In essence, the wheelchair users who evacuate from the Group 1 apartments either require no assistance or experience little exit traffic from other building occupants. Those in Group 2 experience more resistance via difficult-to-navigate egress components or congestion along their egress route.

Since this apartment building is similar to the other 9 in the complex, and university housing must be readily accessible to all disabled people, it is worthwhile to investigate which apartments in the building are “safe” for fire evacuation of wheelchair users and which are not via the two groups of simulations. Thus, apartments are labelled according to their required egress components in **Subsection 4.3.1,** and the simulations analyzed in **Section 4.2** are recategorized in **Subsection 4.3.2.** To confirm the results and identify potential outliers, *another* iteration of 150 simulations[13] were completed and detailed in **Subsection 4.3.3.** Minor adjustments were made to the original categorization system as well.

4.3.1 Initial Categorization of Egress Components

While this research on the selected apartment building has identified key evacuation characteristics among wheelchair users, it is also important to realize the vast number of unique buildings and disabilities in the world today. Each building contains distinct egress routes and components ranging from stairwells to evacuation elevators and even novel alarm systems. Additionally, all building populations will respond to egress routes and fires differently. Thus, it was important to the author to create a categorization of structural components based upon, but not solely inherent to, the current building. For this reason, a malleable and buildable point system was created to represent structural components one may encounter along an egress route. For the current building, the initial system is described in **Table 15.** This point system was created based on perceived effort of WC users to navigate the components with or without their assistants (lower points equate to less perceived effort and thus faster egress times). For example, WC users can traverse ramps and flat hallways/exits without assistance and with low exertion. On the other hand, navigating stairs (up or down) requires assistance. Downward movement was assigned lower points because WC groups moved faster traveling downstairs in the original 174 simulations than they did traveling up. The points in this system are additive to represent the buildable nature of exhaustion and effort

[13] The addition of 150 simulations for the purpose of structural categorization also means that new simulations can be analyzed according to number of wheelchair users (as in **Section 4.2**). These results are provided in the Appendix of this thesis.

as one evacuates from larger buildings. For example, one will likely be able to travel down more stairs than up before becoming tired. Thus for four standard flights of stairs, 4.0 points are assigned for downward movement, while 8.0 points are assigned for upward movement.

Table 15: Initial Structural Point System

Egress Component	**Assigned Points**
Flat Exit (No Incline)	0
Ramp	0.5
1 Flight of Stairs Downward	1.0
1 Flight of Stairs Upward	2.0

Once the point system was created, each apartment's egress route in building 9 was analyzed and assigned points. For this building, the minimum number of points was 0.0 while the maximum was 1.0 using only the exits assigned to each apartment in **Section 4.1**. The small number of points is representative of the small size of the building and short exit routes. In any case where congestion was identified, an additional 1.5 points were added for further hindering the evacuation process. An example from Apartment 2E is provided in **Figure 27** and shows how points were assigned for each apartment. **Table 16** provides the final points for each apartment in the building. From the table, one can see that the Group 1 apartments were all assigned 0.5 points or less. Those originally identified as Group 2 were assigned 1.0 or more points.

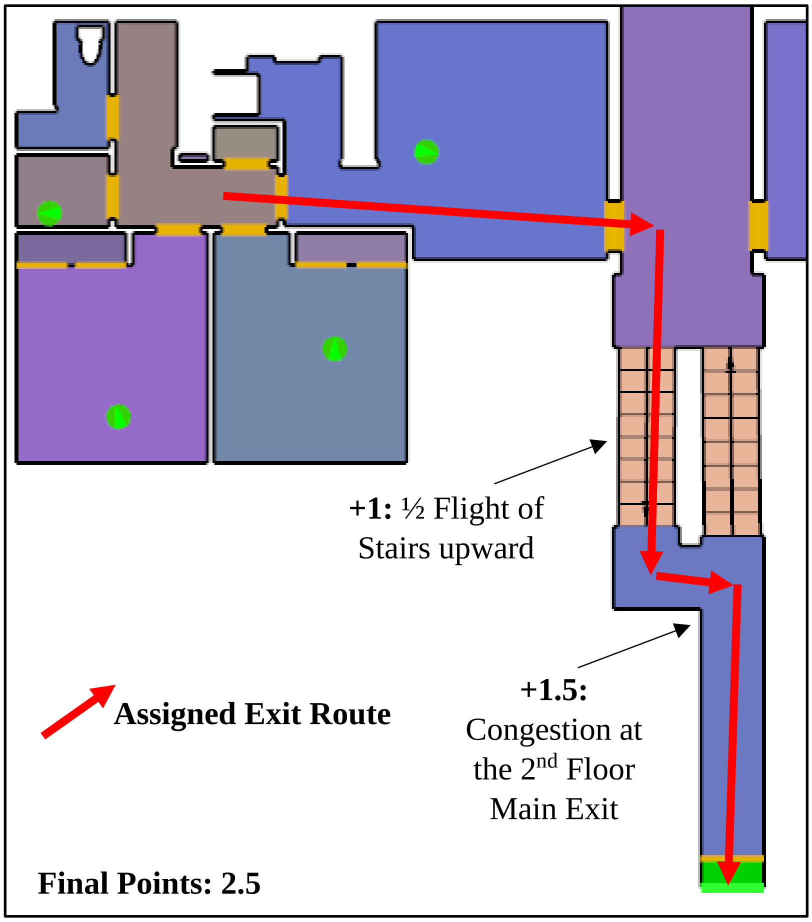


Figure 27: Sample Point Assignment, Apt. 2E

Table 16: Building 9 Structural Point System, Iteration I

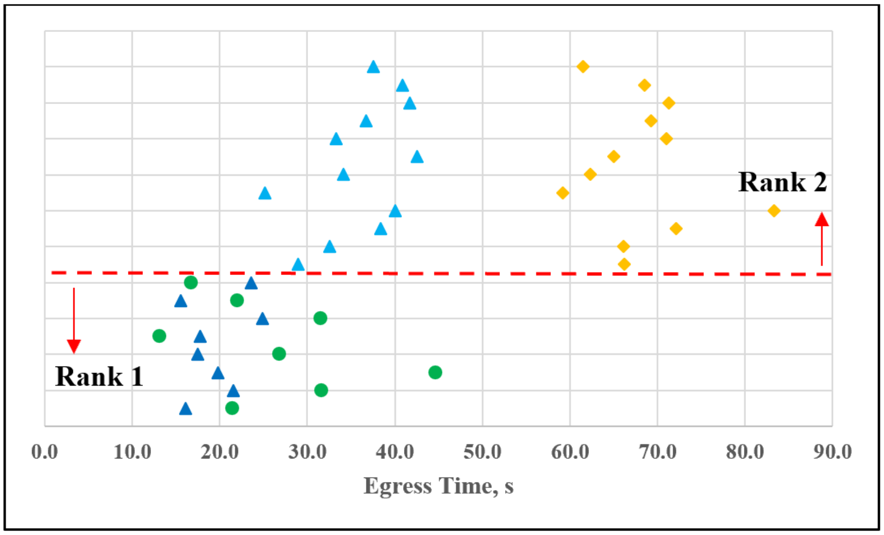
Apart-ment	Initial Group	Assigned Exit	Required Structural Components	Initial Points (from Table 15)	Added Points for Congestion	Final Points
1B	1	Basement Right	Flat Exit	0.0	--	0.0
1C	1	Basement Main	½ Flight Down	0.5	--	0.5
1F	1	Basement Main	½ Flight Down	0.5	--	0.5
1G	1	Basement Left	Flat Exit	0.0	--	0.0
2A	1	2nd Floor Right	Flat Exit	0.0	--	0.0
2B	1	2nd Floor Right	Flat Exit	0.0	--	0.0
2C	2	2nd Floor Main	½ Flight Up	1.0	+1.5	2.5
2D	2	2nd Floor Main	½ Flight Up	1.0	+1.5	2.5
2E	2	2nd Floor Main	½ Flight Up	1.0	+1.5	2.5
2F	2	2nd Floor Main	½ Flight Up	1.0	+1.5	2.5
2G	2	Basement Left	1 Flight Down	1.0	--	1.0
2H	2	Basement Left	1 Flight Down	1.0	--	1.0
3A	2	2nd Floor Right	1 Flight Down	1.0	--	1.0
3B	2	2nd Floor Right	1 Flight Down	1.0	--	1.0

3C	2	2nd Floor Main	½ Flight Down	0.5	+1.5	2.0
3D	2	2nd Floor Main	½ Flight Down	0.5	+1.5	2.0
3E	2	2nd Floor Main	½ Flight Down	0.5	+1.5	2.0
3F	2	2nd Floor Main	½ Flight Down	0.5	+1.5	2.0
3G	1	3rd Floor Ramp	Ramp	0.5	--	0.5
3H	1	3rd Floor Ramp	Ramp	0.5	--	0.5

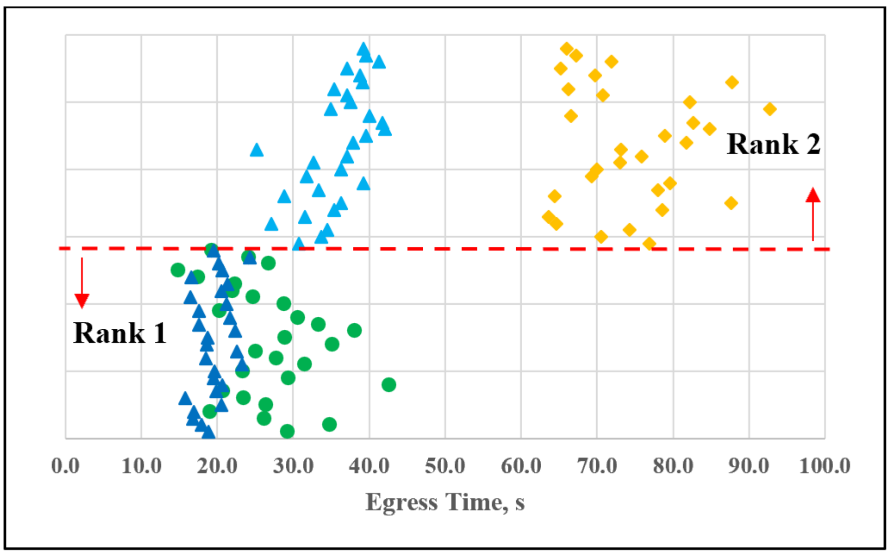
4.3.2 Iteration I

To further confirm that the exit routes from Group 1 apartments are more WC egressible than those in Group 2, the results from the 174 original Pathfinder simulations (plus the benchmark simulation) were re-organized and analyzed by each group. Those in Group 1 (tallying equal to or less than 0.5 structural points) are furthermore labelled as *Rank 1* while those receiving more than 0.5 points are labelled *Rank 2*. From the reorganization, 92 simulations were assigned to *Rank 1* and the remaining 82 were assigned to Rank 2. Divisions by the number of wheelchair users were used to separate building populations and form general egress time ranges.

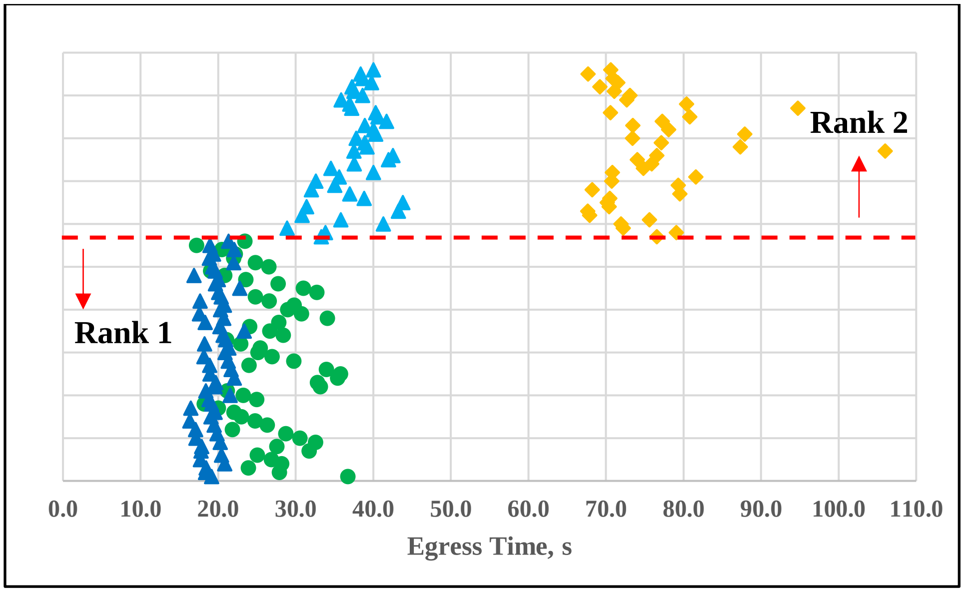
The re-organization of simulations in each set of wheelchair users formed clusters of simulations similar to the original figures that identified Group 1 and Group 2 (**Figures 23-25)**. In general, the new order sorted egress times from smallest to largest, allowing for the calculation of Rank averages and other characteristics. Average exit times for each set of wheelchair user simulations are given in **Figure 28.** From the figure, not only can one see the large difference between the simulations involving wheelchair users in Ranks 1 and 2, but one can also see a slight difference between Rank 1 and Rank 2 apartments in the Benchmark simulation. The egress components involved in Rank 2 exit routes hindered the safe evacuation of all building occupants, not just the disabled evacuees.



a) One WC User



b) Two WC Users



a) Three WC Users

KEY

- Rank 1
- Rank 2
- Benchmark (Rank 1)
- Benchmark (Rank 2)

Figure 28: Iteration I Results

From the figures above, several key conclusions can be drawn. First, in every scenario, WC users experienced significant delays if they originated in a Rank 2 apartment. Since the simulations were idealized by not including behavioral components, smoke, or fire dynamics, this can only be due to the difference in egress components in each rank. The WC users in Rank 1 averaged egress times of 26.0, 26.7, and 25.9 for 1, 2, and 3 WC users, respectively. Those originating in the Rank 2 apartments experienced egress times of 68.0, 74.5. and 75.7 seconds (1, 2, and 3 WC users, respectively). This equates to percent increases of 162%, 179%, and 192% from Rank 1 to Rank 2 with the only simulation changes being the original location of wheelchair users in the building.

Thus, the ability of WC users to self-evacuate is paramount to their safe egress. This is also clear when comparing the Benchmark to Rank 1 and Rank 2. While WC users are disadvantaged compared to non-disabled evacuees in most cases, their egress times are much closer to the benchmark when originating from Rank 1. Across all Rank 1 simulations, the WC users experienced 32.6% slower egress times than the benchmark. For Rank 2, this rose to 99.3%. Based on these results, even self-evacuation and a reduction in exit congestion result in slower movement times for the disabled evacuees. However, giving them the opportunity to evacuate without help from others is a step in the right direction toward equalizing their evacuation experiences with the non-disabled population. Finally, as previously mentioned, there is even a clear distinction between the benchmark exit times in Rank 1 and Rank 2. This equates to increases of 16.4, 16.2, and 16.6 seconds (83.7, 82.7, and 82.6%, respectively) from Rank 1 to Rank 2 for non-disabled occupants in the 1, 2, and 3 wheelchair cases. This indicates that the WC users' disability is not the issue when evacuating from this building. It is instead the structural components (stairs and exit widths) and exit design that hinder safe evacuation.

4.3.3 Iteration II

The moldable nature of the structural point system proposed and analyzed in **Subsections 4.3.1** and **4.3.2** means that every building should be able to be assessed for points and categorized by egressibility of exit routes. Thus, 150 new simulations were completed using the default exit assignments in Pathfinder rather than the previously determined routes for WC users. The new exit assignments for each apartment are provided in **Table 17.** In this iteration, 5 apartments are using new exit routes (*italicized* in the table), while the remaining 15 apartment are using the exits featured in Iteration I. A minor adjustment was also made to the point system and final apartment rankings based on the previous results. An additional point was added to each apartment if WC users required assistance to exit properly. This is due to the extended time it took for WC users and their assistants to evacuate via stairs when compared to those who could self-evacuate. The final point tallies are shown below.

Table 17: Iteration II Exit and Point Assignments

Apart -ment	Exit Assignment	Required Structural Components	Initial Points	Con-gestion	Assist-ance	Final Points
1B	Basement Right	Flat Exit	0.0	--	--	0.0
1C	Basement Main	½ Flight Down	0.5	--	+1.0	1.5
1F	Basement Main	½ Flight Down	0.5	--	+1.0	1.5
1G	Basement Left	Flat Exit	0.0	--	--	0.0
2A	2nd Floor Right	Flat Exit	0.0	--	--	0.0
2B	Basement Right	Flat Exit	0.0	--	+1.0	1.0
2C	Back Main	½ Flight Up	1.0	--	+1.0	2.0
2D	Front Main	½ Flight Up	1.0	+1.5	+1.0	3.5
2E	Front Main	½ Flight Up	1.0	+1.5	+1.0	3.5
2F	Back Main	½ Flight Up	1.0	--	+1.0	2.0
2G	Basement Left	1 Flight Down	1.0	--	+1.0	2.0
2H	Basement Left	1 Flight Down	1.0	--	+1.0	2.0
3A	Basement Right	1 Flight Down	1.0	--	+1.0	2.0
3B	Basement Right	1 Flight Down	1.0	--	+1.0	2.0
3C	Front Main	½ Flight Down	0.5	+1.5	+1.0	3.0
3D	Front Main	½ Flight Down	0.5	+1.5	+1.0	3.0
3E	Front Main	½ Flight Down	0.5	+1.5	+1.0	3.0
3F	Front Main	½ Flight Down	0.5	+1.5	+1.0	3.0
3G	3rd Floor Ramp	Ramp	0.5	--	--	0.5
3H	3rd Floor Ramp	Ramp	0.5	--	--	0.5

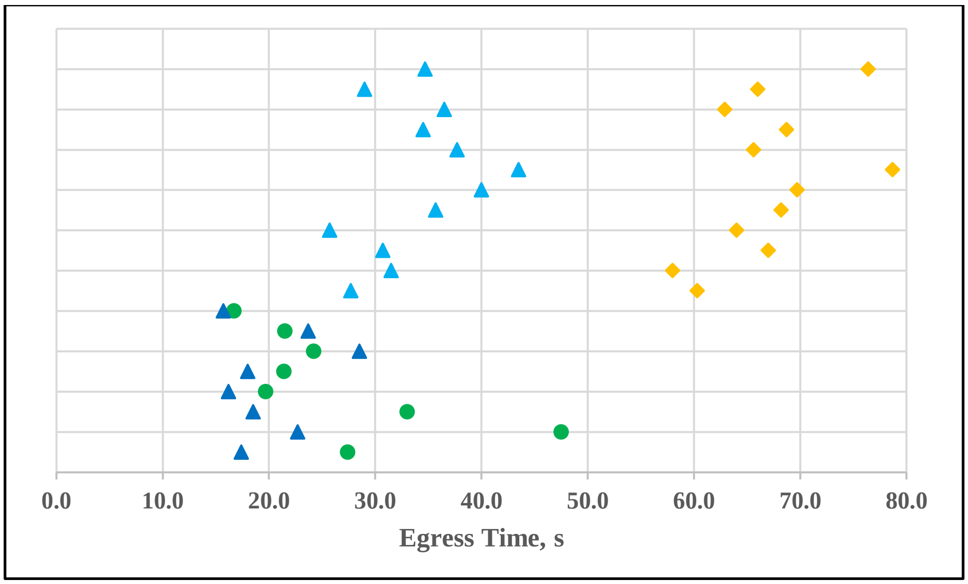
The points above range from 0.0-3.5 for the apartments in building 9. In this iteration, Rank 1 represents apartments receiving points of 1.5 or less, while Rank 2 apartments received more than 1.5 points. Based on these points, the Rank assignments remained the same as in Iteration I. This shows promise for the premise of the point system and represents the ability to modify Rank divisions and point amounts. The Benchmark case was then run for Iteration II, and associated results are provided in **Table 18.** The total population egress time is 43.5 seconds (compared to

42.8 seconds for Iteration I). Non-disabled occupants in this simulation averaged an egress time of 28.4 seconds with a minimum of 15.7 seconds (Apartment 3H) and a maximum of 43.5 seconds (Apartment 3B). The similar benchmark results of Iteration I and II indicate the low likelihood of outlier simulations and confirm the results for the original WC user simulations.

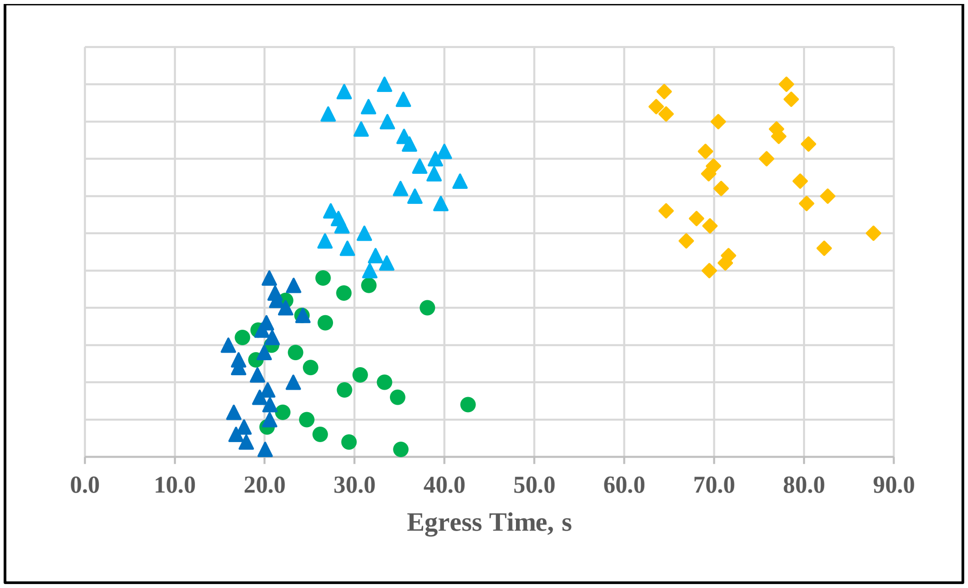
Table 18: Benchmark Exit Times by Apartment, Iteration II

Apartment	Egress Time, s	Total Evacuation Time, s (Pre-Movement plus Egress Time)
1B	16.2	312.6
1C	18.5	314.9
1F	22.7	319.1
1G	17.4	313.8
2A	18	314.4
2B	28.5	324.9
2C	35.7	332.1
2D	27.7	324.1
2E	31.5	327.9
2F	30.7	327.1
2G	29	325.4
2H	34.7	331.1
3A	40	336.4
3B	43.5	339.9
3C	37.7	334.1
3D	25.7	322.1
3E	34.5	330.9
3F	36.5	332.9
3G	23.7	320.1
3H	15.7	312.1

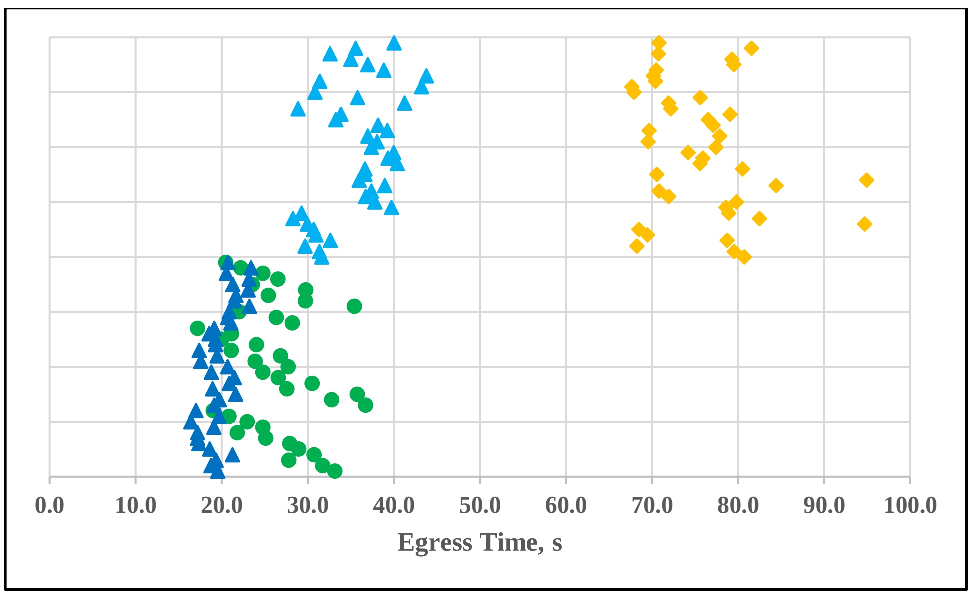
Following the Benchmark case, the new WC user simulations were run. This time, results were automatically categorized by rank and are provided in **Figure 29** below. For the two and three WC user simulations, new combinations of WC users in their Rank apartments were prioritized to gain egress times and evacuation scenarios not otherwise seen in Iteration I. From the figures, one can see the same distinct groups of simulations as in Iteration I. Thus, congestion and stairs are confirmed to be the main source of evacuation issues in this building. Again, these issues are not limited to only the WC users. The non-disabled population in the benchmark simulation also experienced delays when using stairs or the main exit. For example, the deviations between Rank 1 and Rank 2 simulations in this iteration of the Benchmark are 13.8, 12.9, and 15.8 seconds for the 1, 2, and 3 WC user cases. For the WC users, these time delays are compounded. The deviations rose to 40.7, 46.1, and 49.5 seconds when wheelchair users were involved. Overall, this is an average percent increase in evacuation delay of 221.7% resulting solely on whether an evacuee is wheelchair bound or not.



a) One WC User



b) Two WC Users



c) Three WC Users

<u>KEY</u>

● Rank 1

◆ Rank 2

▲ Benchmark (Rank 1)

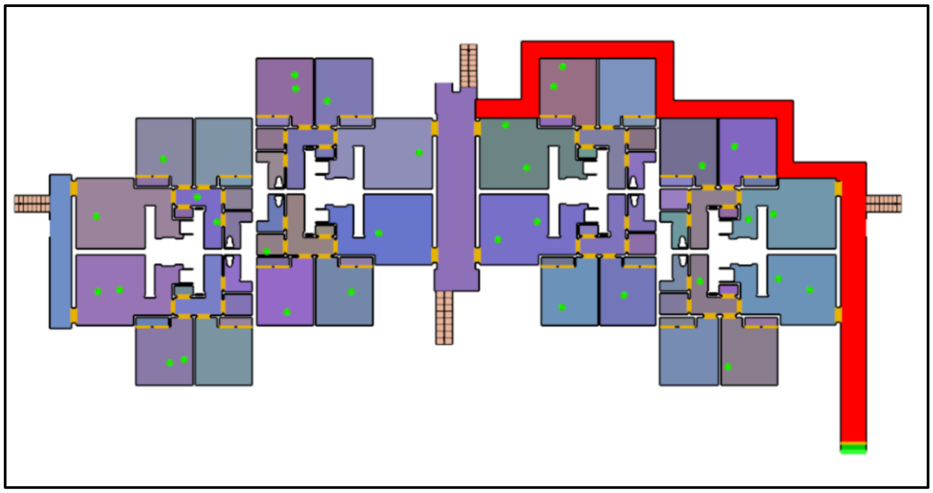
▲ Benchmark (Rank 2)

Figure 29: Iteration II Results

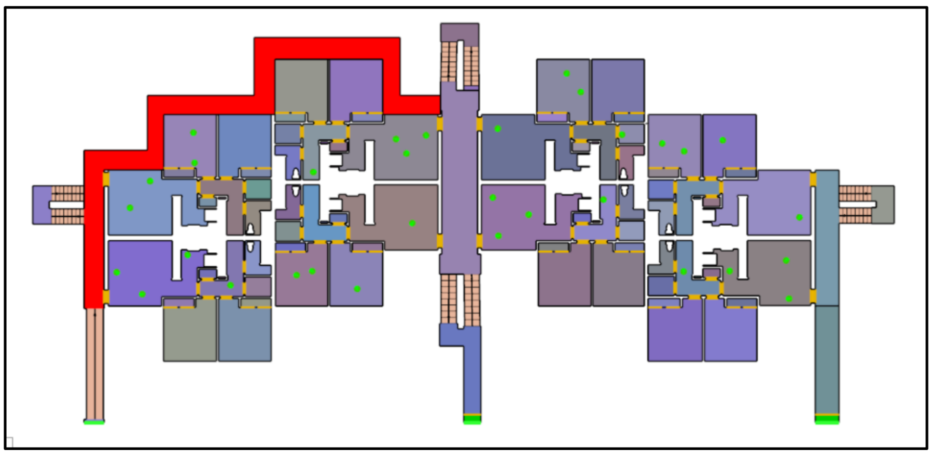
4.4 Structural Modifications

From the results provided in **Subsections 4.3.2 and 4.3.3**, it is clear that building 9 (and likely the remainder of this apartment complex) was not designed for the regular use and visitation of wheelchair users or other people with physical disabilities. Currently, half of the apartments cannot be accessed without the use of stairs. This creates potential evacuation problems for 40 people not including guests in this building alone. While stairs cannot be avoided in most buildings, the configuration of exits can be modified. In this building in particular, the exterior exit design allows for possible additions and reconfiguration. With more exit choices and the ability of WC users to avoid the stairwells where possible, their evacuation times may improve. The addition of egressible exit routes may also ease the burden of finding willing assistants and increases the number of apartments WC users can safely reside in. Since all buildings in this complex feature the same exterior design, improving exit routes can increase the safety for WC users and people with other physical disabilities significantly.

To test this hypothesis, exterior hallways on floors 2 and 3 of the building were added to the Pathfinder model. New floor plans are shown in **Figure 30**. Two sample simulations were then completed that include WC users evacuating using the new routes. The WC users were placed in Apartments 2C and 3F and each egressed using the new hallways on their respective floors. The occupant in apartment 2C completed their route in 65.3 seconds while the evacuee in 3F exited in 53.5 seconds. When compared to the original 1 WC scenarios for these apartments, the WC user from apartment 2C evacuated 0.3 seconds faster using the original exit. However, the evacuee from 3F exited the building 10.0 seconds faster using the new route.



a) Floor 2 Addition



b) Floor 3 Addition

Figure 30: Proposed Egressible Building Additions

These results show promise for improved evacuations with exterior building additions in several ways. First, while the WC user in Apartment 2C evacuated in the same time frame as the original simulation, they did so by using the new route independently. Thus, there is no potential waiting period for assistants (and no fear of being forgotten). Furthermore, the new hallways provide accessible exit routes for eight additional apartments in the building. Whereas before the interior apartments on floors 2 and 3 could only be accessed via stairs, WC users can now reach them using the 3rd floor ramp and 2nd floor right exit. This means that only Apartments 1C and 1F now require stairs. If all buildings in the complex include the new additions, nearly 50 accessible housing units can be added—representing 200 beds. Additionally, the new exits increase the number of egress routes by 33.3%. This resulted in reduced queues at the Front Main Exit for the non-disabled occupants and prevented WC users and their assistants from waiting at stairwells due to other WC groups using the same exit.

5. RESEARCH CHALLENGES, LIMITATIONS, AND FUTURE DIRECTIONS

5.1 Limiting Factors and Research Challenges

Research on PWD can sometimes create an ethical dilemma. This may be why they have generally been overlooked in evacuation research. Regardless, very little is known by the general population about the majority of disabilities identified by the ADA and other organizations. This alone creates several challenges for professionals outside the fields of health and disability studies. The following points identify challenges that must be overcome by evacuation researchers, fire safety professionals, and engineers in order to achieve the main goals of this research.

1. *Inclusivity of all disabilities may not be possible for targeted research studies and time frames.*

   While PWD forms a large portion of the world population, they are still small in number in some locations and buildings. This is due to the long and difficult history of disability which has historically not accepted them into society. Additionally, some forms of disabilities are rare, and others may not be willing to participate in research studies. With an already limited population-focused upon in this research, recruiting people of a wide range of backgrounds and disabilities is not always possible. Using simulation and modelling to reduce this challenge is a viable option, but as noted, many models do not accurately address behavioral components, diverse populations, and disabilities.

2. *Consultation with social science experts may be required for accuracy.*

   Human behavior is often not the expertise of engineers and fire safety officials. This may be one of the reasons it is rarely explored in fire research. Evacuation research in itself is also multi-disciplinary. In order to fully appreciate the wide range of disabilities and behavior possible during a fire evacuation, consultation with experts is required.

This increases the time frame and cost of research projects, but it will undoubtedly increase the accuracy and knowledge of building officials and design engineers as well.

3. *Extensive modification of evacuation and structural models may be necessary.*

   As noted, many evacuation models and experiments lack the ability to fully represent the disabled population and their needs in a fire. This results in studies that only represent a small part of the population (typically wheelchair users and those with other mobility impairments) when in reality, the disabled population includes thousands of unique impairments. Additionally, behavioral aspects of evacuation (route choice, groups, etc.) are not extensively explored in evacuation models. Both of these points combined mean that evacuation simulations for PWD are not often accurate. Improving models requires the addition of more disabilities as well as behaviors through statistical analysis of building populations. Human behavior is also rarely predictable, requiring the use of stochastic capabilities in order to produce results based on probabilistic random distributions.

4. *Questionnaires and small-scale real-time experiments may be needed in order to assess current population views.*

   Small-scale experiments involving real people produce the most precise results and opinions. With changing societal views of disability, they are even more important for fire research. Current population views and thoughts about evacuation are outdated in comparison to technological updates and building designs and, therefore, cannot be used to address the efficiency of evacuation procedures and components.

5. *"New" views on disability may be required as research findings develop and evolve.*

Only disability experts, social scientists, and people with disabilities understand the true extent of disabilities in society. This means that buildings, evacuation routes, and accessible features are often not designed with PWD in mind. The disabled population and field experts must be consulted in order to improve current designs, and educational efforts must be made among engineers and designers to better understand PWD.

6. *The chosen evacuation model has inherent limitations.*

   Pathfinder is one of the most widely accepted, used, and updated evacuation software within the research community [205]. Its selection for this thesis was based on its availability and positive qualities such as visualization of occupants, user-friendliness, and ability to incorporate fire dynamics through the partner software PyroSim. However, this research has identified drawbacks in the current research. First, while Pathfinder is highly customizable, its ability to individualize each run makes it difficult to automate. Without creating an external code, each modified simulation must be manually run and saved. Next, the main interest of this research is occupant exit times. Pathfinder visualization easily displays total building exit time (the time it takes for all occupants to reach safety). However, the user cannot easily find a single evacuee's time. Instead, one must locate a separate file and find the occupant of interest's assigned label in order to find the time. This increases the time it takes to process each simulation significantly, and with hundreds or even thousands of simulation combinations possible (increasing exponentially with increased building size, total occupants, wheelchair users, and rank divisions), manually running simulations is not possible within a reasonable amount of time.

In addition to the challenges presented by society, this thesis also draws several limitations due to study design. These are as follows:

1. *This study is focused on a particular building configuration and hence includes a limited sample size.*

   By using a low-rise apartment building, this study is limited in both the number of egress components and occupants that can logically be included. First, the egress components in the modelled apartment building include stairs, ramps, and flat exits (sidewalks and walkways). While these are imperative to the safe evacuation of all populations and present a basis for future research, they do not include other significant egress components (OEEs, stair chairs, etc.) or structural designs aimed at improving evacuation times (i.e. sky bridges). Second, the number of building occupants and wheelchair users were also limited by the building's living occupancy (maximum of 80 people). This number was used as a baseline "worst-case scenario" due to assumed fluctuations in daily building use, but generally represents a small sample size to collect data from. Additionally, the number of wheelchair users was limited to a maximum of three in the building. After the completion of two iterations of simulations, it is apparent that this is not a large enough population size to fully understand evacuee exit times and movement data. We hope to bridge this limitation in the next phase of research.

2. *The ranking system developed for this thesis is based on previous research suggestions and present results rather than developed exit time data.*

   This research presents a more qualitative look at egress components by categorizing stairs, ramps, and flat exits based on assumed ease of individual egress (of a wheelchair user). While this type of system worked well for the chosen building and small number of egress components, it may present challenges when studying larger, more complex buildings or other structure types. Since the goal of this research is to build a moldable point and ranking ideology, more building types with unique occupancies and populations need to be studied to progress its development.

3. *Human behavior (in terms of non-physical disabilities and evacuation pre-movement) was not addressed.*

   This research focuses primarily on the evacuation movement phase of non-disabled occupants and wheelchair users (a portion of the *functional independence* category of disability) to gain a starting point for future research on other forms of disability. While this is a necessary and critical step toward an inclusive structural evacuation system, it currently does not fully address the pre-movement evacuation phase or social cognition disabilities—where behavior tends to play a larger role [206,207].

4. *This research uses an evacuation simulation software rather than real-time experiments.*

   Evacuation simulation and modelling software has progressed greatly in recent years, as discussed in **Chapters 2** and **3.** However, simulations simply cannot express the same quality, accuracy, and variation in data as that of human-based experiments. Additionally, this thesis features a user-made building model. While this method is supported within the research community and by Pathfinder [208], it does not include items such as furniture, potential blocked exit paths, and other obstacles. This idealizes the simulation environment. Efforts will be made in future research to assess the accuracy of simulations (through real-time evacuation drills) and improve the building model in Pathfinder.

5.2 Future Directions and Research Suggestions

The literature review presented in **Chapter 2** of this thesis highlights the limited number of evacuation studies focused on people with disabilities. As mentioned, this is surprising due to the wide variety of information on evacuation times [27,29,31,83], human behavior [94,101,104], and fire effects for the non-disabled population [98,111,209]. Even within the open literature on egress of PWD, there is a continued lack of research on those with non-physical disabilities. This has made it increasingly difficult to study people with chronic health conditions, sensory disabilities, and cognitive disorders and has resulted in the continued social injustice of such populations. For this reason, research in this area is not only warranted, but also necessary for improving building safety and reducing fire injuries and deaths [77,136,156,210].

The presented review also highlights discrepancies between various definitions of disabilities across NGOs and government organizations alike. Unfortunately, this has resulted in a lack of understanding of many disabilities and their needs in disaster. This is especially true for people with invisible disabilities, as they cannot be visually identified in society and are thus typically forgotten [211,212]. In fact, at the time of this thesis, the author was unable to identify any evacuation research geared toward people who fall into the *medical health* category of disability (which encompasses invisible disabilities and chronic health conditions). And while there are some studies for mobility, visual, hearing, and cognitive impairments, they are still limited in scope and breadth. For example, the vast majority of studies on those with sensory impairments are focused on movement speeds [160,161,164], despite several case studies noting that orientation and improper emergency signals significantly hindered safe evacuation [163,167,168]. Similarly, research on the evacuation processes of those with cognitive impairments has also focused on movement speeds and training [163,175]. However, there is an abundance of social science research focused on the behavioral (mainly decision-making) capabilities and self-determination of those with cognitive impairments—especially within the medical field [213–217]. Notable difficulty in understanding and communication was highlighted, from which one may infer a similar trend as people with these disabilities engage in evacuation activities. More real-time evacuation drills including people in the *social cognition* category of disability are required to gain better insight into this portion of the population.

Interactions between building occupants in heterogenous populations (including disabled and non-disabled evacuees) also present inherent challenges that have not been widely explored in the current literature. First, diverse populations create more complex interactions between both occupants and structures. This has the potential to increase evacuation times as people work to find information about the disaster and fellow evacuees. It is also not well known how people with different types of disabilities interact with each other during fire evacuations. By combining all forms of disability into various evacuation scenarios, researchers may find new and telling information about evacuation assistance or lack thereof. For example, with the already limited amount of knowledge about human behavior in a fire for those with *social cognition* impairments, it is unclear whether evacuees in this category would be willing to assist those within the *functional independence* category, become frustrated with their reduced speeds, or avoid them altogether. This alone can significantly change evacuation times compared to evacuations involving solely non-disabled evacuees or those with only one form of disability.

The use of simulation and modeling technology for fire evacuation research has gained ground in recent years [218,219]. By 2010, there were 26 models recognized by NIST's Fire Research Division [37]. Since then, many more have been introduced through independent research. However, there is still no standardized method or model (either in individual countries or across the world) for studying evacuation, and there is only one created with the intention of studying people with disabilities (BUMMPEE). Even so, BUMMPEE is an independent model with limited functionality, it is not readily available to the public, and it was created over a decade ago. [176]. To the best of the author's knowledge, BUMMPEE has also not been updated or improved since its initial release in 2008. Apart from BUMMPEE, there have been other attempts to include PWD in evacuation models. For example, Pathfinder has the ability to simulate people in wheelchairs, hospital beds, and others requiring assistance, though their speeds and movement paths are user-defined [177,220]. It does not inherently include people with other forms of disability or default speeds and behaviors based on the current literature. This is not unlike other evacuation models on the market. User-defined features like movement speeds allow great customization of research but also create large variations in resulting data and evacuation times. Therefore, the development of a new model and/or improvement of current models with the inclusion of standardized values based on evacuee demographics and characteristics is needed. This will not only allow better collaboration, but it can also lead to more precise predictions of the RSET and ASET in fire scenarios.

Based on the above gaps in evacuation research for people with disabilities, a series of broad suggestions for future research are presented as follows:

1. *Identify accurate and quantifiable representations of all forms of disability in evacuation models.*

   This thesis is the first step in creating a connection between structural components and different types of disabilities. If researchers can accurately quantify how these evacuees use the structural component (time of use, method of use), they can be implemented into current evacuation models.

2. *Re-assess the widely accepted walking speeds of both the able-bodied and disabled populations as studied via real-time evacuation experiments.*

   Currently, there are significant variations between published walking speeds of both the disabled and non-disabled populations. To more accurately address occupant needs during the evacuation process, a consensus must be drawn between published values. This may be done through new studies that focus on heterogenous populations and current building components, as some building codes and commonly used structural components have been updated in recent decades.

3. *Work to form engineering conditions that ensure the continued availability of required materials for people with disabilities during a fire and subsequent evacuation.*

   From stair lifts to sufficient alarm systems and even ventilation systems, building systems that specifically address the needs of PWD are often not included. If engineers can better identify helpful evacuation systems and fire suppression systems, they can become the norm in public buildings worldwide, thus reducing injury and fatality risks in building fires.

4. *Determine how to accurately model highly-heterogenous populations for fire evacuation.*

   To date, there has only been one evacuation model produced with the specific goal of simulating the evacuation of PWD—BUMMPEE. Despite its merit, this model does not include many forms of disability, and it cannot simulate a combination of building populations. This is all too common in other models, which often only include homogenous populations of non-disabled evacuees. Thus, it is unknown how to properly include more representative views of building occupants in evacuation simulations. This may be explored through real-time observations of building populations or virtual reality experiments.

In addition to the general suggestions provided, the author is also working to improve the current research and expand it as follows:

1. *Expand the included structural components through simulation of additional university dormitories and apartment buildings.*

   The present university apartment building was chosen due to its inherent separation of evacuation routes and small size. This allowed for the individual investigation of each structural component without the addition of severe bottlenecking or too many components. However, stairs and ramps are far from the only egress components used in building evacuations. By simulating more buildings, we can gauge the accuracy of the current ranking system and build upon it by adding elevators, stair chairs, and other evacuation methods. The goal of this section of future research is to create a spectrum of component rankings that can be used by non-evacuation experts to address the egressibility of apartment buildings for PWD.

2. *Improve the current structural ranking system through the modification of assigned points.*

   Using points to assign final system ranks is a non-biased way of quantifying structural components in the research. However, the current system is limited in scope. The goal of this future research topic is to re-evaluate current measured speeds of use of such components (walking speeds on ramps, time to traverse stairs, etc.) and incorporate them into the ranking point system. Modified assigned ranks for the current building and the subsequent re-running of simulations can help gain insight into a more accurate system.

3. *Complete additional simulations including more wheelchair users for the* functional independence *category of disability.*

   In the current research, a total of 323 unique simulations were completed for 1-3 wheelchair users. Each had to be manually modified in Pathfinder, resulting in large amounts of run time. Thus, it was not feasible to increase the number of wheelchair users in the initial study. In future studies, the author plans to include a greater number in order to assess the effects of people with disabilities on other building populations during an evacuation.

4. *Expand the research to include the three additional categories of disability listed in the* Disability Evacuation Framework and subsequent definition.

   The overall goal of this research is to progress the safety of people with disabilities in fire scenarios. To properly do this, the inclusion of all forms of disability is preferred. The four-part definition of disability has provided a basis to achieve this goal, and the present thesis has addressed the *functional independence* category. Once the above work on the current research is complete, the next step in this over-arching project is to repeat the work for the *sensory perception, medical health,* and *social cognition* categories of disability. This will further expand the included structural components and improve the quality of the points and ranking system with additional data.

6. CONCLUSION

This chapter summarizes the research topic, present literature, and experiment presented in this thesis. For clarity, the chapter is divided into three sections. First, we review the history of disability and current literature focused on the evacuation of PWD in buildings. This includes a re-visit to the proposed disability definition and its implications in society. Next, we examine the simulation procedures and parameters used to conduct the experiment in this thesis. Finally, conclusions and inferences are presented based on the experimental findings.

6.1 Review of Disability History and Available Evacuation Research

This thesis began with a multidisciplinary look at centuries of social injustice on the disabled population. Marginalization first commenced with classical philosophers, resulting in the labelling of impaired individuals as “abnormal” and “freaks”. In the 19th century, this thinking evolved into new science views of *survival of the fittest.* Non-disabled people were no longer good enough to participate or survive in the advancing world. Even when disability rights movements took root in the mid-20th century, PWD were still left out of legislation discussions and accessibility designs. One example of this comes from the broad definition of disability in the original ADA. Its inability to clearly define what it means to have an impairment resulted in ineffectual accommodations and ambivalent Supreme Court cases labelling people as either “too disabled” or “not disabled enough” [47]. And while hundreds of laws have addressed and improved many facets of life for people with disabilities, inaccessible and inegressible structural designs continue to present problems.

Issues for PWD in the built environment are perhaps most clearly presented when comparing the available bodies of literature on building evacuations for people with and without disabilities. As presented in **Chapter 2** of this thesis, there is an abundance of literature focused on non-disabled evacuees. While this did not *begin* following the 9/11 attacks on the World Trade Centers, the event increased the awareness of evacuation complexity so much so that over 15,000 studies, reviews, and experiments were conducted from 2001 to 2021—few of which focus on the disabled population [77,221]. Ranging from high-rise buildings to human behavior and most recently evacuation modelling, these studies show that building evacuation is a complex phenomenon, even without including people with disabilities. However, including only homogenous populations of non-disabled occupants is not realistic. There are more than one billion people with disabilities in the world, and this number is only rising due to the aging world, obesity epidemic, and improved medical field (increased life expectancy) [33,60,61].

Despite the vast number of PWD in today's society and wide variety of evacuation research on non-disabled people, the literature review presented in this thesis identified only a limited number of studies focused on the disabled population during fire evacuations. Mainly, these are focused on people with functional limitations or physical disabilities, and the related studies preeminently quantify movement speeds and crowd flows. Overall, these studies have proven the benefits of OEEs for self-evacuation and discredited the use of refuge areas to reduce congestion. Sensory disability research is the second most common research area and connects issues with auditory and visual fire alarms to the hindrance of safe evacuation. One astounding example of this comes from a fire at a Russian boarding school for the deaf, where 28 people were killed and 17 more injured because they could not hear an auditory alarm [170]. Finally, research on people with chronic health disorders and mental health conditions are the least abundant. In fact, upon completion of the study collection for the literature review, the author identified zero studies that included people with long-term invisible disabilities such as cancer, heart disease, or diabetes—despite being the leading causes of death in the United States [222].

The lack of research on PWD in fire has brought to light several issues that this thesis and related future research aim to tackle. First, many people with disabilities are forgotten about or neglected during fire evacuations. Several PWD even noted this in a study on refuge areas in high-rise buildings [155]. Another issue identified in the literature review is the need to determine structural aids and barriers to the evacuation process for all disabled people. Many studies noted improved evacuation times when using OEEs and difficulty navigating stairs [136,147–150,152], however, they were all focused on people with functional limitations. This is common despite the general consensus that people with intellectual disabilities egress faster than those with other forms of disabilities while taking the most time to make decisions [175].

More research must be conducted on non-physically disabled people in order to gain the full picture on disability evacuation. If PWD continue to be disregarded in evacuation research, it will result in inaccurate homogenous population experiments, increased injury and death rates for all building occupants, and a wider safety gap in future accessibility legislation. For these reasons, the *Disability Evacuation Framework* and subsequent new disability definition (in regard to evacuation) were created. By subdividing disability types into four main categories with related egress components, researchers, FSOs, and legislators can easily identify the lacking areas and work to improve them. Advancements are most necessary for people with cognitive disabilities and chronic health conditions. However, due to the current lack of research in these areas, it is difficult to find a starting point for improvements. This is especially true for engineers and officials who are unfamiliar with disabilities and the needs of people with various impairments during fires. The *Disability Evacuation Framework* can help in this way as well. It provides questions for officials to refer to that relate to each category of disability, therefore making sure that all prospective evacuation problems are addressed during the design and building phase of new construction. For example, in reference to the *functional independence* category, designers must ask if the building requires people with physical disabilities to find assistance or special evacuation devices in order to safely egress during a fire. If the answer is *yes*, the designer should either modify the design or add accessible evacuation devices such as stair lifts to the building. Furthermore, the definition and framework are open-ended and can be modified to fit the needs of the user. There will always be disabilities that do not directly fit into one or any of the four categories of disability presented in this thesis. However, by referencing the current framework, several categories can be combined, or a new one can be initiated. The author is aware of the changing world population and is willing to improve the framework based on new future research.

6.2 Review of Simulations and Results

The simulation experiment in this thesis is based directly on the results of the included literature review and disability definition. It is understood that the focus of this thesis (*functional independence,* physical disabilities, wheelchair users) is also the most abundant in the literature. However, one must have a reference point for future improvements and research. This thesis is considered "Phase A" of a series of research projects aimed to include all four categories of disability. By starting with the most visited topic in fire evacuation research for PWD, we have referenced past work and made modifications that confirm accurate simulation results and procedures. Moving forward, further improvements to the current research will be made, and new projects will focus on sensory disabilities, chronic impairments, and mental health disorders. Most importantly, additional behavioral capabilities will be added to simulations to better reflect the dynamic qualities of heterogenous populations and fires.

This thesis uses the evacuation software Pathfinder to simulate populations of wheelchair users and non-disabled occupants during a building fire. A low-rise apartment building on the campus of Clemson University (Clemson, SC, USA) was chosen due to its compartmental design, construction materials, and unique egress components; and a comparable model was built in the Pathfinder GUI. Its separate exterior stairwells and ramps allow for complete isolation of evacuation routes and reduce many other variables in the evacuation process of larger, centrally designed buildings. The apartments and egress components were also confirmed for ADA compliance before building occupants were added. To represent a possible worst case evacuation scenario, the building was set to full occupancy (80 people, 4 per apartment) for all simulations. Then, populations including 1, 2, and 3 wheelchair users were completed. In each simulation, wheelchair users were randomly placed in different apartments due to their need for assistance in navigating stairs. Two assistants were assumed to be located in the same apartment of origin as the wheelchair user and immediately willing to help. This eliminated the wait time necessary for WC users to find help and allowed for complete focus on the egress components.

Results first began with estimates of a fire scenario. While fire dynamics and pre-evacuation were not directly studied in this thesis, approximations of flashover, prospective structural failure, and pre-evacuation were determined the gauge the severity of egress times in each simulation. Using the compartment fire software OZone, the flashover point was determined to be approximately 9 minutes originating in the kitchen of an apartment. Structural failure was based on a minimum fire resistance rating of 30 minutes, and pre-evacuation time was computed as 4.94 minutes according to a pre-movement time research database. Thus, building occupants have slightly more than 5 minutes for the egress phase of the evacuation before their apartment is completed engulfed in flames and smoke. They have approximately 25 minutes before potential structural failure to completely evacuate the building.

Overall, the simulation of 1-3 wheelchair users in the building population did not produce results over the 9-minute flashover point or 25-minute structural failure estimate. However, they were still alarming for a number of reasons. First, the largest total population egress times for each number of wheelchair users were between approximately 100% and 200% larger than when no wheelchair users were involved. Given such a small population with only 1.25-3.75% WC users, it is reasonable to assume that larger populations and more wheelchair users would produce even greater time increases. These time increases also do not include the effects of smoke inhalation, low visibility, exhaustion, or waiting for assistance. With the largest overall evacuation time being 7 minutes, the leaves WC users with just two minutes to find help and evacuate from their apartment in an *ideal* scenario.

In addition to the population egress time increases, there were also two distinct groups of simulation time ranges in each WC case. When comparing the structural features of the apartments in each group, those requiring assistance to exit (stairwells) resulted in consistently higher egress times than those from which the WC users could self-evacuate. Thus, the ability of people with physical disabilities to evacuate without relying on others is of the utmost importance. To further confirm this, the original 174 simulations (plus the benchmark) were regrouped according to a structural point system. Apartments from which the egress required assistance or experienced exit congestion received higher point tallies than those where self-evacuation was possible, and two "ranks" were determined. By re-plotting the results figures for each number of WC users according to the two ranks, it was confirmed that stairwell-assisted evacuations can increase egress times by up to 192% in this building. However, the wheelchair users were not the only occupants affected by the stairwells and exit congestion. The benchmark case also saw marked increases from Rank

1 to Rank 2 (up to 83%), indicating that stairs are the least efficient egress option for any type of evacuee. Results were confirmed with a second iteration of 150 simulations as well.

To combat the large time differences between the benchmark and WC user egress times as well as between the assisted and non-assisted evacuation routes, two 1-WC user simulations were completed with suggested structural modifications to the building. On the second and third floors, new exterior hallways were added that connect the central hallway to the 2nd Floor Right exit and the 3rd Floor Ramp. The WC users were placed in interior apartments (typically only stair accessible from the Front or Back Main exits) and assigned to use the new hallways. In one simulation, the WC user exited in nearly the same amount of time as the original. In the other, the WC user exited 10 seconds faster in the new simulation. Thus, the new additions show promise for improved evacuation times of wheelchair users in this building. However, they also allow them to evacuate independently. No longer would the wheelchair users have to rely on others to help them evacuate, and no longer would the WC group cause congestion at the front or main exit of the building during the evacuation.

6.3 Research Conclusions

The main inferences regarding the simulation results and literature review findings from this thesis are:

1. *Current legislation is not sufficient for addressing accessibility issues for PWD.*

   Legislation such as the ADA in the US, *Disability Discrimination Ordinance* in Hong Kong, and *Disability Discrimination Act* in the UK have resulted in life-altering improvements for people with disabilities in the last 30 years. Many people have now re-gained the freedom to enter society and participate in the economy through work, activism, and leisure activities. However, there are still many drawbacks and missed steps among the current laws. Most prominently, the lack of an inclusive, but the lack of an inclusive and clear definition of disability has resulted in organizations either creating their own or self-interpreting the ADA. Therefore, there are inconsistent accessibility features in many public buildings today that do not truly address the needs of PWD. This is clearly true from the building used in this thesis. To tie the above to our case study, the entire apartment complex was renovated in the 2010s and claims to be ADA compliant. Many of the features (ramps and stairwell widths) were also checked for compliance before completing the evacuation simulations. However, wheelchair users cannot navigate stairwells on their own, and half of the building's apartments are only accessible via stairs. To be functional for people with physical disabilities, all apartments should be reachable by non-stair routes.

2. *While all forms of disability are under-valued in evacuation research, studies involving people with mental health disorders and chronic health conditions are the least prominent.*

   The literature review in this thesis revealed few studies focused on invisible illnesses or cognitive disorders, despite an abundance of studies on non-disabled evacuees and a clear need for behavioral research. This makes it difficult for researchers to expand the current field as there are no databases or experiments to work from. Additionally, real-time fire evacuation experiments are lengthy, expensive, and hard to plan. With an already small field of people with disabilities, finding the appropriate number of willing participants is no easy task and presents safety risks. However, real evacuation drills must first be explored prior to simulations, as they involve human intelligence and true evacuation conditions.

3. *For people with physical disabilities, the ability to self-evacuate is key to improving their quality of experience in the built environment and life safety during fires.*

   People with disabilities have often noted feelings of uncertainty and fear when asked about their evacuation experiences in the built environment. They question the ability to find help, locate accessible exits, and even evacuate without facing extreme fatigue. This is compounded by the many fire investigations that have detailed injuries and deaths of PWD as they waited for help in refuge areas (NIST 9/11 study for example). Furthermore, the results of this thesis have also clearly shown improved evacuation times when people with physical disabilities are aware of self-egressible exit routes and can navigate them properly. By providing PWD with marked, independently accessible egress components, they can be truly self-sufficient in the built environment without fear of potential fires.

4. *Stair evacuation can present significant evacuation delays for all populations.*

   Past literature has consistently demonstrated that stairs are harder to navigate for PWD than egress components such as ramps. While this may be obvious from the many accessibility laws around the world that require ramp entrances to buildings such as schools and hospitals, the Rank 1 and 2 simulation groups also revealed that stair-based evacuations were detrimental to the non-disabled evacuees. Stairs cannot and will not be avoided in most buildings, but perhaps improvements can be made to stair width or pitch to make them easier to navigate. Additional ramps and accessible exit routes may also provide building occupants with new options that allow them to avoid stairs if desired as well.

REFERENCES

[1] V.K.R. Kodur, S. Banerji, R. Solhmirzaei, Test methods for characterizing concrete properties at elevated temperature, (2019). https://doi.org/10.1002/fam.2777.

[2] G.A. Khoury, Effect of fire on concrete and concrete structures, n.d.

[3] M. Li, C.X. Qian, W. Sun, Mechanical properties of high-strength concrete after fire, Cement and Concrete Research. 34 (2004) 1001–1005. https://doi.org/10.1016/J.CEMCONRES.2003.11.007.

[4] F. Ali, A. Nadjai, G. Silcock, A. Abu-Tair, Outcomes of a major research on fire resistance of concrete columns, Fire Safety Journal. 39 (2004) 433–445. https://doi.org/10.1016/J.FIRESAF.2004.02.004.

[5] M.Z. Naser, Deriving temperature-dependent material models for structural steel through artificial intelligence, Construction and Building Materials. 191 (2018) 56–68. https://doi.org/10.1016/J.CONBUILDMAT.2018.09.186.

[6] V. Kodur, F. Asce, M. Dwaikat, R. Fike, High-temperature properties of steel for fire resistance modeling of structures, Journal of Materials in Civil Engineering. 22 (2010) 423–434. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000041.

[7] F. Wald, L. Simões da Silva, D.B. Moore, T. Lennon, M. Chladná, A. Santiago, M. Beneš, L. Borges, Experimental behaviour of a steel structure under natural fire, Fire Safety Journal. 41 (2006) 509–522. https://doi.org/10.1016/J.FIRESAF.2006.05.006.

[8] W. Kumar, U.K. Sharma, M. Shome, Mechanical properties of conventional structural steel and fire-resistant steel at elevated temperatures, Journal of Constructional Steel Research. 181 (2021) 106615. https://doi.org/10.1016/J.JCSR.2021.106615.

[9] M. Kucukler, Z. Xing, L. Gardner, Behaviour and design of stainless steel I-section columns in fire, Journal of Constructional Steel Research. 165 (2020) 105890. https://doi.org/10.1016/J.JCSR.2019.105890.

[10] X. Qiang, F.S.K. Bijlaard, H. Kolstein, Post-fire performance of very high strength steel S960, Journal of Constructional Steel Research. 80 (2013) 235–242. https://doi.org/10.1016/J.JCSR.2012.09.002.

[11] M.B. Wong, Size effect on temperatures of structural steel in fire, Journal of Structural Engineering. 131 (2005) 16–20. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:1(16).

[12] L. Gardner, K.T. Ng, Temperature development in structural stainless steel sections exposed to fire, Fire Safety Journal. 41 (2006) 185–203. https://doi.org/10.1016/J.FIRESAF.2005.11.009.

[13] A.H. Buchanan, Fire performance of timber construction, n.d.

[14] B. Östman, D. Brandon, H. Frantzich, Fire safety engineering in timber buildings, Fire Safety Journal. 91 (2017) 11–20. https://doi.org/10.1016/J.FIRESAF.2017.05.002.

[15] P.B. Cachim, Using artificial neural networks for calculation of temperatures in timber under fire loading, Construction and Building Materials. 25 (2011) 4175–4180. https://doi.org/10.1016/J.CONBUILDMAT.2011.04.054.

[16] A. Daware, M.Z. Naser, Fire performance of masonry under various testing methods, Construction and Building Materials. 289 (2021). https://doi.org/10.1016/J.CONBUILDMAT.2021.123183.

[17] S. Russo, F. Sciarretta, Masonry exposed to high temperatures: Mechanical behaviour and properties—An overview, Fire Safety Journal. 55 (2013) 69–86. https://doi.org/10.1016/J.FIRESAF.2012.10.001.

[18] A. Nadjai, F. Ali, R. Jurgen, Compartment masonry walls in fire situations, Fire Technology. 42 (2006) 211–231. https://doi.org/10.1007/s10694-006-7509-6.

[19] G. Bertin, J.M. Most, M. Coutin, Wall fire behavior in an under-ventilated room, Fire Safety Journal. 37 (2002) 615–630. https://doi.org/10.1016/S0379-7112(02)00016-4.

[20] D. Seo, D. Kim, B. Kim, Y. Kwon, An Experimental Study on the Combustibles Investigation and Fire Growth Rate for Predicting Initial Fire Behavior in Building, Procedia Engineering. 62 (2013) 671–679. https://doi.org/10.1016/J.PROENG.2013.08.113.

[21] P.H. Thomas, M.L. Bullen, J.G. Quintiere, B.J. McCaffrey, Flashover and instabilities in fire behavior, Combustion and Flame. 38 (1980) 159–171. https://doi.org/10.1016/0010-2180(80)90048-6.

[22] G.N. Berlin, Managing the variability of fire behavior, Fire Technology. 16 (1980) 287–302. https://doi.org/10.1007/BF02473085.

[23] P.H. Thomas, Fire modeling and fire behavior in rooms, Symposium (International) on Combustion. 18 (1981) 503–518. https://doi.org/10.1016/S0082-0784(81)80056-2.

[24] J.G. Quintiere, Fire behavior in building compartments, Proceedings of the Combustion Institute. 29 (2002) 181–193. https://doi.org/10.1016/S1540-7489(02)80027-X.

[25] R.W. Bukowski, R.C. Spetzler, Analysis of the Happyland Social Club Fire with Hazard I, Journal of Fire Protection Engineering. 4 (1992) 117–130. https://doi.org/10.1177/104239159200400401.

[26] J.L. Bryan, A review of the examination and analysis of the dynamics of human behavior in the fire at the MGM Grand Hotel, Clark County, Nevada as determined from a selected questionnaire population, Fire Safety Journal. 5 (1983) 233–240. https://doi.org/10.1016/0379-7112(83)90021-8.

[27] E.R. Galea, L. Hulse, R. Day, A. Siddiqui, G. Sharp, The UK WTC 9/11 evacuation study: an overview of findings derived from first-hand interview data and computer modelling, Fire and Materials. 36 (2012) 501–521. https://doi.org/10.1002/fam.1070.

[28] R.F. Fahy, Overview of Major Studies on the Evacuation of World Trade Center Buildings 1 and 2 on 9/11, Fire Technology. 49 (2013) 643–655. https://doi.org/10.1007/s10694-012-0290-9.

[29] R.A. Kady, J. Davis, The effect of occupant characteristics on crawling speed in evacuation, Fire Safety Journal. 44 (2009) 451–457. https://doi.org/10.1016/J.FIRESAF.2008.09.010.

[30] Y. Shen, Q.S. Wang, W.G. Yan, J.H. Sun, K. Zhu, Evacuation Processes of Different Genders in Different Visibility Conditions – An Experimental Study, Procedia Engineering. 71 (2014) 65–74. https://doi.org/10.1016/J.PROENG.2014.04.009.

[31] A.R. Larusdottir, A.S. Dederichs, Evacuation of Children: Movement on Stairs and on Horizontal Plane, Fire Technology. 48 (2012) 43–53. https://doi.org/10.1007/S10694-010-0177-6/FIGURES/3.

[32] S. Okishio, T. Handa, An Example of Human Behavior in a Hotel Fire, Fire Science and Technology. 3 (1983) 131–140.

[33] Disability and health, (n.d.). https://www.who.int/news-room/fact-sheets/detail/disability-and-health (accessed September 12, 2021).

[34] P.G. Holborn, P.F. Nolan, J. Golt, An analysis of fatal unintentional dwelling fires investigated by London Fire Brigade between 1996 and 2000, Fire Safety Journal. 38 (2003) 1–42. https://doi.org/10.1016/S0379-7112(02)00049-8.

[35] S.W. Marshall, C.W. Runyan, S.I. Bangdiwala, M.A. Linzer, J.J. Sacks, J.D. Butts, Fatal residential fires: Who dies and who survives?, J Am Med Assoc. 279 (1998) 1633–1637. https://doi.org/10.1001/jama.279.20.1633.

[36] E. Smedberg, G. Carlsson, G. Gefenaite, B. Slaug, S.M. Schmidt, E. Ronchi, Perspectives on egressibility of older people with functional limitations, Fire Safety Journal. 127 (2022) 103509. https://doi.org/10.1016/J.FIRESAF.2021.103509.

[37] E.D. Kuligowski, R.D. Peacock, B.L. Hoskins, A review of building evacuation models, 2nd edition, technical note (NIST TN), Gaithersburg, MD, 2010. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=906951 (accessed September 12, 2021).

[38] D. Wasserman, A. Asch, J. Blustein, D. Putnam, Disability: Definitions, Models, Experience, Stanford Encyclopedia of Philosophy. (2016). https://plato.stanford.edu/archives/sum2016/entries/disability/.

[39] C.J. Kudlick, Disability History: Why We Need Another “Other,” The American Historical Review. 108 (2003) 763–793. https://doi.org/10.1086/ahr/108.3.763.

[40] P. Meldon, Disability History: The Disability Rights Movement, National Park Service: Telling All Americans’ Stories. (2019). https://www.nps.gov/articles/disabilityhistoryrightsmovement.htm.

[41] NIMH » About NIMH, (n.d.). https://www.nimh.nih.gov/about (accessed September 12, 2021).

[42] L. Vanhala, The Diffusion of Disability Rights in Europe, Human Rights Quarterly. 37 (2015) 831–853. http://www.polsoz.fu-berlin.de/en/v/trans- (accessed January 21, 2022).

[43] European Disability Forum | International Disability Alliance, (n.d.). https://www.internationaldisabilityalliance.org/EDF (accessed January 21, 2022).

[44] History | International Disability Alliance, (n.d.). https://www.internationaldisabilityalliance.org/content/history (accessed January 21, 2022).

[45] N. Mehrotra, Disability Rights Movements in India: Politics and Practice, Economic and Political Weekly. (2011) 65–75.

[46] T. Shakespeare, The Social Model of Disability, (n.d.) 195–203.

[47] B.A. Areheart, When Disability Isn’t Just Right: The Entrenchment of the Medical Model of Disability and the Goldilocks Dilemma, (2008) 181–232. http://disabilitylaw.blogspot.com/.

[48] P. Harpur, Embracing the new disability rights paradigm: the importance of the Convention on the Rights of Persons with Disabilities, Disability & Society. 27 (2011) 1–14. https://doi.org/10.1080/09687599.2012.631794.

[49] B. Williamson, Accessible America: A History of Disability and Design, New York University Press, New York, USA, 2019. https://www.degruyter.com/document/doi/10.18574/9781479855582/html (accessed January 21, 2022).

[50] T. Degener, International Disability Law - A New Legal Subject on the Rise: The Interrogational Experts' Meeting in Hong Kong, December 13-17, 1999, Berkeley Journal of International Law. 18 (2000) 180–195.

[51] C. McEwan, R. Butler, Disability and Development: Different Models, Different Places, Geography Compass. 1 (2007) 448–466. https://doi.org/10.1111/J.1749-8198.2007.00023.X.

[52] M. Leonardi, J. Bickenbach, T.B. Ustun, N. Kostanjsek, S. Chatterji, The definition of disability: what is in a name?, The Lancet. 368 (2006) 1219–1221. https://doi.org/10.1016/S0140-6736(06)69498-1.

[53] Public Law 101-325: ADA Amendments Act of 2008, U.S. Equal Employment Opportunity Commission, United States, 2008. https://www.eeoc.gov/statutes/ada-amendments-act-2008 (accessed September 12, 2021).

[54] L.M. Stough, C.B. Mayhorn, Population Segments with Disabilities, International Journal of Mass Emergencies and Disasters. 31 (2013) 384–402. https://www.researchgate.net/publication/268516017.

[55] Comprehensive Preparedness Guide (CPG) 101 Developing and Maintaining Emergency Operations Plans, 2010. https://www.ready.gov/sites/default/files/2019-06/comprehensive_preparedness_guide_developing_and_maintaining_emergency_operations_plans.pdf (accessed September 12, 2021).

[56] National Response Framework, Fourth Edition, 2019. https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf. (accessed September 12, 2021).

[57] International Classification of Functioning, Disability and Health (ICF), (n.d.). https://www.who.int/standards/classifications/international-classification-of-functioning-disability-and-health (accessed September 16, 2021).

[58] Disability, (n.d.). https://www.who.int/health-topics/disability#tab=tab_1 (accessed January 21, 2022).

[59] Definitions of Disability | Disabled World, (2021). https://www.disabled-world.com/definitions/disability-definitions.php (accessed January 21, 2022).

[60] D.E. Alley, V.W. Chang, The Changing Relationship of Obesity and Disability, 1988-2004, JAMA. 298 (2007) 2020–2027. https://doi.org/10.1001/JAMA.298.17.2020.

[61] D.E. Alley, V.W. Chang, J. Doshi, The shape of things to come: obesity, aging, and disability., LDI Issue Brief. 13 (2008) 1–4. https://europepmc.org/article/med/18354852 (accessed January 21, 2022).

[62] P. Clarke, J.A. Ailshire, M. Bader, J.D. Morenoff, J.S. House, Mobility Disability and the Urban Built Environment, American Journal of Epidemiology. 168 (2008) 506–513. https://doi.org/10.1093/AJE/KWN185.

[63] Health Canada, Natural and Built Environments. (2002).

[64] S. Srinivasan, L.R. O'Fallon, A. Dearry, Creating Healthy Communities, Healthy Homes, Healthy People: Initiating a Research Agenda on the Built Environment and Public Health, American Journal of Public Health (AJPH). 93 (2011) 1446–1450. https://doi.org/10.2105/AJPH.93.9.1446.

[65] R. Imrie, M. Kumar, Focusing on Disability and Access in the Built Environment, Http://Dx.Doi.Org/10.1080/09687599826687. 13 (2010) 357–374. https://doi.org/10.1080/09687599826687.

[66] R. Cervero, M. Duncan, Walking, Bicycling, and Urban Landscapes: Evidence From the San Francisco Bay Area, American Journal of Public Health (AJPH). 93 (2011) 1478–1483. https://doi.org/10.2105/AJPH.93.9.1478.

[67] R. Boer, Y. Zheng, A. Overton, G.K. Ridgeway, D.A. Cohen, Neighborhood Design and Walking Trips in Ten U.S. Metropolitan Areas, American Journal of Preventative Medicine. 32 (2007) 298–304. https://doi.org/10.1016/j.amepre.2006.12.012.

[68] N. Humpel, N. Owen, E. Leslie, Environmental factors associated with adults' participation in physical activity: A review, American Journal of Preventive Medicine. 22 (2002) 188–199. https://doi.org/10.1016/S0749-3797(01)00426-3.

[69] C.L. Addy, D.K. Wilson, K.A. Kirtland, B.E. Ainsworth, P. Sharpe, D. Kimsey, Associations of Perceived Social and Physical Environmental Supports With Physical Activity and Walking Behavior, American Journal of Public Health (AJPH). 94 (2011) 440–443. https://doi.org/10.2105/AJPH.94.3.440.

[70] D. Alexander, J.C. Gaillard, B. Wisner, Disability and disaster, Handbook of Hazards and Disaster Risk Reduction. (2012) 413–423. https://doi.org/10.4324/9781315208558-9.

[71] L. Peek, L.M. Stough, Children with disabilities in the context of disaster: A social vulnerability perspective, Child Development. 81 (2010) 1260–1270. https://doi.org/10.1111/j.1467-8624.2010.01466.x.

[72] L.M. Stough, I. Kelman, People with Disabilities and Disasters, Handbook of Disaster Research. (2018) 225–242. https://doi.org/10.1007/978-3-319-63254-4_12.

[73] G. Corbett, How the Design of the World Trade Center Claimed Lives on 9/11, History. (2021). https://www.history.com/news/world-trade-center-stairwell-design-9-11 (accessed September 12, 2021).

[74] M.H. Fox, G.W. White, C. Rooney, J.L. Rowland, Disaster Preparedness and Response for Persons With Mobility Impairments: Results From the University of Kansas Nobody Left Behind Study, Http://Dx.Doi.Org/10.1177/10442073070170040201. 17 (2007) 196–205. https://doi.org/10.1177/10442073070170040201.

[75] L. Hemingway, M. Priestley, View of Natural Hazards, Human Vulnerability and Disabling Societies: A Disaster for Disabled People?, Review of Disability Studies: An International Journal. 2 (2014). https://www.rdsjournal.org/index.php/journal/article/view/337/1037 (accessed September 12, 2021).

[76] J. Cosgrave, Tsunami Evaluation Coalition: Initial Findings, 2005. https://www.researchgate.net/publication/215717804_Tsunami_Evaluation_Coalition_Initial_Findings (accessed September 12, 2021).

[77] K. Christensen, S. Sharifi, A. Chen, Considering Individuals with Disabilities in Building Evacuation: Agent-Based Simulation Study, in: Transportation Research Board, Washington D.C., 2013. https://www.researchgate.net/publication/284166529_Considering_Individuals_with_Disabilities_in_Building_Evacuation_Agent-Based_Simulation_Study (accessed September 15, 2021).

[78] J.D. Averill, D.S. Mileti, R.D. Peacock, E.D. Kuligowski, N. Groner, G. Proulx, P.A. Reneke, H.E. Nelson, Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Occupant Behavior, Egress, and Emergency Communications, Washington D.C., 2005. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=101046 (accessed September 13, 2021).

[79] G. Proulx, R.F. Fahy, Account Analysis of WTC Survivors, in: Proceedings of the 3rd International Symposium on Human Behavior in FIre, Belfast, UK, 2004: pp. 203–214. http://irc.nrc-cnrc.gc.ca/ircpubs (accessed January 26, 2022).

[80] R.R. Gershon, K.A. Qureshi, R. Msn, M.S. Rubin, V.H. Raveis, Factors Associated with High-Rise Evacuation: Qualitative Results from the World Trade Center Evacuation Study, 22 (2006) 165–173. http://pdm.medicine.wisc.edu (accessed January 26, 2022).

[81] Y. Zang, Q. Mei, S. Liu, Evacuation simulation of a high-rise teaching building considering the influence of obstacles , Simulation Modelling Practice and Theory. 112 (2021). https://reader.elsevier.com/reader/sd/pii/S1569190X2100068X?token=0151591759E95F2C98880870014AEF15BDAE943F5739143C81E3E6B3127D549708160F75D22119F897ED06AD3743357F&originRegion=us-east-1&originCreation=20220216194525 (accessed February 15, 2022).

[82] X. Zhang, Study on rapid evacuation in high-rise buildings, Engineering Science and Technology, an International Journal. 20 (2017) 1203–1210. https://doi.org/10.1016/J.JESTCH.2017.04.007.

[83] F. Huo, W. Song, L. Chen, C. Liu, K.M. Liew, Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building, Safety Science. 86 (2016) 165–173. https://doi.org/10.1016/J.SSCI.2016.02.025.

[84] Z. Huang, R. Fan, Z. Fang, R. Ye, X. Li, Q. Xu, H. Gao, Y. Gao, Performance of occupant evacuation in a super high-rise building up to 583 m, Physica A: Statistical Mechanics and Its Applications. 589 (2022). https://doi.org/10.1016/J.PHYSA.2021.126643.

[85] M. Gerges, P. Demian, Z. Adamu, Customising evacuation instructions for high-rise residential occupants to expedite fire egress: Results from agent-based simulation, Fire. 4 (2021). https://doi.org/10.3390/FIRE4020021.

[86] Y. Zeng, W. Song, S. Jin, R. Ye, X. Liu, Experimental study on walking preference during high-rise stair evacuation under different ground illuminations, Physica A:

Statistical Mechanics and Its Applications. 479 (2017) 26–37. https://doi.org/10.1016/J.PHYSA.2017.02.060.

[87] J.H.T. Lam, J.K.K. Yuen, E.W.M. Lee, R.Y.Y. Lee, Experimental study on upward movement in a high-rise building, Safety Science. 70 (2014) 397–405. https://doi.org/10.1016/J.SSCI.2014.07.011.

[88] M. Selçuk Satir, A. Yağmur Toprakli, A Review of Design Parameters for Safe Evacuation in High-Rise Buildings, Gazi University Journal of Science, Part B: Art, Humanities, Design and Planning. 8 (2020) 553–563. http://dergipark.gov.tr/gujsb (accessed January 26, 2022).

[89] Z.M. Fang, W.G. Song, Z.J. Li, W. Tian, W. Lv, J. Ma, X. Xiao, Experimental study on evacuation process in a stairwell of a high-rise building, Building and Environment. 47 (2012) 316–321. https://doi.org/10.1016/J.BUILDENV.2011.07.009.

[90] J. Ma, W.G. Song, W. Tian, S.M. Lo, G.X. Liao, Experimental study on an ultra high-rise building evacuation in China, Safety Science. 50 (2012) 1665–1674. https://doi.org/10.1016/J.SSCI.2011.12.018.

[91] R.D. Peacock, B.L. Hoskins, E.D. Kuligowski, Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories, Safety Science. 50 (2012) 1655–1664. https://doi.org/10.1016/J.SSCI.2012.01.003.

[92] J.H. Choi, E.R. Galea, W.H. Hong, Individual Stair Ascent and Descent Walk Speeds Measured in a Korean High-Rise Building, Fire Technology. 50 (2014) 267–295. https://doi.org/10.1007/S10694-013-0371-4/FIGURES/10.

[93] F. Zhiming, G. Huisheng, H. Zhongyi, Y. Rui, L. Xiaolian, X. Qingfeng, X. Xingpeng, H. Nan, Experimental study on determinants of the evacuation performance in the super-high rise building, Arxiv.Org. (n.d.). https://arxiv.org/abs/2004.04310 (accessed February 2, 2022).

[94] A. Mossberg, D. Nilsson, K. Andrée, Unannounced Evacuation Experiment in a High-Rise Hotel Building with Evacuation Elevators: A Study of Evacuation Behaviour Using Eye-Tracking, Fire Technology. 57 (2021) 1259–1281. https://doi.org/10.1007/S10694-020-01046-1/TABLES/7.

[95] W. Bai, Y. Huo, G.W. Zou, Y. Gao, Simulation of fire evacuation in a high-rise office building, in: IEEE International Conference on Industrial Engineering and Engineering Management, IEEE, 2016. https://doi.org/10.1109/IEEM.2015.7385938.

[96] R.A. Kady, The development of a movement–density relationship for people going on four in evacuation, Safety Science. 50 (2012) 253–258. https://doi.org/10.1016/J.SSCI.2011.08.058.

[97] N. Ding, T. Chen, Y. Zhu, Y. Lu, State-of-the-art high-rise building emergency evacuation behavior, Physica A: Statistical Mechanics and Its Applications. 561 (2021) 125168. https://doi.org/10.1016/J.PHYSA.2020.125168.

[98] W. Xie, E.W.M. Lee, Y. Cheng, M. Shi, R. Cao, Y. Zhang, Evacuation performance of individuals and social groups under different visibility conditions: Experiments and surveys, International Journal of Disaster Risk Reduction. 47 (2020) 101527. https://doi.org/10.1016/J.IJDRR.2020.101527.

[99] M. Isobe, D. Helbing, T. Nagatani, Experiment, theory, and simulation of the evacuation of a room without visibility, Physical Review E. 69 (2004) 066132. https://doi.org/10.1103/PhysRevE.69.066132.

[100] R. Nagai, T. Nagatani, M. Isobe, T. Adachi, Effect of exit configuration on evacuation of a room without visibility, Physica A: Statistical Mechanics and Its Applications. 343 (2004) 712–724. https://doi.org/10.1016/j.physa.2004.06.061.

[101] M. Kobes, I. Helsloot, B. de Vries, J.G. Post, N. Oberijé, K. Groenewegen, Way finding during fire evacuation; an analysis of unannounced fire drills in a hotel at night, Building and Environment. 45 (2010) 537–548. https://doi.org/10.1016/j.buildenv.2009.07.004.

[102] J. Chen, J. Wang, B. Wang, R. Liu, Q. Wang, An experimental study of visibility effect on evacuation speed on stairs, Fire Safety Journal. 96 (2018) 189–202. https://doi.org/10.1016/J.FIRESAF.2017.11.010.

[103] N. Ding, H. Zhang, T. Chen, Experimental Study of Egress Selection Behavior Between Stairs and Elevators During High-Rise Building Evacuation, Fire Technology. 55 (2019) 1649–1670. https://doi.org/10.1007/S10694-019-00822-Y/TABLES/10.

[104] J. Yan, G. He, A. Basiri, Investigation of Potential Cognition Factors Correlated to Fire Evacuation, in: German Conference on Spatial Cognition, 2020: pp. 143–159. https://doi.org/10.1007/978-3-030-57983-8_12.

[105] L. Benthorn, H. Frantzich, Fire alarm in a public building: How do people evaluate information and choose an evacuation exit?, Fire and Materials. 23 (1999) 311–315.

https://doi.org/10.1002/(SICI)1099-1018(199911/12)23:6<311::AID-FAM704>3.0.CO;2-J.

[106] T.J. Shields, K.E. Boyce, A study of evacuation from large retail stores, Fire Safety Journal. 35 (2000) 25–49. https://doi.org/10.1016/S0379-7112(00)00013-8.

[107] S. Horiuchi, Y. Murozaki, A. Hokugo, A Case Study of Fire and Evacuation in a Multi-purpose Office Building, Osaka, Japan, Fire Safety Science. (1986) 523–532. https://doi.org/10.3801/IAFSS.FSS.1-523.

[108] M.A. Ayoub, Simulation modeling and analysis in safety. Part I: Planning and design, Journal of Occupational Accidents. 3 (1980) 3–20. https://doi.org/10.1016/0376-6349(80)90013-9.

[109] J.M. Watts, Computer Models for Evacuation Analysis, Fire Safety Journal. 12 (1987) 237–245.

[110] F. Tang, A. Ren, GIS-based 3D evacuation simulation for indoor fire, Building and Environment. 49 (2012) 193–202. https://doi.org/10.1016/J.BUILDENV.2011.09.021.

[111] M.H. Nguyen, T.V. Ho, J.D. Zucker, Integration of Smoke Effect and Blind Evacuation Strategy (SEBES) within fire evacuation simulation, Simulation Modelling Practice and Theory. 36 (2013) 44–59. https://doi.org/10.1016/J.SIMPAT.2013.04.001.

[112] L. Filippidis, E.R. Galea, S. Gwynne, P.J. Lawrence, Representing the Influence of Signage on Evacuation Behavior within an Evacuation Model:, Journal of Fire Protection Engineering. 16 (2006) 37–73. https://doi.org/10.1177/1042391506054298.

[113] R.F. Cao, E.W.M. Lee, A.C.Y. Yuen, Q.N. Chan, W. Xie, M. Shi, G.H. Yeoh, Development of an evacuation model considering the impact of stress variation on evacuees under fire emergency, Safety Science. 138 (2021). https://doi.org/10.1016/J.SSCI.2021.105232.

[114] L. Tan, M. Hu, H. Lin, Agent-based simulation of building evacuation: Combining human behavior with predictable spatial accessibility in a fire emergency, Information Sciences. 295 (2015) 53–66. https://doi.org/10.1016/J.INS.2014.09.029.

[115] E. Kuligowski, Predicting Human Behavior During Fires, Fire Technology. 49 (2013) 101–120. https://doi.org/10.1007/S10694-011-0245-6/FIGURES/1.

[116] W.F. Yuan, K.H. Tan, An evacuation model using cellular automata, Physica A: Statistical Mechanics and Its Applications. 384 (2007) 549–566. https://doi.org/10.1016/J.PHYSA.2007.05.055.

[117] J. Joo, N. Kim, R.A. Wysk, L. Rothrock, Y.J. Son, Y.G. Oh, S. Lee, Agent-based simulation of affordance-based human behaviors in emergency evacuation, Simulation Modelling Practice and Theory. 32 (2013) 99–115. https://doi.org/10.1016/J.SIMPAT.2012.12.007.

[118] T.T. Pires, An approach for modeling human cognitive behavior in evacuation models, Fire Safety Journal. 40 (2005) 177–189. https://doi.org/10.1016/J.FIRESAF.2004.10.004.

[119] A. Ren, C. Chen, Y. Luo, Simulation of Emergency Evacuation in Virtual Reality, Tsinghua Science and Technology. 13 (2008) 674–680. https://doi.org/10.1016/S1007-0214(08)70110-X.

[120] S. Kasereka, N. Kasoro, K. Kyamakya, E.F. Doungmo Goufo, A.P. Chokki, M. v. Yengo, Agent-Based Modelling and Simulation for evacuation of people from a building in case of fire, Procedia Computer Science. 130 (2018) 10–17. https://doi.org/10.1016/J.PROCS.2018.04.006.

[121] L. Cao, J. Lin, N. Li, A virtual reality based study of indoor fire evacuation after active or passive spatial exploration, Computers in Human Behavior. 90 (2019) 37–45. https://doi.org/10.1016/j.chb.2018.08.041.

[122] R. Lovreglio, E. Ronchi, D. Nilsson, A model of the decision-making process during pre-evacuation, Fire Safety Journal. 78 (2015) 168–179. https://doi.org/10.1016/J.FIRESAF.2015.07.001.

[123] World Report on Disability 2011, Geneva, Switzerland, 2011.

[124] K. Boyce, Safe evacuation for all - Fact or Fantasy? Past experiences, current understanding and future challenges, Fire Safety Journal. 91 (2017) 28–40. https://doi.org/10.1016/J.FIRESAF.2017.05.004.

[125] BSi Committee FSH/14, BS 9999:2008 Code of Practice for Fire Safety in the Design, Management, and Use of Buildings, 2008.

[126] P. Geoerg, F. Berchtold, S. Gwynne, K. Boyce, S. Holl, A. Hofmann, Engineering egress data considering pedestrians with reduced mobility, Fire and Materials. 43 (2019) 759–781. https://doi.org/10.1002/FAM.2736.

[127] O. Bukvic, G. Carlsson, G. Gefenaite, B. Slaug, S.M. Schmidt, E. Ronchi, A review on the role of functional limitations on evacuation performance using the International Classification of Functioning, Disability and Health, Fire Technology. 57 (2020) 507–528. https://doi.org/10.1007/S10694-020-01034-5/TABLES/1.

[128] T. Shimada, H. Naoi, An Experimental Study on the Evacuation Flow of Crowd Including Wheelchair Users, Fire Science and Technology. 25 (2006) 1–14. https://doi.org/10.3210/FST.25.1.

[129] S. Tsuchiya, Y. Hasemi, Y. Furukawa, Evacuation Characteristics of Group with Wheelchair Users, Fire Safety Science. (n.d.).

[130] P.R. DeCicco, Evacuation from Fires, Routledge, New York, 2018. https://books.google.com/books?hl=en&lr=&id=6caWDwAAQBAJ&oi=fnd&pg=PT116&dq=wheelchair+evacuation&ots=AkmAb5lb-c&sig=y0SWYuWvRYW73GBSfYm6dgtt1zA#v=onepage&q=wheelchair%20evacuation&f=false (accessed February 10, 2022).

[131] H. Pan, J. Zhang, W. Song, B. Yao, Fundamental diagram of pedestrian flow including wheelchair users in straight corridors, Journal of Statistical Mechanics: Theory and Experiment. 2021 (2021). https://doi.org/10.1088/1742-5468/ABE93F.

[132] H. Pan, J. Zhang, W. Song, Experimental study of pedestrian flow mixed with wheelchair users through funnel-shaped bottlenecks, Journal of Statistical Mechanics: Theory and Experiment. 2020 (2020). https://doi.org/10.1088/1742-5468/AB6B1C.

[133] B. Zou, C. Lu, Y. Li, Simulation of a hospital evacuation including wheelchairs based on modified cellular automata, Simulation Modelling Practice and Theory. 99 (2020). https://doi.org/10.1016/J.SIMPAT.2019.102018.

[134] L. Catovic, C. Alniemi, E. Ronchi, A survey on the factors affecting horizontal assisted evacuation in hospitals, Journal of Physics: Conference Series. 1107 (2018). https://doi.org/10.1088/1742-6596/1107/7/072001.

[135] V. Alonso-Gutierrez, E. Ronchi, The simulation of assisted evacuation in hospitals, in: G. Balint, B. Antala, C. Carty, J.-M.A. Mabieme, I.B. Amar, A. Kaplanova (Eds.), Fire and Evacuation Modelling Technical Conference, FEMTC, Torremolinos, Spain, 2016: pp. 343–354. https://doi.org/10.2/JQUERY.MIN.JS.

[136] J. Koo, Y.S. Kim, B.I. Kim, K.M. Christensen, A comparative study of evacuation strategies for people with disabilities in high-rise building evacuation, Expert Systems with Applications. 40 (2013) 408–417. https://doi.org/10.1016/J.ESWA.2012.07.017.

[137] L.A. McClure, M.L. Boninger, M.L. Oyster, M.J. Roach, J. Nagy, G. Nemunaitis, Emergency Evacuation Readiness of Full-Time Wheelchair Users With Spinal Cord Injury, Archives of Physical Medicine and Rehabilitation. 92 (2011) 491–498. https://doi.org/10.1016/J.APMR.2010.08.030.

[138] J.S. Tubbs, B. Meacham, A. Kimball, Evacuation Design Strategies and Considerations for Tall Buildings: Suggest...: EBSCOhost, ASHRAE Transactions. 115 (2009) 182–190. https://web.p.ebscohost.com/ehost/detail/detail?vid=0&sid=fbd2d799-6d5f-460f-852a-c096e09ab2f6%40redis&bdata=#db=a2h&AN=40505682 (accessed February 10, 2022).

[139] E. Kuligowski, R. Peacock, E. Wiess, B. Hoskins, Stair evacuation of older adults and people with mobility impairments, Fire Safety Journal. 62 (2013) 230–237. https://doi.org/10.1016/J.FIRESAF.2013.09.027.

[140] E. Kuligowski, R. Peacock, E. Wiess, B. Hoskins, Stair evacuation of people with mobility impairments, Fire and Materials. 39 (2015) 371–384. https://doi.org/10.1002/FAM.2247.

[141] T.J. Shields, K.E. Boyce, N. McConnell, The behaviour and evacuation experiences of WTC 9/11 evacuees with self-designated mobility impairments, Fire Safety Journal. 44 (2009) 881–893. https://doi.org/10.1016/J.FIRESAF.2009.04.004.

[142] E.D. Kuligowski, B. Hoskins, R.D. Peacock, E.A. Wiess, Evacuation of People with Disabilities on Stairs, in: Human Behavior in Fire Symposium, National Institute of Standards and Technology , Cambridge, 2012. https://www.nist.gov/publications/evacuation-people-disabilities-stairs (accessed February 10, 2022).

[143] R.D. Peacock, P.A. Reneke, E.D. Kuligowski, C.R. Hagwood, Movement on Stairs During Building Evacuations, Fire Technology. 53 (2017) 845–871. https://doi.org/10.1007/S10694-016-0603-5/FIGURES/7.

[144] M. Hashemi, Emergency evacuation of people with disabilities: A survey of drills, simulations, and accessibility, Cogent Engineering. 5 (2018) 1–20. https://doi.org/10.1080/23311916.2018.1506304.

[145] C.S. Jiang, S.Z. Zheng, F. Yuan, H.J. Jia, Z.N. Zhan, J.J. Wang, Experimental assessment on the moving capabilities of mobility-impaired disabled, Safety Science. 50 (2012) 974–985. https://doi.org/10.1016/J.SSCI.2011.12.023.

[146] R.D. Peacock, NIST Special Publication 1620: Summary of NIST/GSA Cooperative Research of the Use of Elevators During Fire Emergencies, 2009. https://doi.org/10.6028/NIST.SP.1620.

[147] K. Butler, E. Kuligowski, S. Furman, R. Peacock, Perspectives of occupants with mobility impairments on evacuation methods for use during fire emergencies, Fire Safety Journal. 91 (2017) 955–963. https://doi.org/10.1016/J.FIRESAF.2017.04.025.

[148] M.T. Kinateder, H. Omori, E.D. Kuligowski, NIST Technical Note 1825: The Use of Elevators for Evacuation in Fire Emergencies in International Buildings, 2014. https://doi.org/10.6028/NIST.TN.1825.

[149] M. Szénay, M. Lopušniak, Analysis of movement of persons with disabilities during evacuation by lift, Pollack Periodica. 15 (2020) 209–220. https://doi.org/10.1556/606.2020.15.1.20.

[150] K. Andrée, D. Nilsson, J. Eriksson, Evacuation experiments in a virtual reality high-rise building: exit choice and waiting time for evacuation elevators, Fire and Materials. 40 (2016) 554–567. https://doi.org/10.1002/fam.2310.

[151] A. Mossberg, D. Nilsson, J. Wahlqvist, Evacuation elevators in an underground metro station: A Virtual Reality evacuation experiment, Fire Safety Journal. 120 (2021) 103091. https://doi.org/10.1016/J.FIRESAF.2020.103091.

[152] D. Turhanlar, Y. He, G. Stone, The use of Lifts for Emergency Evacuation - A Reliability Study, Procedia Engineering. 62 (2013) 680–689. https://doi.org/10.1016/J.PROENG.2013.08.114.

[153] P. G., R. IMA, Occupant Behavior and Evacuation During the Chicago Cook County Administration Building Fire, Journal of Fire Protection Engineering. 16 (2006) 283–309.

http://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_69723_35 (accessed February 10, 2022).

[154] J.D. Averill, D.S. Mileti, R.D. Peacock, E.D. Kuligowski, N. Groner, G. Proulx, P.A. Reneke, H.E. Nelson, Federal building and fire safety investigation of the World Trade Center Disaster: Occupant behavior, egress, and emergency communications, Nist Ncstar 1-7. (2005) 1–298.

[155] N.C. McConnell, K.E. Boyce, Refuge areas and vertical evacuation of multistorey buildings: the end users' perspectives, Fire and Materials. 39 (2015) 396–406. https://doi.org/10.1002/FAM.2205.

[156] E. Ronchi, D. Nilsson, Fire evacuation in high-rise buildings: a review of human behaviour and modelling research, Fire Science Reviews. 2 (2013) 1–21. https://doi.org/10.1186/2193-0414-2-7.

[157] A. Soltanzadeh, M. Alaghmandan, H. Soltanzadeh, Performance evaluation of refuge floors in combination with egress components in high-rise buildings, Journal of Building Engineering. 19 (2018) 519–529. https://doi.org/10.1016/J.JOBE.2018.05.029.

[158] Guide to the ABA Chapter 4: Accessible Means of Egress, U.S. Access Board. (n.d.). https://www.access-board.gov/aba/guides/chapter-4-accessible-means-of-egress/ (accessed February 10, 2022).

[159] Area of refuge requirements - IBC, NFPA, & ADA compliance requirements by state | Cornell Communications Emergency Call Systems, Cornell Communications. (2022). https://www.cornell.com/areaofrefugerequirements (accessed February 10, 2022).

[160] J.G. Sørensen, A.S. Dederichs, Evacuation characteristics of visually impaired people – a qualitative and quantitative study, Fire and Materials. 39 (2015) 385–395. https://doi.org/10.1002/FAM.2200.

[161] J.G. Sorensen, Evacuation of People with Visual Impairments, APA, 2014.

[162] K. Lena, A. Kristin, B. Staffan, W. Sara, S. Elena, How Do People with Disabilities Consider Fire Safety and Evacuation Possibilities in Historical Buildings?-A Swedish Case Study, Fire Technology. 48 (2012) 27–41. https://doi.org/10.1007/S10694-010-0199-0/FIGURES/4.

[163] G.; Proulx, J. Pineau, Internal Report No. 712: Review of Evacuation Strategies for Occupants with Disabilities, Ottawa, 1996. www.nrc.ca/irc/ircpubs (accessed February 10, 2022).

[164] D.A. Samoshin, R.N. Istratov, The Characteristics of Blind and Visually Impaired People Evacuation in Case of Fire, in: 11th International Symposium on Fire Safety Science, Moscow, 2014. https://doi.org/10.3801/IAFSS.FSS.11-1160.

[165] S. Zhang, J. Zeng, X. Liu, S. Ding, Effect of obstacle density on the travel time of the visually impaired people, Fire and Materials. 43 (2019) 162–168. https://doi.org/10.1002/FAM.2681.

[166] N. Egodage, F.N. Abdeen, P. Sridarran, Fire emergency evacuation procedures for differently-abled community in high-rise buildings, Journal of Facilities Management. 18 (2020) 505–519. https://doi.org/10.1108/JFM-07-2020-0043/FULL/PDF.

[167] R.W. Shearer, Fire Protection and Safety for the Handicapped, Fire Chief Magazine. (1984) 53–54.

[168] B. Johnson, Evacuation Techniques for Disabled Persons: Research Summary and Guidelines, Ottawa, 1983.

[169] H.A. Burkart, L.J. Carpenter, N.A. Keenan, V.F. Nogarotto, Evaluating the Regulation of Alerting Systems to Facilitate the Evacuation of the Deaf in Australia, 2005.

[170] Fire At Russian School For Deaf Kills 28 , CBS News. (2003). https://www.cbsnews.com/news/fire-at-russian-school-for-deaf-kills-28/ (accessed February 10, 2022).

[171] R.J. Roby, Smoke Detector Alert for the Deaf, Columbia, MD, 2005.

[172] V.C. Bryan, G. Penney, L. Andrews, M.R. Russo, Empirical Study Using Alternative Early Warning Systems to Address Fire in the Homes of Deaf or Hard-of-Hearing Individuals, in: Handbook of Research on Education and Technology in a Changing Society, 2014: pp. 367–379. https://doi.org/10.4018/978-1-4666-6046-5.ch028.

[173] L. Willoughby, Review of the Fire Alarm Scheme for Deaf and hard of hearing Victorians, Melbourne, 2009. https://www.academia.edu/710586/Review_of_the_Fire_Alarm_Scheme_for_Deaf_and_hard_of_hearing_Victorians (accessed February 10, 2022).

[174] I. Thomas, D. Bruck, E. Nober, J. du Bois, Strobe Lights, Pillow Shakers and Bed Shakers as Smoke Alarm Signals, Fire Safety Science. (2008) 415–423. https://doi.org/10.3801/IAFSS.FSS.9-415.

[175] M. Choi, S. Lee, S. Hwang, M. Park, H.S. Lee, Comparison of emergency response abilities and evacuation performance involving vulnerable occupants in building

fire situations, Sustainability (Switzerland). 12 (2020) 1–19. https://doi.org/10.3390/SU12010087.

[176] K. Christensen, Y. Sasaki, Agent-Based Emergency Evacuation Simulation with Individuals with Disabilities in the Population, Journal of Artificial Societies and Social Simulation. 11 (2008). https://www.researchgate.net/publication/5140552_Agent-Based_Emergency_Evacuation_Simulation_with_Individuals_with_Disabilities_in_the_Population (accessed September 15, 2021).

[177] Pathfinder | Thunderhead Engineering, (n.d.). https://www.thunderheadeng.com/pathfinder/ (accessed February 10, 2022).

[178] M. Stefanidou, S. Athanaselis, C. Spiliopoulou, Health Impacts of Fire Smoke Inhalation, Http://Dx.Doi.Org/10.1080/08958370801975311. 20 (2008) 761–766. https://doi.org/10.1080/08958370801975311.

[179] A. Alarifi, H. Phylaktou, G. Andrews, What Kills People in a Fire? Heat or Smoke?, in: The 9th Saudi Students Conference, Birmingham, UK, 2016.

[180] Z. Feng, V.A. González, R. Amor, R. Lovreglio, G. Cabrera-Guerrero, Immersive virtual reality serious games for evacuation training and research: A systematic literature review, Computers & Education. 127 (2018) 252–266. https://doi.org/10.1016/j.compedu.2018.09.002.

[181] M. Kinateder, E. Ronchi, D. Nilsson, M. Kobes, M. Müller, P. Pauli, A. Mühlberger, Virtual Reality for Fire Evacuation Research, in: 2014: pp. 313–321. https://doi.org/10.15439/2014F94.

[182] E.D. Kuligowski, Computer evacuation models for buildings, SFPE Handbook of Fire Protection Engineering, Fifth Edition. (2016) 2152–2180. https://doi.org/10.1007/978-1-4939-2565-0_60/FIGURES/15.

[183] S.M.V. Gwynne, K.E. Boyce, Engineering data, SFPE Handbook of Fire Protection Engineering, Fifth Edition. (2016) 2429–2551. https://doi.org/10.1007/978-1-4939-2565-0_64/FIGURES/21.

[184] Pathfinder User Manual | Thunderhead Support, (2022). https://support.thunderheadeng.com/docs/pathfinder/2022-1/user-manual/ (accessed May 21, 2022).

[185] Clemson Home, » Lightsey Bridge I, (n.d.). https://housing.clemson.edu/building/lightsey-bridge-i/ (accessed May 18, 2022).

[186] M.R. Simon, Clemson University begins planning for 430 beds of student housing, Bryan Mall renovations, Greenville News. (2019).

[187] Lightsey Bridge Cribs - Craig Gaulden Davis Architecture, (2015). https://cgdarch.com/lightsey-bridge-cribs/ (accessed May 18, 2022).

[188] C.H. Facility Support Services, University Facilities, Building Floor Plans, (2022). https://cufacilities.sites.clemson.edu/floorPlans/ (accessed May 18, 2022).

[189] What Are The ADA Ramp Requirements | BraunAbility, (n.d.). https://www.braunability.com/us/en/commercial/white-papers/ada-ramp-requirements.html (accessed May 19, 2022).

[190] Standard Door Size | Standard Door Height and Width | Rustica, (n.d.). https://rustica.com/standard-door-sizes/ (accessed May 19, 2022).

[191] 2nd Session 101st Congress, Public Law 101-336: Americans with Disabilities Act of 1990, ada.gov, United States, 1990.

[192] Chapter 4: Ramps and Curb Ramps, (n.d.). https://www.access-board.gov/ada/guides/chapter-4-ramps-and-curb-ramps/ (accessed May 19, 2022).

[193] Department of Justice ADA Title III Regulation 28 CFR Part 36 (1991), (n.d.). https://www.ada.gov/reg3a.html#Anchor-18203 (accessed May 19, 2022).

[194] Rehabilitation Act of 1973, Section 504, n.d. https://www.hud.gov/program_offices/fair_housing_equal_opp/disabilities/sect504faq (accessed September 17, 2021).

[195] FEMA, Residential Building Fires Involving Individuals with Physical Disabilities, 2011.

[196] D.D. Drysdale, Fire Dynamics, Encyclopedia of Physical Science and Technology. (2003) 869–892. https://doi.org/10.1016/B0-12-227410-5/00244-1.

[197] R. Lovreglio, E. Kuligowski, S. Gwynne, K. Boyce, A pre-evacuation database for use in egress simulations, Fire Safety Journal. 105 (2019) 107–128. https://doi.org/10.1016/J.FIRESAF.2018.12.009.

[198] Fire Safety Policies | Clemson University, South Carolina, (n.d.). https://www.clemson.edu/cusafety/cufd/fire-safety.html (accessed June 2, 2022).

[199] S. Pheasant, C.M. Haslegrave, Bodyspace, CRC Press, 2018. https://doi.org/10.1201/9781315375212.

[200] Pathfinder Verification and Validation | Thunderhead Support, (n.d.). https://support.thunderheadeng.com/docs/pathfinder/2022-1/verification-validation/ (accessed June 8, 2022).

[201] A.C.B. Coutinho, F.R. Neto, C.E.V. Perna, Determination of normative values for 20 min exercise of wheelchair propulsion by spinal cord injury patients, Spinal Cord 2013 51:10. 51 (2013) 755–760. https://doi.org/10.1038/sc.2013.89.

[202] Mobility Device Statistics: United States | Disabled World, (n.d.). https://www.disabled-world.com/disability/statistics/mobility-stats.php (accessed June 5, 2022).

[203] R.H. Demling, Smoke Inhalation Lung Injury: An Update, Eplasty. 8 (2008) e27. /pmc/articles/PMC2396464/ (accessed June 8, 2022).

[204] N. Bénichou, M.A. Sultan, Fire resistance performance of lightweight wood-framed assemblies, Fire Technology. 36 (2000) 184–219. https://doi.org/10.1023/A:1015414827695.

[205] E. Ronchi, M.J. Kinsey, Evacuation models of the future: Insights from an online survey of user's experiences and needs, in: J. Capote, D. Alvear (Eds.), Proceedings of the Advanced Research Workshop: "Evacuation and Human Behaviour in Emergency Situations," Santander, Spain, 2011: pp. 145–155.

[206] M. Kobes, I. Helsloot, B. de Vries, J.G. Post, Building safety and human behaviour in fire: A literature review, Fire Safety Journal. 45 (2010) 1–11. https://doi.org/10.1016/J.FIRESAF.2009.08.005.

[207] M. Forssberg, J. Kjellström, H. Frantzich, A. Mossberg, D. Nilsson, The Variation of Pre-movement Time in Building Evacuation, Fire Technology. 55 (2019) 2491–2513. https://doi.org/10.1007/s10694-019-00881-1.

[208] Use a Blueprint to Sketch a Model | Thunderhead Support, (2022). https://support.thunderheadeng.com/tutorials/pathfinder/blueprint-to-sketch-model/ (accessed May 11, 2022).

[209] Y. Zheng, B. Jia, X.G. Li, R. Jiang, Evacuation dynamics considering pedestrians' movement behavior change with fire and smoke spreading, Safety Science. 92 (2017) 180–189. https://doi.org/10.1016/J.SSCI.2016.10.009.

[210] K.M. Christensen, M.E. Blair, J.M. Holt, The Built Environment, Evacuations, and Individuals With Disabilities A Guiding Framework for Disaster Policy and Preparation, n.d.

[211] N.A. Davis, Invisible Disability, Ethics. 116 (2005) 153–213. https://doi.org/10.1086/453151.

[212] L. Mullins, M. Preyde, The lived experience of students with an invisible disability at a Canadian university, (n.d.). https://doi.org/10.1080/09687599.2012.752127.

[213] M.L. Wehmeyer, Self-Determination and Individuals with Significant Disabilities: Examining Meanings and Misinterpretations, Journal of the Association for Persons with Severe Handicaps. 23 (1998) 5–16. https://doi.org/10.2511/rpsd.23.1.5.

[214] B. Curryer, R.J. Stancliffe, A. Dew, Self-determination: Adults with intellectual disability and their family, Journal of Intellectual and Developmental Disability. 40 (2015) 394–399. https://doi.org/10.3109/13668250.2015.1029883.

[215] A.M. Mayo, M.I. Wallhagen, Considerations of Informed Consent and Decision-Making Competence in Older Adults with Cognitive Impairment, Research in Gerontological Nursing. 2 (2009) 103–111. https://doi.org/10.3928/19404921-20090401-08.

[216] I. Wiesel, E. Smith, C. Bigby, S.-N. Then, J. Douglas, T. Carney, The temporalities of supported decision-making by people with cognitive disability, Social & Cultural Geography. (2020) 1–19. https://doi.org/10.1080/14649365.2020.1829689.

[217] O.C. Okonkwo, H.R. Griffith, J.N. Copeland, K. Belue, S. Lanza, E.Y. Zamrini, L.E. Harrell, J.C. Brockington, D. Clark, R. Raman, D.C. Marson, Medical decision-making capacity in mild cognitive impairment: A 3-year longitudinal study, Neurology. 71 (2008) 1474–1480. https://doi.org/10.1212/01.wnl.0000334301.32358.48.

[218] Y. Hu, X. Liu, F. Wang, C. Cheng, An overview of agent-based evacuation models for building fires, in: Proceedings of 2012 9th IEEE International Conference on Networking, Sensing and Control, IEEE, 2012: pp. 382–386. https://doi.org/10.1109/ICNSC.2012.6204949.

[219] E.D. Kuligowski, Computer Evacuation Models for Buildings, in: SFPE Handbook of Fire Protection Engineering, Springer New York, New York, NY, 2016: pp. 2152–2180. https://doi.org/10.1007/978-1-4939-2565-0_60.

[220] Pathfinder Features | Thunderhead Engineering, (n.d.). https://www.thunderheadeng.com/pathfinder/pathfinder-features/ (accessed September 15, 2021).

[221] H. Hostetter, M.Z. Naser, Characterizing disability in fire evacuation: A progressive review, Journal of Building Engineering. 53 (2022) 104573. https://doi.org/10.1016/J.JOBE.2022.104573.

[222] About Chronic Diseases | CDC, (n.d.). https://www.cdc.gov/chronicdisease/about/index.htm (accessed June 19, 2022).

[223] A.S. Mayer, L.A. Maier, Evaluation of Respiratory Impairment and Disability, Murray and Nadel's Textbook of Respiratory Medicine. 1 (2016) 469-481.e2. https://doi.org/10.1016/B978-1-4557-3383-5.00028-2.

[224] Minimum Design Loads and Associated Criteria for Buildings and Other Structures, American Society of Civil Engineers, Reston, VA, 2017. https://doi.org/10.1061/9780784414248.

[225] 10 CFR § 435.2 - Definitions. - Content Details - CFR-2021-title10-vol3-sec435-2, 2021. https://www.govinfo.gov/app/details/CFR-2021-title10-vol3/CFR-2021-title10-vol3-sec435-2 (accessed May 24, 2022).

[226] Recognizing flashover conditions can save your life, (n.d.). https://www.usfa.fema.gov/blog/cb-050520.html (accessed June 2, 2022).

[227] M.L. Tolerico, D. Ding, R.A. Cooper, D.M. Spaeth, S.G. Fitzgerald, R. Cooper, A. Kelleher, M.L. Boninger, Assessing mobility characteristics and activity levels of manual wheelchair users, J Rehabil Res Dev. 44 (2007) 561–571. https://doi.org/10.1682/JRRD.2006.02.0017.

APPENDIX

List of Acronyms and Abbreviations

ABA: Architectural Barriers Act (1968)
ADA: Americans with Disabilities Act (1990)
APA: American Psychiatric Association
ASCE: American Society of Civil Engineers
ASET: Available Safe Egress Time
BMI: Body Mass Index
CDC: Centers for Disease Control and Injury Prevention
CFR: (US) Code of Federal Regulations
CGD: Craig, Gaulden and Davis, Inc. (Greenville, South Carolina, USA)
CRPD: Convention on the Rights of Persons with Disabilities
DOJ: Department of Justice (United States)
EDF: European Disability Forum
EU: European Union
FEMA: Federal Emergency Management Agency (US)
FSO: Fire Safety Official
GUI: Graphical User Interface
HEED: High-rise Evacuation Evaluation Database
IBC: International Building Code (US)
ICF: International Classification of Functioning, Disability, and Health
IDA: International Disability Alliance
IDC: International Disability Caucus
NCPEDP: National Centre for Promotion of Employment for Disabled People
NFPA: National Fire Protection Association
NIMH: National Institute of Mental Health
NIST: National Institute of Standards and Technology
NSF: National Science Foundation
NYC: New York City
OEE: Occupant Emergency Elevator
PAR: Participatory Action Research
PWD: People/Person with Disability/Disabilities
RJA: Rolf Jenson and Associates
RSET: Required Safe Egress Time
SBIR: Small Business Innovative Research
SFPE: Society of Fire Protection Engineers
TEC: Tsunami Evaluation Coalition
UK: United Kingdom
UN: United Nations
UPIAS: Union of Physically Impaired Against Segregation
US or USA: United States or United States of America

USFA: United States Fire Administration
WC: Wheelchair (User)
WHO: World Health Organization
WTC1: World Trade Center North Tower, Building I
WTC 2: World Trade Center South Tower, Building II
2D: Two-Dimensional
3D: Three-Dimensional

Additional Building Photos and Layouts

Figure 31: Apartment Kitchen and Living Space

Figure 32: Apartment Bedrooms and Bathroom [185]

Figure 33: 3rd Floor Ramp

Figure 34: Left and Right Stairwells

Figure 35: Back Main Stairwell

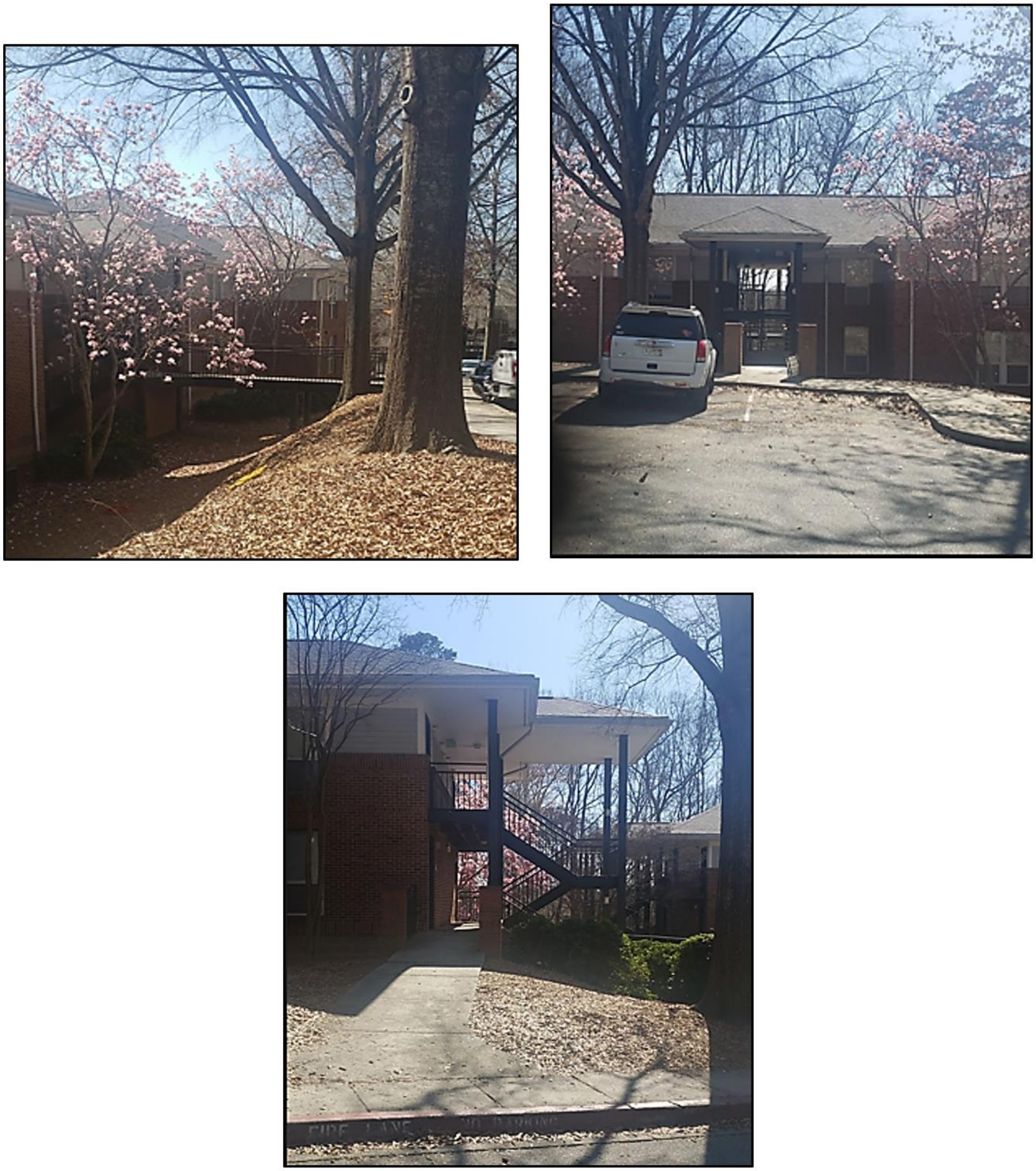


Figure 36: Flat Exits (Front Main and 2nd Floor Right)

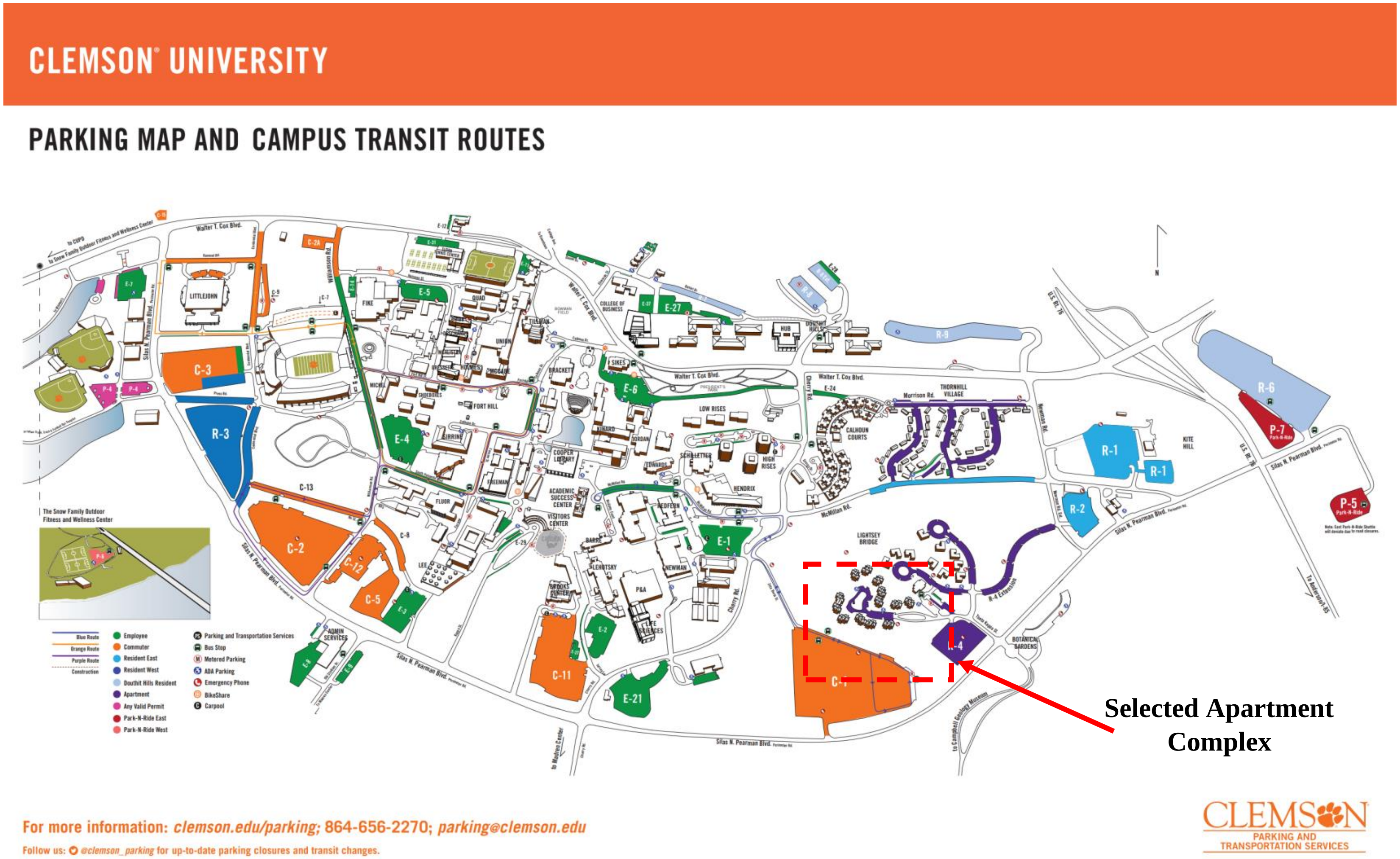


Figure 37: Clemson University Map

Determination of WC User Speed

The speed of wheelchair users in this thesis is based on the assumption that disabled occupants will move with urgency during a fire emergency. Thus, elevated speeds (compared to leisure movement) were used from a 2013 study titled "Determination of Normative Values for 20 min Exercise of Wheelchair Propulsion by Spinal Cord Injury Patients" [201]. Sample characteristics are provided in the table below. For this thesis only the male and female number of participants were of interest (shown). The HP (high paraplegia) and LP (low paraplegia) together represent the paraplegia group. Normative velocity values (by percentile, gender, and paraplegia group are provided in **Table A-2.** This thesis focuses on the 50th percentile velocity values, as highlighted.

Table 19: Study Sample Characteristics [201]

	TT	**HP**	**LP**	**Total**
N	83 (20.1)	151 (36.6)	179 (43.3)	413 (100.0)
***Gender*, N (%)**				
Male	70 (84.3)	118 (78.1)	136 (76.0)	324 (78.5)
Female	13 (15.7)	33 (21.7)	43 (24.0)	89 (21.5)
Age, years				
Mean (±s.d.)	28.7 (8.8)	29.4 (9.2)	30.6 (10.0)	29.8 (9.5)
Median	26.0	26.9	28.4	27.1
Range	18.5–58.6	18.0–62.1	18.0–64.2	18.0–34.2
TSI, years				
Mean (±s.d.)	2.6 (3.0)	2.2 (3.1)	2.3 (4.4)	2.3 (3.7)
Median	1.5	1.1	1.1	1.2
Range	0.1–17.6	0.1–24.3	0.1–42.3	0.1–42.3
***ASIA*, N (%)**				
A	42 (50.6)	131 (86.7)	147 (82.1)	320 (77.5)
B	20 (24.1)	15 (9.9)	13 (7.3)	48 (11.6)
C	17 (20.5)	3 (2.0)	15 (8.4)	35 (8.5)
D	4 (4.8)	2 (1.3)	4 (2.2)	10 (2.4)
Unit				
Sarah Center	47 (56.6)	129 (85.4)	165 (92.2)	341 (82.6)
Sarah North Lake	36 (43.4)	22 (14.6)	14 (7.8)	72 (17.4)

Table 20: Normative Values for 20 min Exercise (Percentiles) [201]

	Percentiles						
	5	**10**	**25**	**50**	**75**	**90**	**95**
Men							
Distance (m)							
TT	494.8	558.2	741.0	988.0	1215.0	1465.5	1546.4
PP	998.2	1106.7	1312.1	1600.6	1842.5	1997.5	2106.0
Velocity (m/min)							
TT	24.7	27.9	37.1	49.4	60.8	73.3	77.3
PP	50.0	55.4	65.6	80.1	92.1	99.9	105.3
Women							
Distance (m)							
TT	—	300.0	473.0	780.0	974.9	1188.0	—
PP	847.4	921.6	1168.4	1331.1	1579.5	1756.2	1901.3
Velocity (m/min)							
TT	—	15.0	23.7	39.0	48.8	59.4	—
PP	42.4	46.1	58.4	66.6	79.0	87.8	95.1

Abbreviations: ASIA, American Spinal Injury Association classification; HP, high paraplegia group; LP, low paraplegia group; TSI, time since injury (years); TT, tetraplegia group; PP, paraplegia group

The calculation of a weighted average wheelchair user speed is determined as follows:

Weighted Average Male Speed: $\frac{70(49.4)+254(80.1)}{70+254} = 73.5\ m/min$

Weighted Average Female Speed: $\frac{13(39)+76(66.6)}{13+76} = 62.6\ m/min$

Combined Gender Weighted Average: $\frac{73.5(324)+62.6(89)}{324+89} = 71.2\ m/min$

Conversion to ft/s: $71.2\ \frac{m}{min}\ x\ \frac{1\ min}{60\ s}\ x\ \frac{3.28\ ft}{1\ m} = \ 3.89\ ft/s$

Additional Simulation Data

Table 21: Building Population Egress Times (Two WC Users), Iteration I

Apartments	Total Population Egress Time, s	Total Building Evacuation Time, s (Pre-Movement plus Egress Time)
1B/1C	42.8	339.2
1B/1F	48.3	344.7
1B/1G	42.8	339.2
2A/1B	42.8	339.2
1B/2B	42.8	339.2

3G/1B	42.8	339.2
3H/1B	42.8	339.2
1C/1F	57.0	353.4
1G/1C	42.8	339.2
2A/1C	42.8	339.2
2B/1C	42.8	339.2
3G/1C	42.8	339.2
3H/1C	42.8	339.2
1G/1F	46.3	342.7
2A/1F	48.3	344.7
2B/1F	48.3	344.7
3G/1F	48.3	344.7
3H/1F	48.3	344.7
2A/1G	42.8	339.2
1G/2B	42.8	339.2
3G/1G	42.8	339.2
3H/1G	42.8	339.2
2A/2B	42.8	339.2
2A/3G	42.8	339.2
2A/3H	42.8	339.2
3G/2B	42.8	339.2
3H/2B	42.8	339.2
3H/3G	42.8	339.2
2H/2G	84.3	380.7
2G/3A	77.3	373.7
2G/3B	85.0	381.4
3D/2G	68.0	364.4
3E/2G	66.5	362.9
3A/2H	88.8	385.2
2H/3B	89.5	385.9
3D/2H	67.5	363.9
3E/2H	90.3	386.7
3A/3B	93.0	389.4
3D/3A	77.3	373.7
3E/3A	72.8	369.2
3D/3B	85.0	381.4
3E/3B	84.5	380.9
3E/3D	82.5	378.9
2D/2C	92.0	388.4
2E/2C	87.5	383.9
2C/2F	95.0	391.4
3C/2C	85.3	381.7
3F/2C	72.0	368.4
2E/2D	101.3	397.7
2F/2D	91.3	387.7

3C/2D	74.0	370.4
3F/2D	71.3	367.7
2F/2E	95.3	391.7
2E/3C	73.5	369.9
3F/2E	69.0	365.4
3C/2F	75.3	371.7
3F/2F	73.3	369.7
3F/3C	75.5	371.9
AVERAGE	63.6	360.0

Table 22: Building Population Egress Times (Three WC Users), Iteration I

Apartments	Total Population Egress Time, s	Total Building Evacuation Time, s (Pre-Movement plus Egress Time)
1B/1C/1F	57.0	353.4
1B/1G/1C	42.8	339.2
2A/1B/1C	42.8	339.2
1B/2B/1C	42.8	339.2
3G/1B/1C	42.8	339.2
3H/1B/1C	42.8	339.2
1B/1G/1F	46.3	342.7
2A/1B/1F	48.3	344.7
1B/2B/1F	48.3	344.7
3G/1B/1F	48.3	344.7
3H/1B/1F	48.3	344.7
2A/1B/1G	42.8	339.2
1B/1G/2B	42.8	339.2
3G/1B/1G	42.8	339.2
3H/1B/1G	42.8	339.2
2A/1B/2B	42.8	339.2
2A/3G/1B	42.8	339.2
2A/3H/1B	42.8	339.2
1B/3G/2B	42.8	339.2
3H/1B/2B	42.8	339.2
3H/3G/1B	42.8	339.2
1C/1G/1F	59.5	355.9
2A/1C/1F	57.0	353.4
1C/2B/1F	47.3	343.7
3G/1C/1F	57.0	353.4
3H/1C/1F	57.0	353.4
2A/1G/1C	42.8	339.2
1G/2B/1C	42.8	339.2
3G/1G/1C	42.8	339.2
3H/1G/1C	42.8	339.2
2A/2B/1C	42.8	339.2

2A/3G/1C	42.8	339.2
2A/3H/1C	42.8	339.2
3G/2B/1C	42.8	339.2
3H/2B/1C	42.8	339.2
3H/3G/1C	42.8	339.2
2A/1G/1F	46.3	342.7
1G/2B/1F	48.3	344.7
3G/1G/1F	46.3	342.7
3H/1G/1F	47.3	343.7
2A/2B/1F	48.3	344.7
2A/3G/1F	48.3	344.7
2A/3H/1F	48.3	344.7
3G/2B/1F	48.3	344.7
3H/2B/1F	48.3	344.7
3H/3G/1F	48.3	344.7
2A/1G/2B	42.8	339.2
2A/3G/1G	42.8	339.2
2A/3H/1G	42.8	339.2
3G/1G/2B	42.8	339.2
3H/1G/2B	42.8	339.2
3H/3G/1G	42.8	339.2
2A/3G/2B	42.8	339.2
2A/3H/2B	42.8	339.2
2A/3H/3G	42.8	339.2
3H/3G/2B	42.8	339.2
2H/3A/2G	84.3	380.7
2H/2G/3B	85.0	381.4
3D/2H/2G	84.3	380.7
3E/2H/2G	84.3	380.7
2G/3A/3B	88.3	384.7
3D/2G/3A	77.3	373.7
3E/2G/3A	77.3	373.7
3D/2G/3B	85.0	381.4
3E/2G/3B	85.0	381.4
2G/3E/3D	82.5	378.9
3A/2H/3B	93.0	389.4
3D/2H/3A	77.3	373.7
3A/3E/2H	94.8	391.2
3D/2H/3B	85.0	381.4
3E/3B/2H	95.3	391.7
2H/3E/3D	82.5	378.9
3D/3A/3B	88.3	384.7
3A/3E/3B	93.0	389.4
3E/3A/3D	82.5	378.9
3E/3D/3B	85.0	381.4

2D/2E/2C	123.3	419.7
2D/2C/2F	101.3	397.7
3C/2D/2C	89.8	386.2
3F/2D/2C	87.0	383.4
2E/2C/2F	101.0	397.4
2E/3C/2C	88.8	385.2
3F/2E/2C	89.5	385.9
2C/3C/2F	83.8	380.2
2C/3F/2F	91.3	387.7
3F/2C/3C	81.0	377.4
2E/2F/2D	111.0	407.4
2D/3C/2E	89.3	385.7
3F/2D/2E	88.5	384.9
2D/3C/2F	82.5	378.9
3F/2D/2F	84.0	380.4
3F/2D/3C	77.3	373.7
2E/3C/2F	81.8	378.2
3F/2E/2F	84.0	380.4
3F/2E/3C	78.3	374.7
3F/3C/2F	78.5	374.9
AVERAGE	63.0	359.4

Table 23: Results for One WC User, Iteration II

Apartment	WC User Egress Time, s	Deviation from Benchmark Egress Time, s	Total Evacuation Time, s (Pre-Movement plus Egress Time)
1B	19.7	+3.5	316.1
1C	33.0	+14.5	329.4
1F	47.5	+24.8	343.9
1G	27.4	+10.0	323.8
2A	21.4	+3.4	317.8
2B	24.2	-4.3	320.6
2C	68.2	+32.5	364.6
2D	60.3	+32.63	356.7
2E	58.0	+26.5	354.4
2F	67.0	+36.3	363.4
2G	66.0	+37.0	362.4
2H	76.4	+41.7	372.8
3A	69.7	+29.7	366.1
3B	78.7	+35.2	375.1
3C	65.6	+27.9	362.0
3D	64.0	+38.3	360.4
3E	68.7	+34.2	365.1
3F	62.9	+26.4	359.3

3G	21.5	-2.2	317.9
3H	16.7	+1.0	313.1

Table 24: Results for Two WC Users, Iteration II

Apartments	First WC User Egress Time, s	Last WC User Egress Time, s	Average WC User Egress Time, s
1G/1F	27.4	42.9	35.1
1G/1C	27.4	31.4	29.4
1B/1G	24.9	27.4	26.2
2A/1G	13.1	27.4	20.3
3G/1G	22.0	27.4	24.7
3H/1G	16.6	27.4	22.0
1C/1F	31.8	53.5	42.6
1B/1F	24.9	44.7	34.8
2A/1F	13.1	44.7	28.9
3G/1F	22.0	44.7	33.3
3H/1F	16.6	44.7	30.6
3H/1C	16.6	33.6	25.1
2A/1B	13.1	24.9	19.0
3G/1B	22.0	24.9	23.5
3H/1B	16.6	24.9	20.8
2A/3G	13.1	22.0	17.5
3H/3G	16.6	22.0	19.3
3G/2B	22.0	31.6	26.8
3H/2B	16.8	31.6	24.2
2B/1F	31.6	44.7	38.1
2A/2B	13.1	31.6	22.3
1G/2B	26.1	31.6	28.8
1C/2B	31.6	31.6	31.6
1B/2B	21.4	31.6	26.5
2D/2C	62.3	76.7	69.5
2C/2E	63.6	78.9	71.3
2C/2F	64.9	78.4	71.6
2F/2D	74.8	89.8	82.3
3D/2D	61.2	72.7	66.9
2F/2E	81.8	93.7	87.7
3D/2E	63.0	76.2	69.6
3D/2F	61.9	74.3	68.1
3D/2G	62.8	66.6	64.7
2C/3B	72.6	88.0	80.3
3C/2C	80.3	85.0	82.7
3E/2C	67.7	73.9	70.8
3A/3B	67.7	91.4	79.6
3C/3A	67.5	71.3	69.4

3E/3A	68.6	71.3	70.0
3E/3B	68.6	83.1	75.9
3F/3B	61.2	76.9	69.1
3C/3E	74.0	87.0	80.5
3F/3E	70.0	84.4	77.2
2H/2G	71.0	82.9	76.9
3A/2G	65.2	75.8	70.5
3D/2G	62.8	66.6	64.7
3E/2G	62.0	65.2	63.6
3A/2H	71.2	86.0	78.6
3D/2H	62.8	66.2	64.5
3E/2H	68.6	87.5	78.1

Table 25: Results for Three WC Users, Iteration II

Apartments	First WC User Egress Time, s	Second WC User Egress Time, s	Last WC User Egress Time, s	Average WC User Egress Time, s
1C/1G/1F	13.6	30.0	56.0	33.2
1B/1G/1F	24.9	27.4	42.9	31.7
2A/1G/1F	13.1	27.4	42.9	27.8
3G/1G/1F	22.0	27.4	42.9	30.8
3H/1G/1F	16.6	27.4	42.9	29.0
1B/1G/1C	24.9	27.4	31.4	27.9
3H/1G/1C	16.6	27.4	31.4	25.1
2A/1B/1G	13.1	24.9	27.4	21.8
3G/1B/1G	22.0	24.9	27.4	24.8
3H/1B/1G	16.6	24.9	27.4	23.0
2A/3G/1G	13.1	22.0	27.4	20.8
2A/3H/1G	13.1	16.6	27.4	19.0
1B/1C/1F	24.9	31.8	53.5	36.7
2A/1C/1F	13.1	31.8	53.5	32.8
3G/1C/1F	22.0	31.8	53.5	35.8
2A/1B/1F	13.1	24.9	44.7	27.6
3G/1B/1F	22.0	24.9	44.7	30.5
2A/3G/1F	13.1	22.0	44.7	26.6
2A/3H/1F	13.1	16.6	44.7	24.8
3H/3G/1F	16.6	22.0	44.7	27.7
2A/1B/1C	13.1	24.9	33.6	23.9
3G/1B/1C	22.0	24.9	33.6	26.8
2A/3H/1C	13.1	16.6	33.6	21.1
3H/3G/1C	16.6	22.0	33.6	24.1
2A/3G/1B	13.1	22.0	24.9	20.0
3H/3G/1B	16.6	22.0	24.9	21.2
2A/3H/3G	13.1	16.6	22.0	17.2
1B/1C/2B	21.4	31.6	31.6	28.2

1B/1G/2B	21.4	26.1	31.6	26.3
2A/1B/2B	13.1	21.4	31.6	22.0
2B/1C/1F	30.8	31.6	43.9	35.4
1G/1C/2B	26.1	31.6	31.6	29.7
2A/1C/2B	13.1	31.6	31.6	25.4
2A/2B/1F	13.1	31.6	44.7	29.8
2A/1G/2B	13.1	26.1	31.6	23.6
3G/1G/2B	22.0	26.1	31.6	26.5
3H/1G/2B	16.8	26.1	31.6	24.8
2A/3G/2B	13.1	22.0	31.6	22.2
2A/3H/2B	13.1	16.8	31.6	20.5
2D/2C/2E	65.6	82.2	94.4	80.7
2D/2C/2F	63.8	80.8	94.1	79.6
2D/3D/2C	57.6	66.6	80.6	68.2
2E/2C/2F	64.1	79.5	92.7	78.8
3D/2E/2C	57.6	69.1	81.8	69.5
2C/3D/2F	63.8	65.7	75.9	68.5
2E/2F/2D	79.7	94.7	109.7	94.7
3D/2E/2D	61.9	85.8	99.8	82.5
3D/2F/2E	63.0	77.7	96.1	78.9
2C/3A/3B	72.6	77.0	86.2	78.6
3A/3C/2C	74.2	80.3	85.0	79.8
3E/2C/3A	67.7	73.9	74.2	71.9
3F/2C/3A	61.2	71.9	79.4	70.8
3C/2C/3B	80.3	85.0	88.0	84.4
3E/2C/3C	92.5	94.6	97.7	94.9
3F/2C/3C	58.1	74.1	79.5	70.6
2F/2C/3E	74.9	78.8	87.9	80.5
3C/3A/3B	67.6	67.7	91.4	75.6
3A/3E/3B	67.7	68.6	91.4	75.9
3F/3A/3B	61.2	72.9	88.5	74.2
3A/3C/3E	71.3	74.0	87.0	77.4
3F/3C/3A	58.1	74.0	76.6	69.6
3F/3A/3E	70.0	79.2	84.4	77.9
3F/3C/3B	58.1	74.0	76.9	69.7
3F/3B/3E	70.0	76.9	84.4	77.1
2H/2G/3A	71.0	75.8	82.9	76.6
2H/2G/3B	71.0	82.9	83.4	79.1
3D/2H/2G	62.8	71.0	82.9	72.2
3E/2H/2G	62.0	71.0	82.9	72.0
2G/3A/3B	65.2	74.9	86.8	75.6
3D/2G/3A	62.8	65.2	75.8	67.9
3E/2G/3A	62.0	65.2	75.8	67.7
3D/2G/3B	62.8	65.2	83.4	70.4
3E/2G/3B	62.0	65.2	83.4	70.2

2G/3D/3E	65.2	66.5	79.8	70.5
2H/3A/3B	67.7	79.4	91.4	79.5
3E/2H/3A	71.3	73.8	92.8	79.3
3D/2H/3B	62.8	66.2	83.4	70.8
3E/3B/2H	69.2	83.1	92.4	81.6
2H/3D/3E	66.2	66.5	79.8	70.8

Table 26: Building Population Egress Times (One WC User), Iteration II

Apartment	Total Population Egress Time, s	Total Building Evacuation Time, s (Pre-Movement plus Egress Time)
1B	40.5	336.9
1C	43.8	340.2
1F	47.5	343.9
1G	55.0	351.4
2A	40.5	336.9
2B	40.5	336.9
2C	71.0	367.4
2D	63.3	359.7
2E	60.3	356.7
2F	69.5	365.9
2G	67.3	363.7
2H	95.5	391.9
3A	71.3	367.7
3B	80.0	376.4
3C	67.3	363.7
3D	66.3	362.7
3E	26.8	366.7
3F	66.5	362.9
3G	40.5	336.9
3H	40.5	336.9
AVERAGE	57.7	356.3

Table 27: Building Population Egress Times (Two WC Users), Iteration II

Apartments	Total Population Egress Time, s	Total Building Evacuation Time, s (Pre-Movement plus Egress Time)
1G/1F	46.3	342.7
1G/1C	43.5	339.9
1B/1G	43.5	339.9
2A/1G	43.5	339.9
3G/1G	43.5	339.9
3H/1G	43.5	339.9
1C/1F	57.0	353.4

1B/1F	48.3	344.7
2A/1F	48.3	344.7
3G/1F	48.3	344.7
3H/1F	48.3	344.7
3H/1C	43.5	339.9
2A/1B	43.5	339.9
3G/1B	43.5	339.9
3H/1B	43.5	339.9
2A/3G	43.5	339.9
3H/3G	43.5	339.9
3G/2B	43.5	339.9
3H/2B	43.5	339.9
2B/1F	45.8	342.2
2A/2B	43.5	339.9
1G/2B	43.5	339.9
1C/2B	43.5	339.9
1B/2B	43.5	339.9
2D/2C	78.3	374.7
2C/2E	80.5	376.9
2C/2F	79.8	376.2
2F/2D	91.3	387.7
3D/2D	75.3	371.7
2F/2E	95.3	391.7
3D/2E	77.5	373.9
3D/2F	75.8	372.2
3D/2G	68.0	364.4
2C/3B	88.3	384.7
3C/2C	85.3	381.7
3E/2C	74.0	370.4
3A/3B	93.0	389.4
3C/3A	72.8	369.2
3E/3A	72.8	369.2
3E/3B	84.5	380.9
3F/3B	78.5	374.9
3C/3E	90.0	386.4
3F/3E	86.0	382.4
2H/2G	85.7	382.1
3A/2G	77.5	373.9
3D/2G	68.0	364.4
3E/2G	67.5	363.9
3A/2H	88.3	384.7
3D/2H	68.0	364.4
3E/2H	90.1	386.5
AVERAGE	63.5	359.9

Table 28: Building Population Egress Times (Three WC Users), Iteration II

Apartments	Total Population Egress Time, s	Total Building Evacuation Time, s (Pre-Movement plus Egress Time)
1C/1G/1F	59.5	355.9
1B/1G/1F	46.3	342.7
2A/1G/1F	46.3	342.7
3G/1G/1F	46.3	342.7
3H/1G/1F	47.3	343.7
1B/1G/1C	43.5	339.9
3H/1G/1C	43.5	339.9
2A/1B/1G	43.5	339.9
3G/1B/1G	43.5	339.9
3H/1B/1G	43.5	339.9
2A/3G/1G	43.5	339.9
2A/3H/1G	43.5	339.9
1B/1C/1F	57.0	353.4
2A/1C/1F	57.0	353.4
3G/1C/1F	57.0	353.4
2A/1B/1F	48.3	344.7
3G/1B/1F	48.3	344.7
2A/3G/1F	48.3	344.7
2A/3H/1F	48.3	344.7
3H/3G/1F	48.3	344.7
2A/1B/1C	43.5	339.9
3G/1B/1C	43.5	339.9
2A/3H/1C	43.5	339.9
3H/3G/1C	43.5	339.9
2A/3G/1B	43.5	339.9
3H/3G/1B	43.5	339.9
2A/3H/3G	43.5	339.9
1B/1C/2B	43.5	339.9
1B/1G/2B	43.5	339.9
2A/1B/2B	43.5	339.9
2B/1C/1F	45.8	342.2
1G/1C/2B	43.5	339.9
2A/1C/2B	43.5	339.9
2A/2B/1F	48.3	344.7
2A/1G/2B	43.5	339.9
3G/1G/2B	43.5	339.9
3H/1G/2B	43.5	339.9
2A/3G/2B	43.5	339.9
2A/3H/2B	43.5	339.9
2D/2C/2E	95.8	392.2
2D/2C/2F	95.5	391.9

2D/3D/2C	82.0	378.4
2E/2C/2F	94.0	390.4
3D/2E/2C	83.3	379.7
2C/3D/2F	77.3	373.7
2E/2F/2D	111.0	407.4
3D/2E/2D	101.3	397.7
3D/2F/2E	97.5	393.9
2C/3A/3B	87.8	384.2
3A/3C/2C	85.3	381.7
3E/2C/3A	75.8	372.2
3F/2C/3A	79.5	375.9
3C/2C/3B	88.3	384.7
3E/2C/3C	99.0	395.4
3F/2C/3C	81.0	377.4
3F/2C/3E	89.3	385.7
3C/3A/3B	93.0	389.4
3A/3E/3B	93.0	389.4
3F/3A/3B	90.0	386.4
3A/3C/3E	90.0	386.4
3F/3C/3A	76.8	373.2
3F/3A/3E	86.0	382.4
3F/3C/3B	78.5	374.9
3F/3B/3E	86.0	382.4
2H/2G/3A	85.3	381.7
2H/2G/3B	86.0	382.4
3D/2H/2G	85.3	381.7
3E/2H/2G	85.3	381.7
2G/3A/3B	90.0	386.4
3D/2G/3A	78.2	374.6
3E/2G/3A	78.2	374.6
3D/2G/3B	86.0	382.4
3E/2G/3B	86.0	382.4
2G/3D/3E	83.1	379.5
2H/3A/3B	93.0	389.4
3E/2H/3A	95.5	391.9
3D/2H/3B	86.0	382.4
3E/3B/2H	95.8	392.2
2H/3D/3E	83.1	379.5
AVERAGE	67.2	363.6