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EXITUS: AN AGENT-BASED EVACUATION SIMULATION MODEL
FOR HETEROGENEOUS POPULATIONS

by

Matthew T. Manley

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Education
(Management Information Systems)

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2012

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ABSTRACT

Exitus: An Agent-Based Evacuation Simulation Model for Heterogeneous Populations

by

Matthew T. Manley, Doctor of Philosophy

Utah State University, 2012

Major Professor: Dr. Yong Seog Kim
Department: Management Information Systems

Evacuation planning for private-sector organizations is an important consideration given the continuing occurrence of both natural and human-caused disasters that inordinately affect them. Unfortunately, the traditional management approach that is focused on fire drills presents several practical challenges at the scale required for many organizations but especially those responsible for national critical infrastructure assets such as airports and sports arenas.

In this research we developed Exitus, a comprehensive decision support system that may be used to simulate large-scale evacuations of such structures. The system is unique because it considers individuals with disabilities explicitly in terms of physical and psychological attributes. It is also capable of classifying the environment in terms of accessibility characteristics encompassing various conditions that have been shown to have a disproportionate effect upon the behavior of individuals with disabilities during an emergency.

The system was applied to three unique test beds: a multi-story office building, an international airport, and a major sports arena. Several simulation experiments revealed specific areas of concern for both building managers and management practice in general. In particular, we were able to show (a) how long evacuations of heterogeneous populations may be expected to last, (b) who the most vulnerable groups of people are, (c) the risk engendered from particular design features for individuals with disabilities, and (d) the potential benefits from adopting alternate evacuation strategies, among others.

Considered together, the findings provide a useful foundation for the development of best practices and policies addressing the evacuation concerns surrounding heterogeneous populations in large, complex environments. Ultimately, a capabilities-based approach featuring both tactical and strategic planning with an eye toward the unique problems presented by individuals with disabilities is recommended.

(125 pages)

PUBLIC ABSTRACT

Exitus: An Agent-Based Evacuation Simulation Model for Heterogeneous Populations

by

Matthew T. Manley, Doctor of Philosophy

Utah State University, 2012

Evacuation planning is important for businesses given the continuing occurrence of both natural and human-caused disasters throughout the world. Unfortunately, the traditional fire-drill approach is impractical for many large organizations but especially those responsible for airports and sports arenas. The purpose of this research was to develop a new computer program capable of simulating large scale evacuations in such buildings. The program, called Exitus, is different from other evacuation simulators in the way it considers the physical, psychological, and social characteristics of individuals with disabilities during emergency situations.

In this research, Exitus was used to simulate evacuations of three buildings located near the university campus; a multi-story office building, an international airport and a major sports arena. The results of the simulations pointed to several important considerations for managers including: (a) how long evacuations of such buildings may be expected to last, (b) who the most vulnerable groups of people are, (c) what architectural features help or hinder evacuations, and (d) the potential benefits of certain evacuation strategies over others. Ultimately, a management approach featuring both tactical and strategic planning with an eye toward the unique problems presented by individuals with disabilities is recommended.

DEDICATION

To my wife, Kandi, who walked every step of the journey with me.

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There are many people I wish to thank. The first of these is my program advisor, Dr. Yong Seog Kim, who spent many hours motivating and guiding me in this effort. I have greatly enjoyed our discussions through which my understanding of agent-based simulation, data mining, and the management information systems field in general has been greatly expanded.

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Most importantly, I wish to thank my family: my wife who postponed many of her own hopes and dreams to support me; my children who gave up friends and schools for new adventures in Cache Valley; and my parents who have only ever told me how proud they are. Without them, none of this would have been possible.

Matthew T. Manley

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CHAPTER I

INTRODUCTION

Research Motivation

Evacuation planning efforts within the last decade have been overwhelmingly focused on the role of public sector organizations. Both the National Response Plan (U.S. Department of Homeland Security [USDHS], 2004) and its successor, the National Response Framework (USDHS, 2008), emphasized the coordination of government-sponsored services over private sector involvement and citizen participation (Kapucu & Van Wart, 2006). Under the provisions of these two initiatives, municipal, county, state, and federal governments are becoming progressively more responsible for disaster planning and response, including evacuations, as the scale of the disaster dictates.

However, private sector organizations own 85% of the nation's critical infrastructure, provide employment for the vast majority of people, and produce essential goods and services such as food, water, transportation and power (Kean et al., 2004). Thus, there is a compelling need to support private sector organizations in this effort as well. Disasters have long been recognized as social phenomena requiring decentralized decision making and intensive human interaction for successful response (Quarantelli & Dynes, 1977). Localized adaptation to disaster circumstances, regardless of scale, requires flexibility that hierarchies of centralized authority often have difficulty providing (Kapucu & Van Wart, 2006).

Unfortunately, the traditional management approach focused on fire drills

presents several practical challenges at the scale required for many private organizations but especially those responsible for national critical infrastructure assets such as airports or sports arenas. Structures containing several thousands of occupants or that support round the clock operations incur enormous costs with each fire drill unless special procedures are developed. As a result, such organizations often conduct oversimplified exercises that merely ensure that participants know where the nearest exits are. Understandably, the more realistically hazards are replicated, the greater the potential danger to participants. Thus, extreme care is required, which leads to further costs (Johnson, 2005).

Fortunately, computer-based decision support systems (DSS) capable of modeling, complex human relationships in a variety of disaster scenarios and environments provide an attractive alternative for addressing many of these limitations. Regrettably, the data surrounding catastrophic events is sparse and difficult to acquire, if it exists at all. Therefore, research focusing on simulation models that can perform “what-if” analysis using the only available information (e.g., geographical and spatial data), while replicating the behavior and social interaction of human evacuees, is needed.

Problem Statement

Numerous studies from a variety of scientific fields have developed evacuation simulation models in response to the research motivation described in the previous section (Blue & Adler, 1999; Helbing, 1992; Kirchner & Schadschneider, 2002). At the same time, several studies have established the disproportionate vulnerability experienced

by individuals with disabilities during a disaster (Chou et al., 2004; Vanderkooy, 2002). Note that more than 12% of the working population has some form of physical, sensory, or mental disability (Rehabilitation Research and Training Center on Disability Demographics and Statistics, 2005) and are thus more likely to suffer during a disaster situation. However, very few studies have developed evacuation simulation models that incorporate individuals with disabilities to develop a better understanding of specific vulnerabilities (Christensen & Sasaki, 2008). Thus, the information stemming from model development in this area is limited. Ultimately, a better understanding of individuals with disabilities in the context of emergency evacuations is necessary for private organizations that have a responsibility to ensure their safety. Therefore, the purpose of this research is to develop a new emergency evacuation DSS that facilitates further examination of the relationship between individuals with disabilities and the environment in order to ameliorate their vulnerability during a disaster.

The model developed for this research is called Exitus. Exitus is a comprehensive DSS that may be used to simulate large scale evacuations of complex structures. The model was designed to address the limitations of previous examples while incorporating several new concepts surrounding the social dynamics of individuals with disabilities. The model is also capable of classifying the environment in terms of accessibility characteristics encompassing various conditions that have been shown to have a disproportionate effect upon the behavior of individuals with disabilities during an emergency.

Research Questions

The primary question guiding this research was: what should managers do to reduce the vulnerability of individuals with disabilities during emergency evacuations? The following supporting questions were also addressed. How long should evacuations that include individuals with disabilities be expected to last? Where should individuals with disabilities evacuate to? Who among individuals with disabilities are most at risk? What environmental features impede or facilitate the evacuation of individuals with disabilities?

Organization

The remainder of this dissertation is organized as follows. Chapter II presents a literature review examining two streams of research; evacuation simulation models and the vulnerability of individuals with disabilities during disaster situations. This is followed by an analysis of the only study available that considered both.

Chapter III presents a description of the research methodology. The prevalence, advantages, and limitations of the agent-based simulation methodology are discussed. This is followed by a description of the specific study procedures.

Chapter IV presents the development and evaluation of a new evacuation model called Exitus. The system architecture, implementation, and validation results are described. The model is then used to simulate evacuations from a multi-story office building. The chapter concludes with a discussion of the findings.

Chapter V presents the inclusion of individualized social forces as a mechanism

for increasing the realism and predictive accuracy of Exitus. The implementation of Helbing's (1992) social force theory and subsequent validation results are described. The model is then used to simulate evacuations from an international airport. The chapter concludes with a discussion of the findings.

Chapter VI presents the inclusion of localized group relationships to further increase the usefulness of the model. The implementation of Hall's (1963) proxemic theory and subsequent validation results are described. The model is then used to simulate evacuations from a major sports arena. The chapter concludes with a discussion of the findings.

Chapter VII presents the major conclusions stemming from the simulation experiments presented in Chapters IV, V, and VI. Avenues for further research are also addressed.

CHAPTER II

LITERATURE REVIEW

Definitions and Assumptions

In this research, evacuation is defined as the organization and movement of people from potentially dangerous locations, caused by the threat or occurrence of a disastrous event, to locations of safety. Two basic modes of evacuation are derived from this definition—pre-event and post-event. Pre-event evacuations are conducted in response to the threat of a disaster using a priori estimations of evacuation and threat propagation times in order to minimize risk to humans. For example, an office building may be evacuated in response to an impending hurricane in order to protect employees from the storm. On the other hand, post-event evacuations are conducted in response to the occurrence of a disaster using a posteriori knowledge of the environment in order to mitigate the consequences to humans. For example, an airport may be evacuated after an explosion in order to limit the casualties resulting from further disintegration of the structure and/or the environment.

In both cases, a short evacuation time is the most important consideration in avoiding the consequences of the event. In this research, evacuation time is considered in terms of two distinct parts; recognition time and egress time. Recognition time is the time required to become aware of either the threat or occurrence of a dangerous situation. Egress time is the total time required to develop a course of action and physically move away from danger, a cycle that may repeat itself multiple times before safety is reached.

In each case, duration is influenced by a wide variety of factors such as the tendency to panic, familiarity with evacuation procedures, and reliability of alarm systems.

Consequently, one of the overriding goals of this research is to simulate these factors as realistically as possible in order to reliably predict evacuation times in a variety of environments and scenarios. Due to the seriousness of emergency situations, simulated evacuation times are treated as the lower bound of reality.

Comparison of Modeling Approaches

Many simulation models have been developed to predict evacuation time in both open and enclosed spaces in a variety of disciplines. Considered together, existing models represent a wide array of approaches and techniques that often overlap in their implementation. As a result, researchers have adopted many different methods for categorizing them in an attempt to arrive at an organized view. For example, some focus on underlying theoretical constructs (Pelechano & Malkawi, 2008) while others stress the scale of independent variables (Guo & Huang, 2008). In this research we adopt an approach emphasizing the specificity of the central human element found in all models. From this perspective there are three general approaches evident from the literature (a) macroscopic, (b) microscopic, and (c) mesoscopic.

Macroscopic modeling is characterized as a top-down approach in which collective human dynamics are related to model parameters through a closed-form formula without differentiating between the constituent parts. Crowds are represented in an aggregate manner using characteristics such as average velocity, spatial density, and

flow rate in relation to building location and time. Individual movements of evacuees, such as local directional changes, are not explicitly represented. Consequently, macroscopic models are computationally efficient, providing for the simulation of large crowds with relative ease. Examples of macroscopic models include queuing (Lovas, 1994; Smith, 1991), network (Choi, Francis, Hamacher, & Tufekci, 1984), and fluid-dynamic models (Helbing, 1992), among others.

A classic example of macroscopic modeling is found in an early work by Chalmet, Francis, and Saunders (1982). In this study, an 11-story office building was modeled as a network composed of origin, destination, and transshipment nodes corresponding to work centers, exits, and a variety of intermediate building locations respectively. Adjacent nodes were connected by arcs corresponding to hallways, stairwells, and other connecting features representing evacuation routes through the building. Movement through the network was modeled according to the flow rate of evacuees along different routes (see Ahuja, Magnanti, & Orlin, 1993, for a good discussion of network flow theory). By comparing their results to those of a real world fire drill, the authors were able to suggest procedural improvements and provide a feeling for how much time could be saved by utilizing other strategies stemming from more efficient stairwell utilization.

While macroscopic models are very good at reproducing the general density-flow profiles observed in evacuating crowds (Colombo & Rosini, 2005; Helbing, Johansson, & Al-Abideen, 2007), they are unable to explain emergent crowd phenomena. Emergence refers to the process of global pattern formation based on interactions at lower levels that

occur naturally without influence from external signals or conventions. For example, lane formation occurs when opposite traveling flows dynamically form distinct symmetries such that conflicts with opposing individuals are reduced (Helbing & Molnar, 1995). This limitation is understandable given that macroscopic models are expressions of deductive reasoning (i.e., given a set of axioms that the conclusion must follow). In so doing, many simplifying assumptions must be made in order to keep such theorems tractable. In contrast, emergent phenomena arise spontaneously from complex, dynamic interactions at lower levels that cannot be understood by superimposition of aggregate contributions in this manner.

Microscopic modeling is characterized as a bottom-up approach in which people are modeled as individual entities that can possess unique attribute values such as speed and size. Formulae or rules encapsulating spatial transition probabilities are repeatedly applied leading to temporal changes in state or behavior. Microscopic models are computationally intensive, making simulation of large crowds difficult on traditional single-processor systems. However, parallel computing techniques have, in some cases, been used successfully to overcome this limitation (Quinn, Metoyer, & Hunter-Zaworski, 2003). Examples of microscopic models include particle-based (Bouvier, Cohen & Najman, 1997; Helbing 1991; Helbing & Molnar, 1995) and cellular automata models (Blue & Adler, 1999; Burstedde, Klauck, Schadschneider, & Zittartz, 2001). Helbing's social force model (Helbing, 1991; Helbing & Molnar, 1995) was the most widely cited example. A thorough treatment of the author's work as it relates to this research is given in Chapter V.

Another well-known example of microscopic modeling is found in a more recent study by Kirchner and Schadschneider (2002). In this research, the evacuation of a simple room with a single exit was modeled as a cellular automaton in which space was discretized into a two-dimensional matrix of cells, each of which was either empty or occupied by a single evacuee. Movement from cell to cell was determined at discrete time steps according to transition probabilities influenced by values embedded in a dynamic floor field or matrix overlay. In this way, the authors were able to model social interactions inspired by chemotaxis, a social cooperation strategy observed in other biological systems amongst evacuees (see Ben-Jacob, 1997, for a detailed description of chemotactic signaling in bacterial colonies). The results of the authors' experiment led to the successful reproduction of collective effects similar to observations reported in empirical crowd studies (Helbing, Molnar, Farkas & Bolay, 2001).

As Kirchner and Schadschneider's (2002) results suggested, microscopic models have been shown to successfully reproduce emergent phenomena. In addition to lane formation, studies of Helbing's social force model have reproduced clogging, oscillation, and other phenomena related to crowd behavior (Helbing, Buzna, Johansen, & Werner, 2005; Helbing & Molnar, 1995). Clogging occurs in a variety of situations at critical densities, i.e., when many people are trying to leave a room at the same time (Helbing, Farkas, & Viscek, 2000; Tajima, Takimoto & Nagatani, 2001) or when flows mutually block each other (Fukui & Ishibashi, 1999). Oscillation occurs when counter flows at bottleneck areas spontaneously take turns getting through. Other cellular automata studies have also been able to reproduce these phenomena (Blue & Adler, 2001; Song, Yu, Xu,

& Zhang, 2005).

Mesoscopic modeling is characterized as a combination of both macroscopic and microscopic techniques. With this approach, an evacuee's spatial movement is individually specified but remains dependent on aggregate conditions rather than interactions with other participants. The blending of techniques imposes an additional computational burden in that calculations must be performed for each evacuee and then aggregated at each time step. As a result, fewer studies utilizing the mesoscopic approach have been documented. Examples of mesoscopic models from the literature are primarily found in the gas-kinetic group of models (Henderson, 1971; Henderson & Jenkins, 1974).

A representative example from this category is found in research by Hoogendoorn and Bovy (2000). In this study, evacuees in a simple 20 x 15 meter area representing a hallway were modeled as a set of interacting particles. Changes in particle position were calculated at each time step based on individual velocity and angle. Interactions among particles were modeled by means of transition probabilities influenced by overall particle density. That is, at each time step the microscopic attributes of particles were parameterized according to probabilities driven by the macroscopic state of the system (readers are referred to Bouvier et al., 1997, for a thorough treatment of the mesoscopic generalization of particle systems). The results of Hoogendoorn and Bovy's study demonstrated aggregate flow-density relationships similar to those observed in macroscopic model studies. However, in terms of reproducing emergent phenomena, mesoscopic models suffer from the same limitation as macroscopic models. In this case, the authors were unable to reproduce lane formation in experiments involving

intersecting counter flows.

Note that several commercial evacuation models have been developed in addition to the examples already discussed. Commercial evacuation models are those that have been created by individuals or corporations outside of academia. In some cases, commercialized models are clearly preceded by academic research such as EVACNET+ (Kisko & Francis, 1985). In other cases, commercial models are developed in parallel; often under the sponsorship of trade associations or specific government agencies, e.g., the Air Transport Association of America (AEREVAC) or the Federal Aviation Administration (EXODUS). Such models are made available to the public under a variety of licensing schemes including free access, fee based for personal use, or through a consultancy relationship only.

A good review of commercial evacuation models was recently presented by Kuligowski and Peacock (2005). In this review, the authors classified 30 models according to 11 major criteria and 53 subcriteria resulting in an information rich taxonomy of the commercial domain. A simplified view of the models classified according to the modeling approach defined here (i.e., macroscopic, mesoscopic, and microscopic) is presented in Table 1. Six of the models reviewed by the Kuligowski and Peacock were not included because their current availability was unknown or they were no longer in use. Note that 14 of the models utilized the microscopic approach suggesting the technique's popularity among commercial developers.

Table 1

Classification of Commercial Models According to Approach

Model	Approach
FPETool	Macroscopic
EVACNET4	Macroscopic
TIMTEX	Macroscopic
STEPS	Macroscopic
Simulex	Macroscopic
EESCAPE	Macroscopic
ALLSAFE	Macroscopic
WAYOUT	Mesosopic
PathFinder	Mesosopic
Egress Complexity	Mesosopic
PedGo	Microscopic
PED/PAX	Microscopic
GridFlow	Microscopic
ASERI	Microscopic
BldEXO	Microscopic
EXITT	Microscopic
Legion	Microscopic
Myriad	Microscopic
CRISP	Microscopic
EGRESS 2002	Microscopic
SGEM	Microscopic
EXIT89	Microscopic
BGRAF	Microscopic
EvacSim	Microscopic

Note: Based on information presented in a review by Kuligowski and Peacock (2005).

Vulnerability of Individuals with Disabilities

Parallel to the development of the evacuation models reviewed earlier, several studies have examined the disproportionate vulnerability experienced by individuals with disabilities during a disaster. The research in this area considers a wide array of impairments and environmental characteristics. For example, Wright, Cook, and Webber (1999) focused on the walking speed of individuals with visual impairments under different emergency lighting conditions; whereas, Vanderkooy (2002) examined the response of individuals with hearing impairments to audible alarms. Despite the variety of emphasis and implementation, three common ideas supporting the notion of disproportionate vulnerability arise from the literature. First, disaster and disability are social phenomena characterized by preexisting inequalities that influence exposure to risk. Second, hazardous conditions can limit functional competency or the ability to take protective action exposing individuals with disabilities to greater risk. Third, social distancing leading to exclusion from emergency planning and procedures exposes individuals with disabilities to greater risk.

Historically, disasters have been viewed as purely natural occurrences that indiscriminately affect everyone (Peek & Stough, 2010). However, recent social science studies present a different view asserting that disasters are social phenomena characterized by the combination of hazardous conditions and human action (Cutter, Boruff, & Shirley, 2004). Stated another way, the impact of disasters arise from the interaction of political, economic and social factors that influence people's ability to respond to adverse situations (Peek & Stough, 2010). Due to preexisting inequalities in

many of these areas, some groups are naturally exposed to greater risk than others (Morrow, 1999). Likewise, the concept of disability itself has been redefined. In the past, disability studies in the United States have used the Americans with Disabilities Act (1990) definition that identifies disability as a physical or mental impairment that substantially limits one or more of the major life activities of the individual (Rimmer, Braddock, & Pitetti, 1996). However, more recent studies have adopted the World Health Organization's (2001) International Classification of Functioning, Disability, and Health, which indicates that disability results from the interaction between the health condition of an individual and their personal and environmental setting (Hemingway & Priestley, 2006). During a disaster, the effects of these interactions are amplified for those already limited in terms of personal autonomy and social resources leading to greater risk (Morrow, 1999).

A recent example from the research in this area was presented by Chou and colleagues (2004). In this population-based cohort study, the authors identified the mortality risk factors for an earthquake that occurred on September 21, 1999, in the Taichung region of Taiwan. Two government-managed information sources, the Family Registry Database and the National Health Insurance Enrollment Database, were used to analyze demographic and health status data for 1,202,002 residents over several weeks following the event. The results of the study revealed that people with mental disabilities, people with moderate physical disabilities, and people who had been hospitalized just prior to the earthquake were the most vulnerable to disruptions in basic services, with the degree of vulnerability being inversely proportional to income level. The significant

association between disability, socioeconomic status, and earthquake mortality lead the authors to conclude that the resulting deaths did not happen randomly.

As suggested by this research, functional competency defined by disability-environment interactions may be limited during a disaster exposing individuals with disabilities to greater physical risk. Depending on the nature of impairment and the condition of the environment, individuals with disabilities may not be able to take the same protective actions as individuals without disabilities. For example, individuals with mobility impairments may evacuate at slower speeds due to emergency conditions resulting from complex environments created by structural damage (Clark-Carter, Heyes, & Howart, 1986). Likewise, individuals with hearing impairments may have difficulty recognizing audible alarm signals that may be altered by intervening walls, doors, and ambient noise (Vanderkooy, 2002). Finally, individuals with cognitive impairments simply may not recognize signs of environmental damage or understand the impending threat (Kailes & Enders, 2007). A good review of the literature in this area was presented by Christensen, Collins, Holt, and Phillips (2006). In this review, 16 studies clearly demonstrated that individuals with disabilities were unable to evacuate as effectively as others in existing structures exposing them to greater risk.

Wright and colleagues (1999) compared the mean walking speed of individuals with visual impairments and individuals without disabilities under different emergency lighting conditions and way-finding provisions along an evacuation route. The authors examined walking speed using ceiling-mounted emergency luminaires, photoluminescent markings, electroluminescent strips, LED strips and miniature incandescent way-finding

strips. The results of the study indicated that the walking rate of visually impaired subjects was only 43% to 69% of nonimpaired individuals on level parts of the route and 70% to 87% on stairs. The evacuation performance for both groups was highest with powered way-finding systems such as ceiling-mounted lighting. Non-powered systems, such as photoluminescent markings, resulted in the slowest speeds and were considered more difficult to use.

A less obvious situation may result from social distancing, which leads to exclusion from emergency response planning and procedures further exposing individuals with disabilities to greater risk. The perception of individuals with disabilities has been shown to elicit conflicting behavior from others. While those perceiving individuals with disabilities often verbally express compassion and willingness to help they also express discomfort and anxiety through avoidance of physical contact and other nonverbal cues (Kleck, 1968, 1969). In the pre-event context of disaster, nonverbal avoidance behaviors often manifest themselves in exclusion from emergency response planning, policies and training (Fox, White, Rooney, & Rowland, 2007; Rowland, White, Fox, & Rooney, 2007). As a result individuals with disabilities may be unprepared to take protective action before and during an emergency (Center for Independence of the Disabled, 2004).

A good example of the vulnerability created by social distancing and exclusion is presented by Rooney and White (2007). In this study the authors conducted a survey in which 56 respondents with mobility impairments that experienced either a natural or human-caused disaster described what was most helpful for survival and the difficulties

they experienced before and after the event. The results of the study indicated that disability-related disaster preparedness was instrumental in determining their survival, independence, health, and safety. Several problems arose when they were excluded from community and workplace evacuation plans. In one case, an individual was left behind when others without disabilities were evacuated. In another case, individuals were not able to locate accessible shelters or accessible temporary housing. In several cases participants reported that response personnel were wholly unaware of disaster relief options for individuals with disabilities. Rooney and White concluded that individuals with disabilities were at great risk due to a lack of, or inadequacies in, preparedness and response procedures.

The BUMMPEE Model

Notwithstanding the two major research streams presented earlier in Chapter II, the only evacuation model that considered the vulnerability of individuals with disabilities during a disaster was BUMMPEE (Bottom-Up Modeling of Mass Pedestrian flows—implications for the Effective Egress of individuals with disabilities).

BUMMPEE is a microscopic simulation model first presented in Christensen and Sasaki (2008). The specific purpose of this model was to explore how well the built environment accommodated the needs of individuals with disabilities in evacuation situations by incorporating both environmental and population characteristics that accurately describe the diversity and prevalence of disabilities in the population. The following discussion focuses on the aspects of the BUMMPEE model most relevant to this research. Readers

are referred to the published manuscript for a more thorough treatment of the system.

The criteria established by the authors for describing the heterogeneity of individuals with disabilities in the simulated population were based upon representative factors that have already been shown to have an effect on evacuation behavior (Christensen et al., 2006). Six criteria were identified including: (a) individual speed, (b) individual size, (c) ability to negotiate specific kinds of terrain (i.e., stairs, etc.), (d) ability to interpret the environment, (e) individual psychological profile (i.e., ability to concentrate, learn, or remember), and (f) need for assistance. The BUMMPEE model addressed these criteria by establishing distinct populations including nondisabled, motorized wheelchair users, nonmotorized wheelchair users, visually impaired, hearing impaired, and stamina impaired, which were defined by variations in the six criteria. Note that psychological profile was modeled for the overall population only. The ability to interpret the environment was not specifically addressed either as it was assumed that the variation in other criteria would capture the operative behavior of the disability.

The criteria for describing the built environment were based upon factors that have been shown to have a disproportionate effect on individuals with disabilities (Christensen et al., 2006) as well as generally accepted accessibility axioms. Four criteria were identified including: (a) exit character, (b) route character, (c) obstacle character, and (d) planned systems character. The BUMMPEE model addressed these by categorizing each component of the built environment for the differing effects of each criterion on individuals with disabilities. For example, stairs would be assigned values indicating whether or not they could be used to exit the structure, whether or not the route

was traversable (expressed in terms of speed for each population type), whether or not they represented an obstacle to be negotiated (expressed in the same manner as route character), and whether or not they represented a planned system feature or those defined by the Americans with Disabilities Act Accessibility Guidelines (ADAAG) such as areas of rescue assistance. Note that elevators were classified as nonexits and unusable in terms of route character and obstacle character for all population types in the BUMMPEE model.

The primary mechanism underlying the movement of participants through the simulated environment was based upon reinforcement learning, a well-known machine learning technique in which participants determine ideal directional choices based on environmental feedback specific to their population type (Sutton & Barto, 1999). That is, participants learned the best route through the built environment by exploring their surroundings and storing the information for later use during timed evacuation simulation runs. As Christensen and Sasaki (2008) indicated, this technique is useful for modeling different levels of familiarity with the environment by limiting the degree of prior exploration. However, it is difficult to ascertain how much training is necessary to model a realistic population type profile since it is expressed primarily in terms of simulated exploration hours. Note that with enough training, learning algorithms are expected to converge upon a global optimum, or in this case, full knowledge of the structure for every participant. However, it is unclear how much training is required to do so.

In this particular study, the BUMMPEE model was evaluated by comparing the results of a real world evacuation to several simulated ones using the same setting and

population parameters. The Human Service Research Center on the Utah State University campus served as the built environment for both the real-world and simulated evacuations. The building is a four-story office complex with three exits on the ground floor, of which only one is accessible by individuals with disabilities. Seventy-one participants were evacuated based upon the population parameters of the real-world event. Specifically, 65 participants were nondisabled, 4 participants were stamina impaired, 1 participant was a wheelchair user, and 1 participant was visually impaired. The population and environmental criteria including speed, size, and ability to negotiate specific terrain were assigned according to the best available empirical data. Two hundred fifty simulations were conducted to account for variations in individual simulations.

The results of the comparison revealed that the evacuation time, or the time at which the final participant exited the building, for the real-world event was 155 seconds (s) while the mean evacuation time for the 250 simulations was 122s. Note that the model did not explicitly consider response delay. Response delay refers to the human tendency to wait some time before recognizing an evacuation alert. For example, Purser and Bensilum (2001) observed that participants took an average of 29s to respond to an evacuation signal. According to Christensen and Sasaki, this value was very similar to the 33s discrepancy between real-world and simulated evacuation times observed in their study. Thus, they concluded that the results were comparable.

The manner in which Christensen and Sasaki (2008) modeled the heterogeneity of evacuees and the characteristics of the built environment represents a significant step

forward for microscopic evacuation simulation models. Past research has demonstrated a tendency to standardize towards a singular form of mobility impairment by limiting only the speed of movement (Christensen et al., 2006). The establishment of several new criteria for describing the diversity and prevalence of individuals with disabilities in the population may be viewed as a standard that future models should implement.

On the other hand, several opportunities for enhancing the realism of the simulations, and thus the general reliability and predictive capability of the model, exist. First, a psychological profile was modeled for the overall population only, even though it is reasonable to assume evacuees would vary by type. For example, individuals may choose different evacuation destinations and routes according to population-specific characteristics. Second, limiting assumptions regarding the use of specific environmental components were made even though past research may support a more progressive approach. For example, elevators were not accessible by any population notwithstanding evidence that supports their usefulness during evacuations (Bazjanik, 1977). Third, the underlying movement algorithm required arbitrary parameterization when other techniques may offer more prescribed control. For example, the breadth-first search algorithm (Knuth, 1997) would allow the modeling of structural layout knowledge in terms of area visited instead of exploration hours. Fourth, certain evacuation behaviors were not modeled when doing so would potentially bring results more in line with real-world performance. For example, initial response delay was not modeled even though it closely accounted for the discrepancy observed between simulated and real world evacuation times.

Conclusion

Despite numerous existing evacuation models only one was found that represented disability and environment interactions in a manner consistent with the findings of social science research in this area. Thus, the information stemming from evacuation models, which specifically consider the vulnerability of individuals with disabilities, is limited. In one respect, the BUMMPEE model represents an important standard for future model development seeking to provide further understanding in this area. However, several opportunities for enhancing the realism of the simulated evacuations were also identified.

Theoretical Framework

The purpose of this research is to generate further understanding regarding the vulnerability of individuals with disabilities during emergency evacuations by concentrating on the development of a new model. Because of the inherent complexity of disability and environment interactions, it was useful to define a theoretical evacuation framework to highlight factors guiding the conceptual design. The factors were largely derived from evidence presented in the literature review concerning the vulnerability of individuals with disabilities during a disaster.

The theoretical evacuation framework defined for this research includes four factors: (a) individual characteristics, (b) operational management, (c) the built environment, and (d) population distribution. Individual characteristics refer to all of the physical and psychological attributes that influence behavior during an evacuation.

Examples of such characteristics include visual, auditory, and cognitive capabilities (Clark-Carter et al., 1986; Kailes & Enders, 2007; Vanderkooy, 2002). Operational management refers to the implementation of procedures designed to control behavior during an evacuation and includes all the equipment, personal, and training required to do so. Social distancing leading to exclusion from emergency procedures was found to be a major contributor to the vulnerability of individuals with disabilities during a disaster (Fox et al., 2007; Rooney & White, 2007; Rowland et al., 2007). The built environment refers to the physical setting in which the evacuation takes place. The characteristics of the built environment interact with individual characteristics and operational management to further shape behavior during an evacuation (Hemingway & Priestley, 2006; Morrow, 1999; Peek & Stough, 2010). Population distribution refers to the proportions of different population types participating in an evacuation. Considering the emergent nature of crowd behavior, it was postulated that the different population distributions would result in fundamentally different individual-level interactions leading to novel pattern formation on a global scale (see Bonabeau, 2002, for a thorough discussion of emergence theory in relation to simulation). Note that three of the four factors, individual characteristics, operational management and the built environment, closely resemble those included in other evacuation frameworks proposed in the literature (Christensen, Blair, & Holt, 2007). Figure 1 shows a graphical representation of the theoretical evacuation framework defined in this study.

The relationship between these four factors is expected to determine overall evacuation performance. That is, for any given emergency the interactions between the

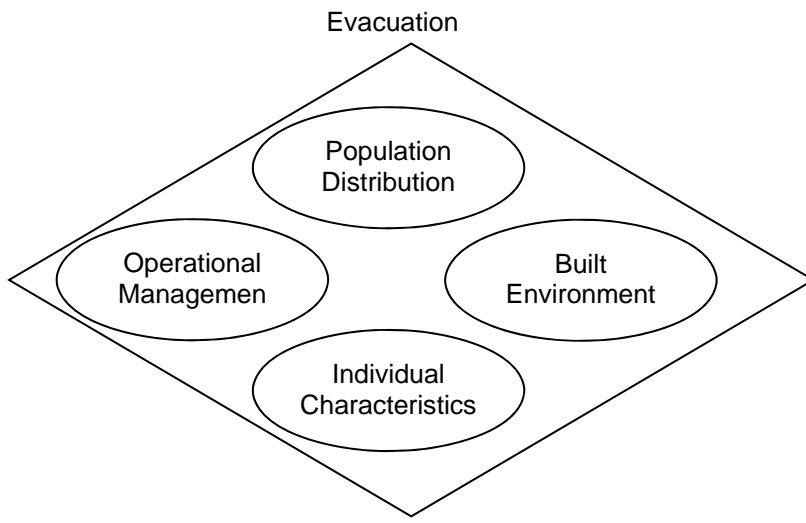


Figure 1. Theoretical evacuation framework.

unique manifestations of each factor are expected to influence the overall evacuation time for better or worse. For example, unexpected changes to the built environment such as structural damage or smoke accumulation may negate the positive effects of well thought out response procedures, or environmental design, resulting in unacceptably long evacuation times. Understanding the relationships between the four factors of evacuation is necessary to be able to reduce the vulnerability of individuals with disabilities. As a result, the simulation experiments presented in later chapters were designed around the manipulation of one or more of these factors.

CHAPTER III

RESEARCH METHOD

General Approach

The research methodology used in this study was agent-based simulation (ABS). ABS is the formalization of methods used to drive the production of microscopic models and observe their output for research purposes. Based on the literature review, microscopic models were the most adept at reproducing expected flow-density profiles and emergent behavior of pedestrian crowds, both of which are central to this research. In terms of the scientific method, ABS has been contrasted with induction and deduction as a “third way” (Gilbert, 1996). That is, ABS is like deduction because it begins with a set of assumptions. However, it does not prove theorems. Instead, ABS generates data that can be analyzed inductively. Nevertheless, it does so based on rule output as opposed to direct observation (Axelrod, 1997). Thus, ABS is an exploratory approach that allows researchers to form generalizations explaining complex phenomena for which data is difficult to obtain.

ABS is a well established research methodology that has been successfully used in a wide variety of applications including traffic congestion (Burmeister, Haddadi, & Matylis, 1997), infectious disease epidemiology (Haung, Sun, & Hsieh, 2004), and the growth and decline of ancient societies (Kohler, Gumerman, & Reynolds, 2005). Though generally underrepresented within the management information systems (MIS) field (Vitolo & Coulston, 2004), ABS has been used to study stock market trading (Luo, Liu,

& Davis, 2002), portfolio management (Sycara, Paolucci, Van Velsen, & Giampapa, 2003), and workflow management (Merz, Lieberman, & Lamersdorf, 1997).

A recent example from the MIS domain used ABS to investigate knowledge sharing among organizations (Wang, Gwebu, Shanger, & Troutt, 2009). In this study, the authors were able to systematically test several assumptions regarding employee behavior that revealed emergent, though counterintuitive, outcomes. For example, the authors discovered that lowering the benefits from shared knowledge significantly increased the level of contribution contradicting many previous studies in this area. Through the use of ABS the authors were able to demonstrate the restrictive effect of specific conditions and assumptions used by prior research in this area.

Several advantages have contributed to the growing popularity of ABS in recent years. In particular ABS is adept at revealing novel and coherent structures arising at the level of the aggregate system that cannot be seen by examining agents in isolation (Corning, 2002). For example, the study of a crowd clamoring to purchase an item might reveal movement in a generally different direction than many of the individuals comprising it. In terms of individuals with disabilities, ABS has an important advantage in the ability to incorporate multiple perspectives in a simple and flexible manner. Other approaches often force researchers to make limiting assumptions that may contradict real-life behavior. ABS is ideal for modeling problems where conflicting interests are essential (Wang et al., 2009), which is why it has been adopted for this study.

ABS, however, is not without its challenges. Some of the potential risks faced by researchers using this method include: (a) failure to state a clear objective, (b) failure to

frame an answerable question, (c) inappropriate level of complexity, (d) wrong assumptions regarding the model, and (e) misinterpretation of simulation output (Thesen & Travis, 1995). The reason for committing many of these errors is often related to the nature of the system under consideration. Human beings are characterized by a multifaceted psychology that is often difficult to quantify, calibrate, or justify.

In regards to individuals with disabilities, this difficulty extends to physical characteristics as well. For example, there is a notable lack of empirical evidence supporting the specification of certain disability and environment interaction parameters. While several studies report the speed of individuals with disabilities in varying environmental conditions (Clark-Carter et al., 1986; Vanderkooy, 2002; Wright et al., 1999), there are none available that specifically examine this trait in regard to negotiating obstacles such as immovable seating, tables, and so forth. As a result, parameter values must be specified based on rudimentary assumptions. For example, in this research the maximum speed for negotiating obstacles was specified as 0.0 meters per second (m/s) for wheelchair users because it was assumed that they are inherently unable to pass over or manipulate environmental features of this type.

Procedures

A generalized form of ABS derived from Axelrod (1997) and Dooley (2002) was used for this study. The following six steps were observed: (a) design, (b) development, (c) verification, (d) validation, (e) experimentation, and (d) publication. The remainder of this section summarizes each step. Details specific to their execution in this research are

also provided.

The design step involves the overarching specification of the evacuation model. Several decisions must be made during this step such as what should be omitted or included in the model, selection of hardware and software platforms, and so forth. These decisions are primarily driven by the problem specification and assumptions regarding the system to be modeled. In this study, these assumptions were encapsulated in the theoretical evacuation framework developed from the literature review. However, the results of the BUMMPEE analysis, qualitative fieldwork, and direct observations also played an important role. For example, the representation of agent attributes and environmental characteristics were directly influenced by the BUMMPEE design. Likewise, an interview with a disabled student influenced the decision to include assisted evacuation capabilities. Finally, direct observations of elevator travel times provided the data for the parameterization of this feature within the model. Further detail regarding the influence of these activities is presented in subsequent chapters.

The development step refers to the process of writing the software that implements the model design. Many purpose-built ABS platforms have been created to facilitate this task such as SWARM (Terna, 1998) and Repast (North, Collier, & Vos, 2006). Other researchers have created models from the ground up using general programming languages such as Java, Lisp, C or C++ (Pan, Han, Dauber, & Law, 2007), which is the approach adopted in this study. The evacuation model was developed as a stand-alone program using C++ and the MFC library for the Windows platform.

The verification step is conducted to make sure the software has internal validity.

That is, verification ensures that the program code reflects the behavior implicit in the specification of the conceptual model. In this study, code walkthroughs, input-output testing, code debugging, and calculation verification were used to verify the correctness of the implementation.

The validation step is conducted to make sure the model demonstrates external validity. That is, validation ensures that the model can be relied on to reflect the behavior of the system being investigated. Two methods are commonly used to do so. First, simulation results are compared to the behavior observed in real world systems. In this study, simulated evacuation performance was compared to the results of a real world fire drill for a multi-story office building that included individuals with disabilities. Second, simulation results are replicated in different contexts. In this study, simulations were conducted in three different environments: (a) a multi-story office building, (b) an international airport, and (c) a major sports arena. A detailed description of each environment is provided in subsequent chapters.

The experimentation step refers to the design and implementation of simulation runs in order to generate further understanding of the problem. Experimentation is often executed in an iterative manner. That is, implementations often generate insight leading to new designs that trigger the cycle again. In this research, experiments were created by specifying several simulation scenarios distinguished by the systematic alteration of key parameters. Based on the results of these scenarios, further experiments were created and implemented. For example, several scenarios were executed to determine the number of people who could be safely evacuated from a building before life-threatening bottlenecks

arose. The results of these scenarios led to further experiments examining the effects of elevator use on the occurrence of this phenomenon.

The final step is the publication of results. That is, the outcomes of the experiments are published in a format ready for use by the academic or practitioner communities or both. Note that the review process associated with the publication of research often lead to comments and/or suggestions that are fed back into subsequent model designs. Figure 2 depicts a graphical representation of the research methodology used in this study.

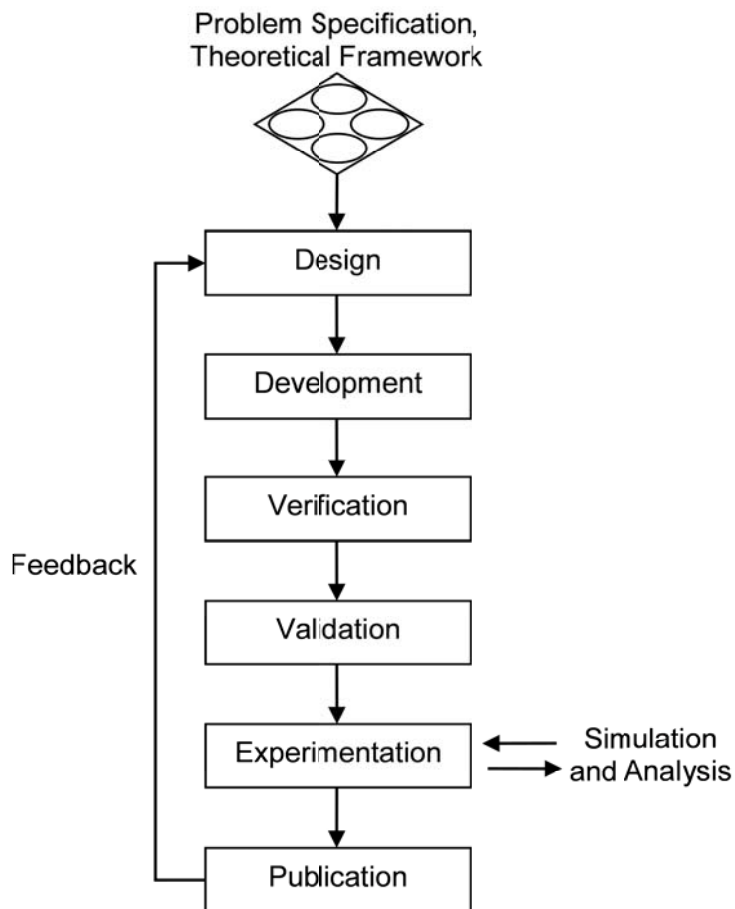


Figure 2. Research methodology used in this study.

CHAPTER IV

SIMULATION OF AN OFFICE BUILDING EVACUATION

Introduction

This chapter describes the development of a new ABM called Exitus. Exitus was specifically designed to address the limitations of prior evacuation models in regard to the representation of the interaction between the environment and individuals with disabilities (see Chapter II for a thorough review of the specific opportunities for improvement in this area). In this initial phase of the research, the model was used to simulate evacuations from a multi-story office building. Several experiments surrounding the assessment of emergency response plans were conducted. The results of the experiments led to the identification of several factors that contribute to the development of optimized emergency evacuation procedures for heterogeneous populations.

System Architecture

In the Exitus model virtual evacuees or agents were created after the manner specified in Christensen and Sasaki (2008). That is, six distinct agent types were created: (a) nondisabled; (b) motorized wheelchair users, (c) nonmotorized wheelchair users, (d) visually impaired, (e) hearing impaired, and (e) stamina impaired. Each type embodied both physical and psychological characteristics that address the established criteria for describing the functional competency of people with and without disabilities in the general population. Such criteria included speed, size, ability to negotiate terrain, and

others (Christensen et al., 2006). For example, nonmotorized wheelchair agents traveled at a faster speed (0.89 m/s) than stamina impaired agents (0.78 m/s) on a level plane but could not do so on stairs without help. Motorized and Nonmotorized wheelchair agents were programmed to attempt to find refuge areas in a building whereas other agent types were not. A refuge area is a location designed to protect people with disabilities during an emergency when self-evacuation is unsafe or impossible.

Agents existed within a virtual environment discretised into a two-dimensional grid of cells each representing 0.023 m^2 . In accordance with Christensen and Sasaki (2008), each cell contained accessibility information encompassing various conditions that have been shown to have a disproportionate effect upon the behavior of individuals with disabilities during an emergency evacuation (Christensen et al., 2006). The accessibility characteristics were: (a) exit character, (b) route character, and (c) obstacle character, each of which referred to the functional demand imposed by the environment upon an individual's competency to meet it in relation to their disability. More specifically, accessibility characteristics were defined for each cell by ordinal position within a seven digit number. For example, exit character e was defined for cell x as *all exit* ($e[x]=1$), *limited exit* ($e[x]=2$), *no exit* ($e[x]=3$), or *refuge* ($e[x]=4$). Similarly, route character r was defined for cell x as *default speed* ($r[x]=1$), *stair speed* ($r[x]=2$), *obstacle speed* ($r[x]=3$), and so on. Feature id, floor number, and other information were also embedded in this value.

Agents moved from cell to cell at each discrete time step according to a transition probability similar to traditional cellular automaton models. The transition probability

was influenced by the interaction of agent and accessibility characteristics previously described. Specifically, agents determined transition probability p as their velocity v modified by the route character c for the current location i,j in relation to the signal interval t , which yields equation (1). The transition probability (p) is then compared to a real-valued random number u generated from a uniform distribution determining whether or not an agent could move (m), as in equation (2).

$$p = \frac{vc_{ij}}{t} \quad (1)$$

$$m \rightarrow p \geq u[0,1] \quad (2)$$

Given the decision to move, agents exhibited three behaviors: (a) response delay, (b) destination choice, and (c) direction choice. The implementation of these behaviors was designed to address the limitations demonstrated in the original BUMMPEE model. Response delay refers to the human tendency to wait some time before responding to an evacuation alert (Proulx & Fahy, 2001). At the beginning of a simulation each agent was assigned a random delay generated from a normal distribution having $M = 29s$ and $SD = 9s$ (Purser & Bensilum, 2001). At each signal interval the agent checked to see if the current time had exceeded the delay. If so, the agent executed destination and direction choice behaviors. If not, the agent waited until the next opportunity for movement. Destination choice behavior refers to the selection of intermediate and final destinations based upon available exits according to agent type preferences. When the simulation started, each agent chose a final destination from all available exits based on proximity to their current location. If the agent was not on the same level as the final destination an

intermediate one was chosen from the set of available connecting features such as a stairways or elevators using the same mechanism. The selection of intermediate and final destinations was driven by population type. For example, individuals using wheelchairs favored areas of refuge over other alternatives if available. Direction choice behavior refers to the selection of the next prospective location or cells. Given the decision to move, an agent evaluated the obstacle character c or penetrability of each cell corresponding to the set of four cardinal directions, $D \in \{north, south, east, west\}$, based on the agent's origin at $(0,0)$ as depicted in Figure 3. Note that some agent types occupied more space than others. For example, hearing impaired agents occupied 3×3 cells whereas motorized wheelchair agents occupied 5×5 cells. If a cell was impenetrable according to agent type characteristics, e.g., the cell was part of a wall or occupied by another agent, the direction was removed from the set of available choices.

The agent's final movement was determined by the shortest path to the destination. Shortest paths were quantified by means of static floor fields (SFF; Kirchner & Schadschneider, 2002) describing the shortest time to an exit or connecting feature such as a stairway. Specifically, SFF cells contained values indicating the time to

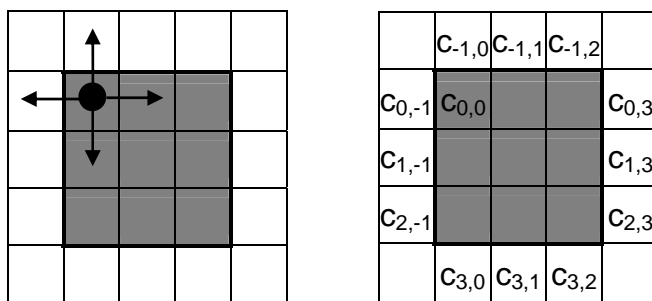


Figure 3. Direction choice and corresponding obstacle character.

destination from their location as an integer. For example, an exit cell had a value of 0 while one farther away was greater. Agents selecting a direction were motivated to choose the one having the lowest time to destination. Figure 4 depicts a graphical representation of a simple SFF in Cartesian space with time-to-exit values for each coordinate. Note the single exit located in the middle of the south wall denoted by time-to-exit values of 0. Black cells indicate impenetrable areas such as a wall. SFFs are easily generated for irregular and complex geometries using a standard breadth-first search algorithm (Knuth, 1997). This way, knowledge of the structure was controllable according to geographical area as opposed to more indirect concepts such as exploration hours.

Verification and Validation

The internal and external validity of the model was assessed as follows. First, the program code was evaluated to determine whether or not it reflected the behavior implicit

	10	9	8	8	8	8	9	10	
	9	8	7	7	7	7	8	9	
	8	7	6	6	6	6	7	8	
	7	6	5	5	5	5	6	7	
	6	5	4	4	4	4	5	6	
	5	4	3	3	3	3	4	5	
	4	3	2	2	2	2	3	4	
	3	2	1	1	1	1	2	3	
			0	0	0	0			

Figure 4. Static floor field for 10 x 10 area.

in the specification of the conceptual model. Code walkthroughs, input-output testing, code debugging, and calculation verification were used to verify the correctness of the implementation. Micro-level behaviors during test simulations were observed as well. Individual agents demonstrated realistic path-finding behavior or purposeful movement toward destinations such as stair wells and exits without excessive wandering.

Second, the model's output was compared to the historical behavior of the real-world target system. In this case, the Human Services Research Center (HSRC) building located on the Utah State University campus was used for the comparison. Note that the HSRC building is the same structure used to validate the BUMMPEE model (a full description of the structure is provided in the following section). The results of one hundred simulations using the same building and population distribution demonstrated comparable results at a mean evacuation time of 152s compared to 155s for the real world exercise.

Simulation Experiments

Experiment 1: Assisted Evacuations

The objective of the first experiment was to estimate the effectiveness of an alternative evacuation strategy known as assisted evacuations. The main idea of the assisted evacuation strategy is to pair each individual using a motorized or nonmotorized wheelchair with a nondisabled assistant capable of helping them throughout the entire building evacuation exercise. This is in contrast to the typical defend-in-place strategy requiring individuals with disabilities to wait in refuge areas until they can receive help

from firefighters or other emergency response personnel.

Assisted evacuations are the typical approach observed in post event studies (Shields, Boyce, & McConnell, 2009) despite the prevalence of refuge area policies in formal plans. The results from an interview with a student who participated in an unplanned evacuation also support the inclusion of assisted evacuations in the experiment design. The unplanned evacuation occurred in the Taggart Student Center on the Utah State University campus during October 2009. Despite having used a wheelchair for several years the student did not know what a refuge area was or where one might be located. Furthermore, the student's first inclination was to seek help from someone else. With no other apparent options, the student asked a university employee to assist her out of the building. When asked what she would have done if the employee had not been available, the student responded by indicating she would have found someone else to assist her. From this student's view, an assisted evacuation appeared to be the only reasonable means for safely exiting the building.

The experiment was conducted using the same HSRC map employed in the BUMMPEE and Exitus validations. The HSRC building is a four-story office complex occupying roughly 4,000 m². The building is designed to provide private offices, modular workspace, and conference facilities in support of research and development projects conducted at the university. In this respect it is very similar to other buildings found on the campus. For example, the Education building and Early Childhood Education Center are very similar in design. The building contains three exits located on the ground floor only one of which is accessible by individuals with disabilities. Designated refuge areas

are located adjacent to the stairwells on every floor with the exception of the second or ground floor. Figure 5 depicts the map of the HSRC building used in this experiment. Gray areas denote exits, refuge areas, and stairwells; black areas denote walls and other impenetrable space.

Seventy-one agents were evacuated during the simulations in accordance with the total used during the model validation. The diversity and prevalence of individuals with disabilities was assigned based on distributions defined by U.S. Census Bureau (2003) values (i.e., 86% nondisabled, 3% motorized wheelchair, 3% nonmotorized wheelchair, 1.5% hearing impaired, 5% lower stamina, and 1.5% visually impaired). The criteria for speed, size, and ability to negotiate obstacles was assigned according to empirical data when available (Boyce, Shields, & Silcock, 1999; Wright et al., 1999) and accessibility axioms when not. Table 2 depicts these parameter settings in detail. Note that the speed and size of agents moving together were also required. Because of the lack of empirical



Figure 5. Map of HSRC building.

Table 2

Specification of Agent Parameters

Agent type	Maximum speed (m/s)			Size (m ²)
	On level plane	On stairs	Over obstacle	
Nondisabled	1.25	0.70	0.70	0.21
Motorized wheelchair	0.69	0.00	0.00	0.58
Nonmotorized wheelchair	0.89	0.00	0.00	0.58
Hearing impaired	1.25	0.70	0.70	0.21
Visually impaired	0.86	0.61	0.00	0.21
Lower stamina	0.78	0.36	0.00	0.21

data in this area rudimentary assumptions were necessary. Specifically, the speed of a wheelchair agent and nondisabled assistant moving together was assumed to be the average of their individual settings. Similarly, the size of the wheelchair agent and nondisabled assistant were specified as the sum of both.

The simulation scenarios were based upon a pre-event evacuation similar to the one conducted for the real world fire drill. The scenarios differed in terms of evacuation strategy and the proportion of individuals with disabilities. Scenario A utilized the refuge area strategy. Scenario B utilized the assisted evacuation strategy. Scenarios C and D utilized the assisted evacuation strategy with greater proportions of individuals with disabilities. It is generally recognized that improvements in life expectancy have resulted in higher rates of disease and disability among the elderly (Parker & Thorslund, 2006). Scenarios C and D were devised to evaluate the effectiveness of assisted evacuations in light of these expected demographic changes. However, to maintain clarity, only the

numbers of individuals using wheelchairs were increased. Last, rather than execute new simulations for Scenario A, the results of the validation runs were used since they met the required specification. One hundred simulations were conducted for each scenario. Evacuation performance was measured in terms of mean evacuation time or MET in seconds. The definition of simulation scenarios is depicted in Table 3.

Overall, the results of the experiment demonstrated that assisted evacuations were comparable to the use of refuge areas. However, increasing the proportion of wheelchair agents resulted in noticeably slower times. The results of the experiment are presented in Table 4. An alpha level of .05 was used for all statistical tests.

Though there was an increase of 8.30s in the observed MET between Scenarios A and B it was not statistically significant. By definition, the assisted evacuation strategy required wheelchair types to reach a refuge area and then continue to a building exit. Thus, the slight increase is attributed to the extra distance travelled. The order of MET by agent type for Scenario A was also very similar to the simulation results of Scenario B with agents using wheelchairs and those with lower stamina taking the longest to evacuate. Note that Scenario A was similar to the original BUMMPEE validation in that

Table 3

Specification of Scenarios for Assisted Evacuation Experiment

Scenario	Population distribution	Evacuation strategy	Simulations
A	1x wheelchair	Refuge area	100
B	1x wheelchair	Assisted evacuations	100
C	2x wheelchair	Assisted evacuations	100
D	4x wheelchair	Assisted evacuations	100

Table 4

Simulation Results for Assisted Evacuation Experiment (in seconds)

Scenario	Statistic	All types	Nondisabled	Visual	Motor ^a	Nonmotor ^b	Hearing	Lower stamina
A	MET	150.64	122.35	76.05	95.46	111.48	73.63	133.79
	SD	24.17	12.81	38.15	39.88	25.44	20.42	25.82
B	MET	158.94	126.24	80.75	121.13	127.16	72.76	132.48
	SD	28.88	18.12	33.47	41.24	26.00	19.88	23.78
C	MET	178.62	119.82	80.86	152.24	150.15	65.05	133.72
	SD	28.62	14.42	40.28	37.15	26.70	20.01	23.12
D	MET	197.01	127.16	81.25	174.87	180.29	69.46	140.44
	SD	30.09	16.40	33.95	37.05	30.04	26.63	21.45

^aMotorized Wheelchair

^bNonMotorized Wheelchair

disabled individuals were considered evacuated not only by exiting the building but by reaching a refuge area as well. This is an overly optimistic approach given that disabled individuals are considered evacuated when in reality they may still be inside the building. Considering the hidden rescue time RT for the simulations in Scenario A (i.e., the time required for emergency responders to arrive at the scene, locate the individuals inside, and help them out of the building), we may reformulate our results in terms of the following equation, $MET_B < (MET_A + RT \rightarrow \infty)$, indicating the effectiveness of assisted evacuations over the refuge area strategy. From an emergency management perspective these results are useful because they point to the feasibility of adopting a total evacuation strategy for individuals with disabilities as opposed to defend-in-place.

The METs for Scenario C and D were significantly different from Scenario B. As expected the MET for motorized and nonmotorized wheelchair agents in both groups

increased dramatically while all other types stayed relatively the same. While the MET for Scenario C remained under the three minute rule of thumb the value for Scenario D was significantly higher. In other words, the building configuration did not appear to support the safe evacuation of occupants using assisted evacuations at more than twice the current number of wheelchair users within accepted limits. From an emergency management perspective this presents a potential problem, namely, how to safely evacuate populations with greater proportions of individuals with disabilities as might occur in settings such as hospitals, nursing homes or the like. The simulation results support the need for reconsidering current practices surrounding building design and construction in order to accommodate this shifting demographic.

Experiment 2: Architectural Capacity

The objective of the second experiment was to estimate the architectural capacity of the building in an emergency evacuation by systematically testing multiple scenarios that differed in terms of the total number of agents and the proportion of agents with disabilities. The intention was to identify parametric levels required to produce unsafe conditions resulting from congestion. While the visualization component of Exitus was capable of providing confirmation of clogging it was important to be able to represent the phenomenon numerically. Thus it was decided to measure the density of adjacent locations over time. More specifically, the density of clogged locations was expected to increase while the density of adjoining locations decreased because no more agents were able to get through. Note that it is very common for clogging to occur near or in stairwells because evacuees are trained to follow these routes to find an exit. Therefore, it

was expected that the density of the stairwell landings in the HSRC building would increase while the density of adjoining flights declined to zero. However, it was unclear how many agents with and without disabilities these locations could accommodate before such conditions arose. Density was calculated by dividing the total area of the location by the total area of the agents occupying it.

In order to find the maximum evacuation capacity of the built environment, the total number of agents and the number of agents with disabilities on the third floor were systematically increased. Nine simulation scenarios were devised. The distribution of agent types was based upon the U.S. Census Bureau values used in the first experiment. However, only one agent type was manipulated to maintain clarity. In this case, agents using wheelchairs were selected based on results in Boyce, Shields, Silcock, and Dunne (2002). In this study, evacuees using wheelchairs caused considerable congestion when they entered the flow of nondisabled evacuees in a stairway. The beginning number of agents and value of each increment were arbitrarily chosen. The intention was to continue, creating new scenarios if necessary, until clogging occurred. The definition of simulation scenarios for the second experiment is depicted in Table 5.

The results of the experiment revealed occurrences of clogging in the northwest landing of the HSRC building during Scenarios J, L, and M only. That is, clogging occurred when there were 400 individuals evacuating with at least twice the normal proportion of individuals using wheelchairs or when there were 200 individuals evacuating with four times as many wheelchair users than found in the current population. It was interesting to note that Scenario K did not result in clogging. This finding was

Table 5

Specification of Scenarios for Architectural Capacity Experiment

Scenario	Population distribution	Total agents
E	1x Wheelchair	100
F	2x Wheelchair	100
G	4x Wheelchair	100
H	1x Wheelchair	200
I	2x Wheelchair	200
J	4x Wheelchair	200
K	1x Wheelchair	400
L	2x Wheelchair	400
M	4x Wheelchair	400

attributed to the fact that there were fewer individuals with disabilities in this scenario. It is expected that individuals with disabilities will tend to occupy more space, move slowly, and hence be more likely to cause clogging by blocking the progress of individuals without disabilities. Figure 6 presents screenshots taken during the simulations that provide visual confirmation of the clogs.

In Scenarios J, L, and M the density of the northwest landing was observed to increase as clogging occurred. At the same time the density of the flight of stairs adjacent to it declined to 0 because no more agents were getting through. In Scenario J the clogging resolved itself after approximately 50 seconds. In Scenarios L and M the clogging remained for the duration of the simulation. Note that the clogging in Scenario M started earlier (approximately 115 seconds after the evacuation started) than in other scenarios mainly because it contained the largest number of agents and the largest number of agents with disabilities. Figure 7 depicts density graphs showing the occurrence of clogging over time for these scenarios.

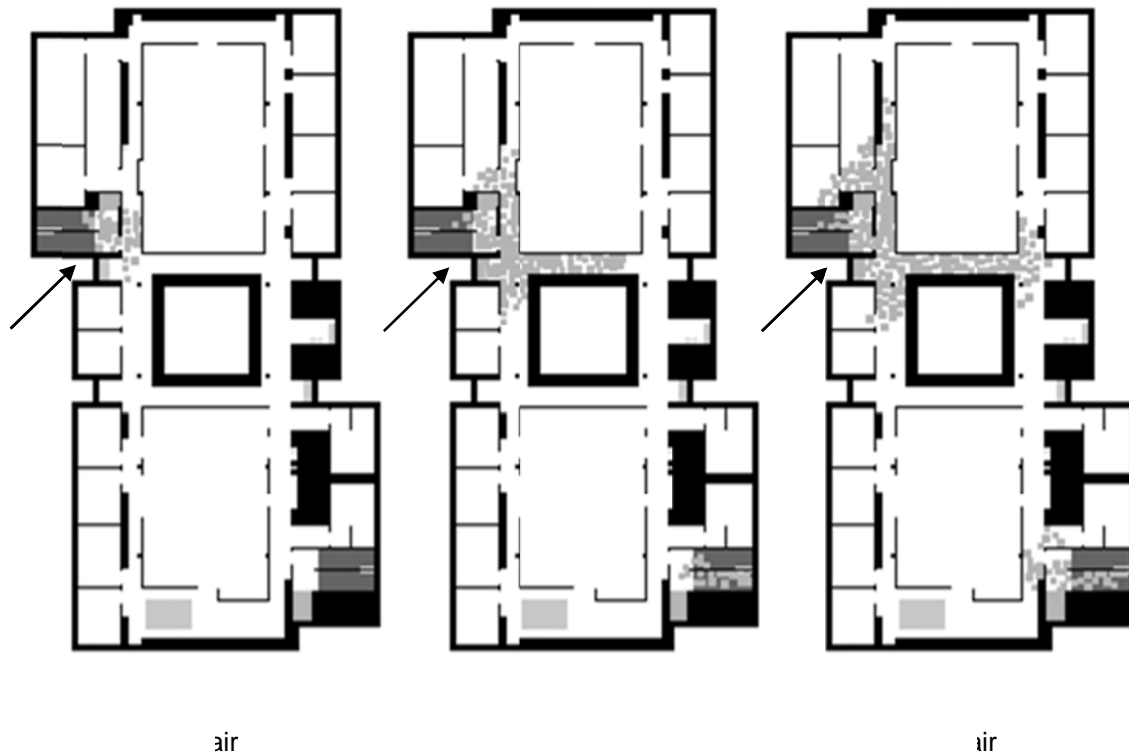


Figure 6. Formation of clogs during Scenarios J, L, and M.

Experiment 3: Elevator Utilization

The objective of the third experiment was to determine whether or not the use of elevators would have an effect on the clogging phenomenon observed in Experiment 2. By convention, elevators are typically grounded during evacuations. The implication is that escape on foot through stairwells is safer. However, as the results of Experiment 2 demonstrate, congestion in stairwells can reach levels where movement stops altogether. On the other hand, elevators have been shown to provide a safe evacuation route when combined with proper planning and control procedures (Bazjanik, 1977). Scenarios J, L, and M from Experiment 2 were repeated with the addition of two functioning elevators on the east side of building. However, only individuals using wheelchairs were allowed

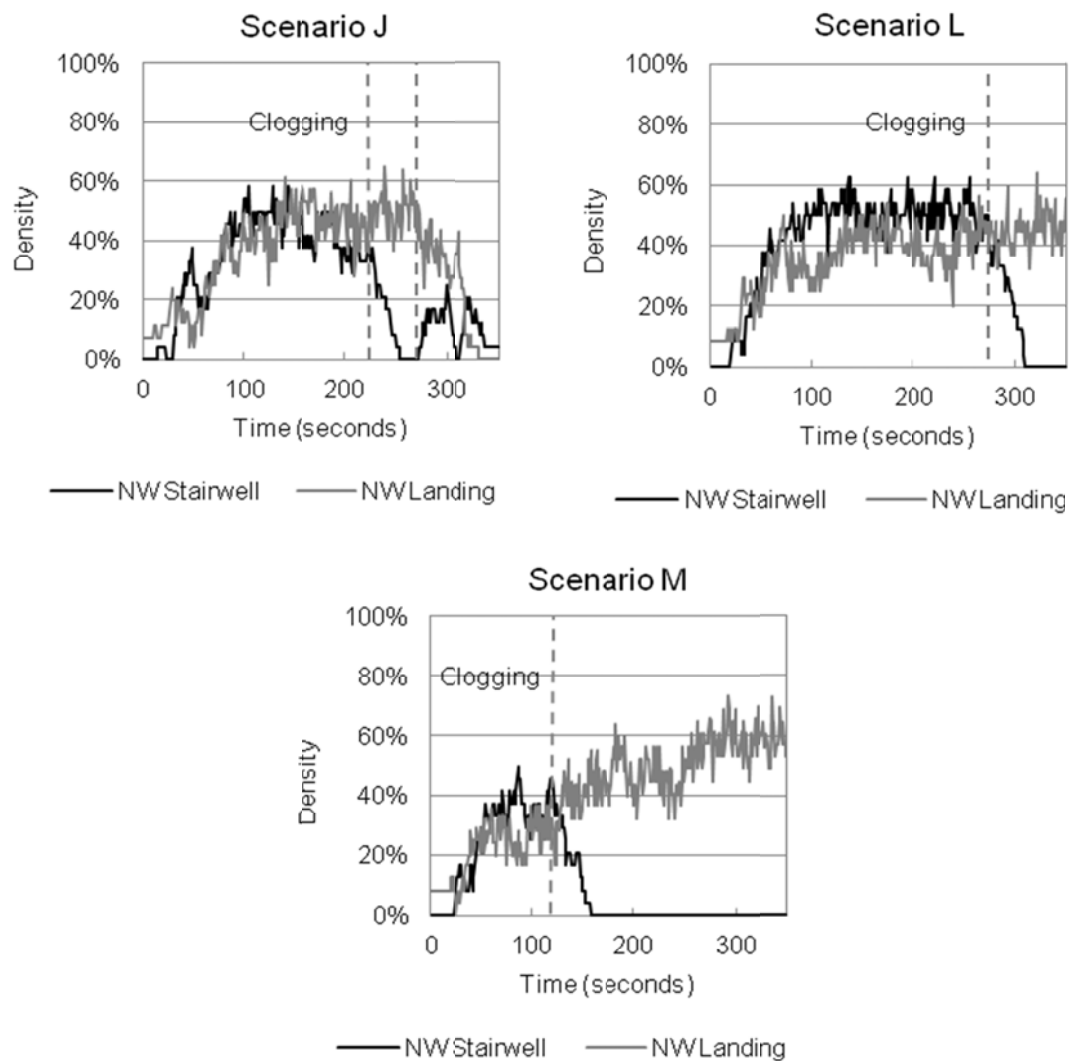


Figure 7. Density graphs depicting clogging in architectural capacity experiment.

to utilize them, which can be regulated by operational managers or evacuation leaders.

Elevator speed was determined by measuring the time taken to travel from floor to floor during several elevator rides in the actual building. The mean elevator speed was measured at 3 seconds per floor. Elevator capacity was determined by dividing the size of the elevator by the size of a simulated wheelchair user. Each elevator was able to accommodate 2 wheelchair users. Figure 8 presents the density graphs when the use of

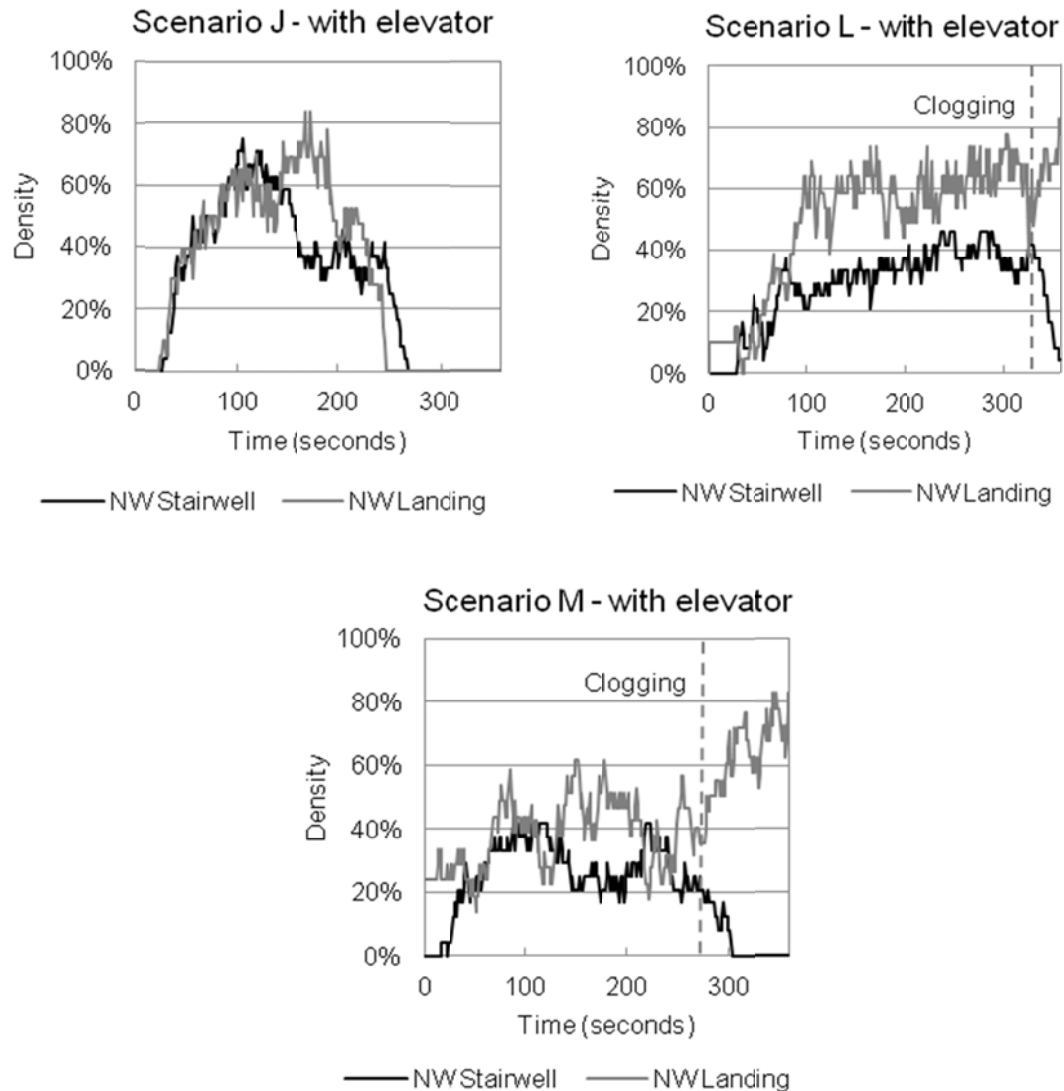


Figure 8. Density graphs depicting clogging in elevator utilization experiment.

elevators was allowed for agents in Scenarios J, L and M or those in which the clogging phenomena was observed in Experiment 2.

Overall, the effect of using elevators to evacuate individuals with disabilities was very useful. First, the use of elevators eliminated the clogging that occurred during Scenario J. While the clogging phenomenon was still observed in Scenarios L and M, it

appeared much later in the simulations. Thus more agents were able to evacuate with the controlled use of elevators than were able to during Experiment 2. Table 6 presents a comparison of the percentage of agents who were able to evacuate from both experiments. Note that a time limit of 5 minutes was implemented for each simulation given that the accepted rule of thumb is that evacuations should be completed within 3. Since the clogging did not always resolve itself before the limit was reached, not all agents were able to evacuate in each scenario. Also note that the percentage of agents who successfully evacuated in Scenario L and M increased significantly when elevator use was allowed.

Managerial Implications

Given the lack of basic research-supported information to guide best practices and policies for the emergency evacuation of individuals with disabilities, the proposed model represents an important foundation for public practice and future study directions. Based on the results of the evaluation experiments Exitus was able to simulate emergency evacuations of heterogeneous populations in a realistic manner. From both macro and

Table 6

Agents Evacuated With and Without Elevators

Scenario	Without elevator ^a	With elevator ^b
J	98%	100%
L	51%	85%
M	17%	75%

^aExperiment 2

^bExperiment 3

micro perspectives the model performed consistent with expectations regarding the behavior of individuals with and without disabilities. As a result, several important findings were uncovered that inform emergency management practice including: (a) the potential life saving benefits of assisted evacuations, (b) who is most at risk, (c) future challenges arising from shifting population demographics, (d) the positive impact of elevator use on overall evacuation performance, and (e) a propensity for clogging under certain conditions on the third floor of the building.

The feasibility of adopting assisted evacuations for individuals with disabilities was evident from the results of Experiment 1. Groups naturally form around those resourceful enough to recruit others to their aid during crisis situations. For example, evacuees using wheelchairs during the September 11th attacks were able to find and organize others to carry them out of the building (Shields et al., 2009). The simulation results demonstrate the effectiveness of incorporating this natural tendency into formal evacuation planning featuring an assisted evacuation strategy for individuals with disabilities. However, careful consideration must be given to identifying those most vulnerable during emergencies. In particular, people using wheelchairs and those with lower stamina were at the greatest risk. While evacuees using wheelchairs are clearly identifiable, those with lower stamina may not be so. This group may include the elderly, people with chronic health conditions, or those with temporary ones such as minor injuries. The simulation results emphasize the need for a broad approach in terms of identifying individuals with disabilities early and often as conditions change to ensure their safety during crisis situations.

It is important that the architect or engineer test the structure's design to determine how well it meets evacuation requirements while changes in design are possible. The importance of considering heterogeneous populations during the design phase of building development was manifest from the results of Experiment 2. In this experiment, the northwest landing of the HSRC building was prone to clogging under certain parametric levels. Note that merely increasing the number of evacuees alone did not result in clogging. Increased proportions of individuals with disabilities were also required to reproduce the phenomenon. Under normal conditions this particular building characteristic may not be a cause for concern. However, designers should consider the risk engendered during special events such as conferences or company-wide meetings when many people are gathered in one location. Architects and engineers should carefully consider the implications of these situations to establish best practices regarding the design of built environments. The use of models such as Exitus to measure and disseminate empirical data concerning the behavior of individuals with disabilities under the impetus of internal and external stimuli may aid in doing so.

At the same time, the results from Experiment 3 demonstrate the positive impact of utilizing elevators on this phenomenon. Though higher density situations still resulted in clogging, more agents were able to exit the building before egress became impossible. It is important to recognize that elevators also have a number of other characteristics that make them desirable for the use of evacuations. They are comparatively fast, equally suitable to a variety of people including those with and without disabilities, can be controlled outside of the emergency zone, and are independent of the psychological state

of those using them (Bazjanik, 1977).

Conclusion

The research contributions of this phase of the research are two-fold. First, the Exitus system was developed. Exitus incorporates a greater range of mental and physical characteristics expressed by individuals with disabilities than prior evacuation models resulting in more realistic simulations of heterogeneous populations. Second, the system was used to evaluate the effectiveness of different evacuation strategies in a multi-story office building. Both assisted evacuations and controlled elevator utilization were better alternatives for individuals with disabilities than refuge areas and general elevator prohibition. Several issues were also highlighted which contribute to the development of optimized emergency response plans including the capacity of stairwells and future impact of shifting population demographics.

CHAPTER V

SIMULATION OF AN AIRPORT EVACUATION

Introduction

The following chapter presents an extension of the Exitus model. The new version is distinguished from its predecessor in two ways. First, the underlying data structures were modified to accommodate large environments and populations. Second, agent behavior algorithms were modified to incorporate social forces. In this phase of the research, the model was used to simulate evacuations from a large international airport. Several experiments based upon the discovery of a dirty bomb in one of the airport's explosive detection systems were then conducted. The results of the experiments led to the identification of several factors that contribute to the development of optimized emergency evacuation procedures for airports and heterogeneous populations in general.

System Architecture

In this phase of the research, the Exitus model's agent behavior algorithms were expanded to incorporate recent developments in cellular automaton models surrounding the realization of social forces in a discreet environment (Kirchner & Schadschneider, 2003; Song, Yu, Wang, & Fan, 2006). Specifically, an agent's final direction choice and movement was modified to consider the effect of several forces derived from Helbing's social force model (Helbing, 1991; Helbing & Molnar, 1995). The social force model describes pedestrian movement based upon the idea that behavioral changes are guided

by social fields (Lewin, 1951), which are a measure for the internal motivation to perform certain actions. The model is expressed in several equations of motion inspired by Newtonian mechanics.

The social force model describes the influence of obstacles, other pedestrians, and points of interest on the movement of the agent as follows. A driving force f_α reflects the primary motivation of the agent α to move towards the destination with velocity v_α . Psycho-social forces $f_{\alpha\beta}^{ps}$ and physical forces $f_{\alpha\beta}^{ph}$ describe the interactions with other pedestrians β as given in equation (3). Psycho-social forces reflect the need to maintain distance between the agent and other pedestrians. Physical forces reflect contact with other pedestrians and obstacles.

$$f_{\alpha\beta} = f_{\alpha\beta}^{ps} + f_{\alpha\beta}^{ph} \quad (3)$$

Physical interactions with other pedestrians are further developed into a term describing body compression factors and sliding friction or the tendency to slow down when passing other pedestrians at close proximity f_{ab} . In addition to these, attractive forces are also considered such as attraction to the intended destination f_{ai} and attraction towards the group as a whole $f_{\alpha\beta}^{att}$. That is, if an agent becomes separated from the larger group by any distance they will be motivated to rejoin them. Finally, agents are individuals and may differ in their behavior from the assumed laws. Consequently a random fluctuation force ε is included to account for this possibility. Overall the social force model may be described as the sum of several partial forces that represent the different influences that occur upon pedestrians in the real world as given in equation (4).

Readers are referred to Helbing (1991) and Helbing and Molnar (1995) for a full discussion of the details of this model.

$$\frac{dv_{\alpha}t}{dt} = f_{\alpha} + \sum_{\beta} f_{\alpha\beta} + \sum_b f_{\alpha b} + \sum_i f_{\alpha i} + \sum_{\beta} f_{\alpha\beta}^{att} + \varepsilon \quad (4)$$

Translation of the social force model to a cellular automaton requires generalization of the constituent forces into their basic forms for application in discrete update rules, namely (a) attraction, (b) repulsion, and (c) friction. Attraction refers to the desire to move toward a destination. Attraction is quantified by means of static floor fields (SFF; Kirchner & Schadschneider, 2003), which describe the shortest time to an exit or connecting feature such as a stairway. Specifically, SFF cells contain values indicating the time to destination from their location as an integer (see Chapter IV). For example, an exit cell will have a value of 0 while one further away is greater. Agents selecting a direction will be motivated to choose the one having the lowest time to destination.

Repulsion refers to the desire to avoid injury resulting from collision with obstacles in proximity to the desired direction. In other words, though agents are motivated to follow the shortest path to an exit their intermediate directional choices are influenced by the desire to avoid collision with nearby walls, barriers, or other agents along the way. Repulsion is expressed as a sigmoid function that defines the probability of rejecting a destination cell r_{ij} in response to the total hardness of surrounding cells h_{ij} and the agent's speed v (Song et al., 2006). The notion of hardness simply refers to an object's renitence or ability to resist physical pressure (i.e., walls are more renitent than

people or agents). If an agent is repulsed a penalty is added to the destination cell's time to destination t_{ij} to reflect its undesirability in relation to its neighbors. This temporary time to destination value tt_{ij} is subsequently used to make the final direction choice. Equations (5), (6), and (7) depict the formal definitions for hardness, repulsion probability, and the temporary time to destination where η = hardness of an individual cell and D is the set of coordinates surrounding the destination cell.

$$h_{ij} = \sum_{[i] \in D} \eta_{ij} \quad (5)$$

$$r_{ij} = \frac{1 - e^{-h\nu}}{1 + e^{-h\nu}} \quad (6)$$

$$tt_{ij} = t_{ij} + \begin{cases} 0 \rightarrow u[0,1] < r_{ij} \\ 1 \rightarrow u[0,1] \geq r_{ij} \end{cases} \quad (7)$$

After temporary time to destination values have been determined agents select the cell with the lowest, $\min(d)$, in order to update their position. However, friction must also be considered. Friction refers to the necessity of physically slowing down when an agent is in contact with an obstacle or other agents and is thus connected to repulsion in that the hardness of surrounding cells is the determining factor. Thus, friction is realized in terms of a transition probability from the current location to the destination cell f_{ij} in a manner similar to repulsion modified by a coefficient, $\theta \in [0,1]$; in accordance with Song and colleagues (2006), the desire to avoid injury is considered greater than the effect of physical contact once a choice has been made. This value is then compared to a random number u in order to determine whether or not the agent actually updates their

current position a_{ij} as depicted in equations (8) and (9). The application of friction probability to agent movement over several discrete time steps results in slower overall speeds through narrow passageways, congested areas, and so forth.

$$f_{ij} = \theta \times r_{ij} \quad (8)$$

$$\alpha_{ij} = \min(D) \rightarrow f_{ij} \geq u[0,1] \quad (9)$$

The hardness and friction related parameters were based on results found in Song and colleagues (2006). These values were set as follows:

$$\eta = \begin{cases} 1 & (\text{agent}) \\ 2 & (\text{wall}) \end{cases} \quad (10)$$

$$\theta = 0.7 \quad (11)$$

Verification and Validation

The model was validated by comparing the mean evacuation time of several simulations to the evacuation time of a real world exercise. Since the airport under examination has never had occasion to conduct a complete evacuation of all terminals the model was validated using the same procedure described in the previous chapter. In this case, the results of one hundred simulations using the HSRC building and same population distribution demonstrated comparable results at a mean evacuation time of 159s.

Simulation Experiments

Experiment 4: Dirty Bomb Detection

The objective of the simulation experiment was to estimate the impact of dirty bomb detection on evacuation times for heterogeneous populations. The experiment was conducted using the map of an international airport in the United States. The airport is the 25th busiest in the nation with eight airlines transporting several millions of passengers on an annual basis.

The airport complex is a two-story structure consisting of three terminals, five concourses, and 83 aircraft gates. The structure is patterned after the pier terminal design. In this design the passenger processing sequence including ticketing, baggage check, and security screening is centralized in the terminal building while access to aircraft occurs along both sides of long piers that extend away from it as depicted in Figure 9. The piers provide access to greater numbers of aircraft while simplifying navigation through the building. On the other hand, passengers are required to walk long distances to travel from the ticket counters to aircraft gates. The Amsterdam Schiphol and London Heathrow airports are also good examples of this design. Note that the fifth pier or concourse connected to terminal three of the airport complex was not included when the structure was digitally mapped. As a result it is not included in the simulations.

Six thousand agents were evacuated during the simulations. Based on an interview with airport management this value represented a reasonable midpoint in terms of the number of people present at any given time (R. Berg, personal communication, October 11, 2010). The diversity and prevalence of individuals with disabilities was

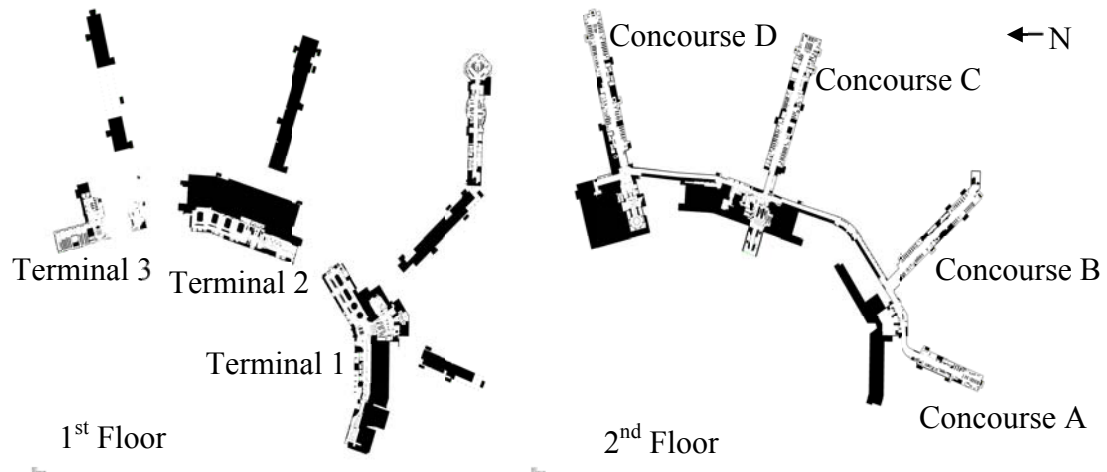


Figure 9. Map of an international airport.

assigned in a manner similar to previous Exitus experiments (see Chapter IV). In this case, however, it was assumed that individuals using wheelchairs were accompanied by a nondisabled assistant to help negotiate stairs. Elevators are typically disabled and thus not accessible during an emergency evacuation in the airport. Furthermore, airlines are required to provide free wheelchair assistance between curbside and cabin seat to comply with the Air Carrier Access Act (U.S. Department of Transportation, 2009).

The simulation scenarios were based upon the discovery of a dirty bomb by an explosive detection system (EDS) machine within the airport. A dirty bomb is a radiological weapon that combines radiological material with conventional explosives to potentially contaminate a large area. EDS machines typically use computed axial tomography enhanced with image processing software to automatically detect such devices in passenger bags. Consequently, ESD machines form a critical element of aviation security. In Terminals 1 and 3, portable EDS machines are positioned near the

ticket counters. In Terminal 2, an in-line EDS is integrated with the baggage handling system in a restricted area located to the south of the main building. According to airport management, the discovery of an explosive device in any of these locations represent the most likely bomb-related scenario faced by the organization (D. Korzep, personal communication, October 11, 2010).

Two important procedures specified by the airport's emergency response plan were incorporated into the simulations. First, a hot zone was established around the location of the bomb. A hot zone is a 300-foot perimeter that only bomb disposal personnel are allowed to enter. As a result, agents are potentially prohibited from using certain exits or other building features to evacuate depending on the location of the center. Second, a controlled evacuation of the entire airport was executed. A controlled evacuation is one in which agents are directed backwards through security checkpoints to use terminal exits that lead to areas such as parking lots or access roads. Agents are not allowed to use concourse exits leading to areas where aircraft and other heavy equipment pose additional safety threats.

Four simulation scenarios were specified according to the presence and location of the dirty bomb. Scenario A was conducted without a bomb to establish a baseline for subsequent comparisons. Scenario B simulated bomb detection in one of the portable EDS machines positioned in front of the ticketing counter in Terminal 1. Scenario C simulated bomb detection in the inline EDS machine located to the south of Terminal 2. Scenario D simulated bomb detection in a portable EDS machine near the ticketing counter in Terminal 3. Note that the resulting hot zone in Scenario B effectively

prevented agents from using the main stairwells connecting the first and second levels of Terminal 1. As a result, agents were required to use alternate routes of egress (ROE). Fifty simulations were conducted for each scenario, an arbitrary number selected to account for variations between individual simulations. Simulation performance was measured by evacuation time or the time at which an agent exited the airport in seconds. The specification of scenario parameters is depicted in Table 7.

Table 8 depicts the METs for all terminals and agent types in Scenario A. While the overall MET was congruent with real-world expectations expressed by airport management further analysis yielded several unique and unexpected aspects of agent interactions with the airport environment. An alpha level of .05 was used for all statistical tests.

A two-sample t test was conducted to compare the MET for all agents evacuating through terminals 1 and 2 in Scenario A. The results indicated that the MET for all agents evacuating through Terminal 1 was significantly slower than the MET for all agents evacuating through Terminal 2, $t(49) = 5.29, p < 0.001$. Likewise, the MET for all agents evacuating through Terminal 1 was significantly slower than the MET for those

Table 7

Specification of Scenarios in Bomb Detection Experiment

Scenario	Bomb location	Simulations
A	N/A	50
B	Terminal 1 (portable EDS)	50
C	Terminal 2 (inline EDS)	50
D	Terminal 3 (portable EDS)	50

Table 8

Simulation Results for Scenario A (in seconds)

Terminal	Statistic	All types	Nondisabled	Motor ^a	Nonmotor ^b	Visual	Lower stamina	Hearing
All	MET	2169.84	2135.29	1937.76	1936.41	1990.03	2165.31	1911.54
	SD	148.98	153.91	133.05	129.58	140.20	145.29	164.95
One	MET	2169.08	2135.29	1937.76	1936.41	1990.03	2164.56	1911.54
	SD	149.55	153.91	133.05	129.58	140.20	145.84	164.95
Two	MET	1021.72	855.49	638.37	673.86	837.33	1017.66	766.47
	SD	33.11	34.10	99.90	148.97	42.93	28.54	49.61
Three	MET	1120.61	1020.04	913.08	914.60	931.92	1108.43	850.24
	SD	264.71	43.03	53.47	53.36	62.23	267.31	99.91

^aMotorized Wheelchair^bNonMotorized Wheelchair

evacuating through Terminal 3, $t(49) = 5.29$, $p < 0.001$. These results are understandable given that two concourses feed Terminal 1; whereas, only one concourse each feed Terminals 2 and 3. In other words, more agents were required to exit through Terminal 1 than Terminals 2 and 3 (2,209 mean agents compared to 987 and 2,061, respectively) increasing the competition for limited capacity ROEs. Figure 10 depicts unusually large queues of waiting agents at the stairwells in Terminal 1. Periodic clogging lasting several seconds at a time was also observed at these locations. Note that concourse B, extending from Terminal 1, is also approximately 30% longer than the next longest concourses, C and D. As a result agents originating in the northernmost area of concourse B had to walk farther than their counterparts in other areas of the airport likely contributing to the overall slower MET.

While The METs for terminals 2 and 3 were not significantly different the standard deviations were, $F(50, 50) = 63.91$, $p < 0.001$, suggesting the influence of a

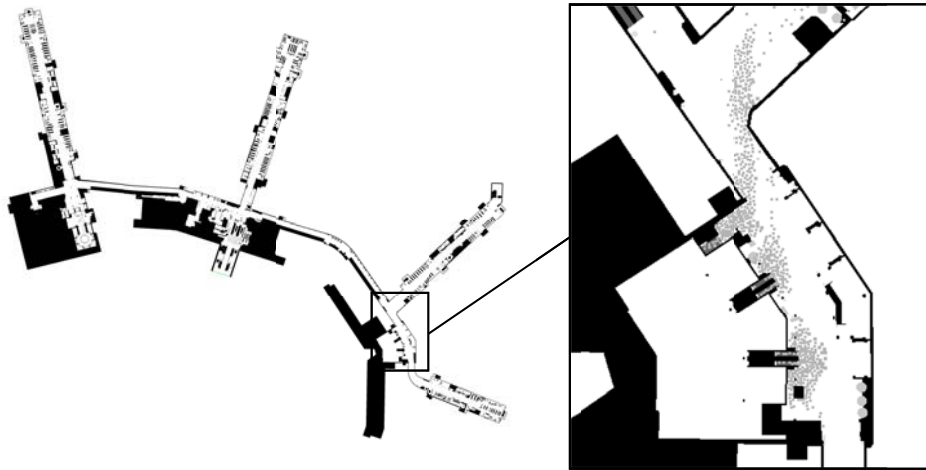


Figure 10. Queuing at stairways in Terminal 1.

previously unconsidered aspect of the built environment. From a design perspective the buildings are similar in terms of their general shape and area. However, the interior space is more complex and crowded in Terminal 3. Ticketing, baggage check, restaurants, and various types of both permanent and temporary seating all share the same area in Terminal 3. Thus the movement of agents among the obstacles is likely subdiffusive in character as it relates to MET. Only ticketing and baggage check occupy the main area of Terminal 2 while associated food services and seating are located in concourse C. Note that the standard deviations for all disabled groups (i.e., motorized wheelchair, nonmotorized wheelchair, visually impaired, hearing impaired, and lower stamina agents), were significantly different while those for nondisabled agents were not. These results lend further credence to the offered explanation given the sensitivity of disabled agents to this particular aspect of the built environment (see Table 2).

A comparison of METs by agent type revealed that those with lower stamina took the longest time to exit overall. The METs for this group were very similar to the METs

for all agents in each terminal. By definition, MET is based on the time the last agent exited the airport. Thus the times for the slowest agents will always be very similar to the MET for all. A similar relationship is observed when comparing METs from Terminal 1 to the METs for all-terminals by agent type. The next slowest group to exit was nondisabled agents. Though counterintuitive this is understandable given the potential combined effect of several factors such as initial position, response delay, and ratio of nondisabled to other agent types. That is, nondisabled agents were more likely to start farther away from an exit and respond to the alarm later placing them at a disadvantage in accessing highly congested ROEs. Interestingly, the next slowest group to exit was visually impaired, which represents a departure from the results found in Chapter IV. Though the evacuation rate of visually impaired agents was very similar to faster moving groups (i.e., nondisabled and hearing impaired), some of them remained in the airport longer than motorized and nonmotorized wheelchair users who evacuated at an overall slower rate. Figure 11 depicts the mean evacuation curves for all agent types.

Tables 9 and 10 depict the METs and number of agents evacuated for each terminal in scenarios A, B, C, and D. A two-sample *t* test was first conducted to compare the MET for all terminals in scenarios A and B. The results indicated that the MET for scenario B was significantly faster than the MET for scenario A, $t(49) = 5.29, p < 0.001$. In this case, the hot zone in scenario B effectively disabled all of the stairways in Terminal 1 as the EDS machine containing the bomb was located in front of the ticketing counter immediately adjacent to them. As a result, agents originating on the second floor in concourses A and B were forced to find exits in Terminal 2 instead of Terminal 1. In

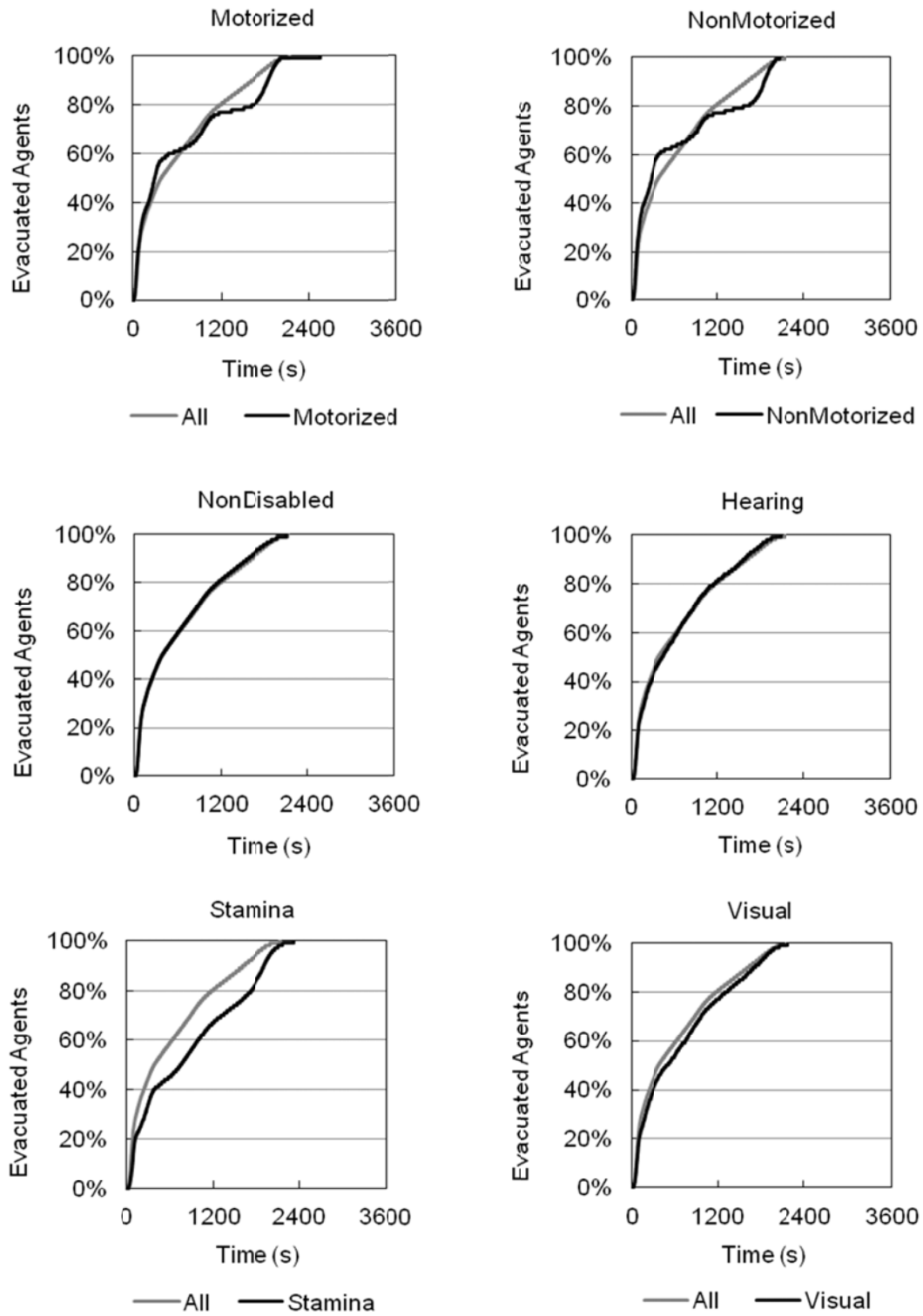


Figure 11. Mean evacuation rates by agent type in Scenario A.

Table 9

METs for Scenarios A, B, C, and D (in seconds)

Terminal	Scenario A	Scenario B	Scenario C	Scenario D
All	2169.84	2038.95	2168.79	2262.94
One	2169.08	883.82	2168.79	2227.59
Two	1021.72	2037.37	1014.85	1033.91
Three	1120.61	1132.53	1071.49	1628.23

Table 10

Mean Number of Evacuated Agents for Scenarios A, B, C, and D

Terminal	Scenario A	Scenario B	Scenario C	Scenario D
All	6000.00	6000.00	6000.00	6000.00
One	2295.44	911.98	2299.58	2369.16
Two	1643.52	3024.32	1638.80	1713.54
Three	2061.00	2063.68	2061.56	1917.24

this situation, even with approximately twice the mean number of agents using Terminal 2, it was still quicker to leave the airport through that location. This finding is attributed to the extra capacity provided by a wide exit located on the second floor of Terminal 2. Agents who chose this exit did not have to wait for stairway access to leave the building. Nor were they required to wait in a queue as was observed at other exits with narrower widths.

In contrast, the MET for all terminals in Scenario D was significantly slower than the MET for Scenario A, $t(49) = 2.57$, $p = 0.01$. In this case, the bomb's hot zone disabled all of the stairwells nearest the ticketing counters and EDS machines in Terminal

3. Only three stairways remained accessible in the opposite corner of the building. As a result, agents originating in concourse D were still able to find an egress from Terminal 3 instead of another. Unfortunately, the overall reduction in stairway capacity significantly lengthened the time required to evacuate the building despite the fact that fewer agents left through terminal three in this scenario than any other. That is, agents were required to wait in long queues for their turn to use the stairways that provide access to the first floor of terminal three and the exits located there ultimately resulting in a significantly slower MET.

The MET for Scenario C was not significantly different from Scenario A. In this case, the hot zone prevented agents from using some of the exits on the first floor of Terminal 2 but did not impact the stairways leading to the second floor of the building. This is primarily due to the location of the automated EDS facility. In this terminal, baggage is checked at the ticketing counters and routed via a conveyor belt to EDS machines on the south side of the main building far from the main passenger processing area. Consequently, agents were able to use the exits throughout the remainder of the terminal including those located near the baggage claim carousels on the opposite side of the building without impacting overall evacuation performance.

Experiment 5: Repulsion Sensitivity

The objective of the second simulation experiment was to analyze the sensitivity of evacuation time to repulsion probability for individuals with disabilities. Several studies have shown that individuals with certain disabilities prefer to avoid crowded situations (Peck, 2010; Rittner & Kirk, 1995). Those with lower stamina may have

difficulty standing for long periods of time and moving around (Peck, 2010). Those using wheelchairs and those with visual impairments may also have difficulty maneuvering (Daniels, Rogers, & Wiggins, 2004). As a result, individuals with these disabilities are more sensitive to the proximity of obstacles in high-density situations. Sensitivity was reflected by systematically increasing and decreasing the perceived hardness of walls and agents that underlie repulsion probability. Only the hardness parameters for wheelchair agents, visually impaired agents and lower stamina agents were changed in accordance with the literature previously cited. The degree of change was chosen arbitrarily.

The sensitivity experiment was conducted by repeating Scenario D from Experiment 1 using the new parameter settings. Scenario D was chosen because it resulted in the worst evacuation performance. More specifically, we wanted to know how the outcome of the worst-case scenario would change using a more realistic representation of psychological profiles. Note that this approach reflects conventional uncertainty analysis techniques that emphasize worst-case scenarios and the impact of the uncertainty for individual variables in order to fully understand exposure to risk (Jaycock, 1997). Table 11 depicts three new scenarios and the corresponding change to the hardness parameter.

Table 11

Specification of Scenarios for Repulsion Sensitivity Experiment

Scenario	Bomb Location	Simulations	Hardness (η)
E	Terminal 3 (Portable EDS)	50	+50%
F	Terminal 3 (Portable EDS)	50	+100%
G	Terminal 3 (Portable EDS)	50	+150%

Figure 12 depicts the change in MET for all agents in Scenarios D, E, F, and G. A one-way ANOVA revealed that the MET was significantly different, $F(3, 96) = 3.49$, $p = 0.02$. Post-hoc analysis using the Bonferroni-Holm test revealed that scenarios D and G were statistically significantly different from each other ($p = 0.003$) while the differences between all other scenarios were not. Thus we can conclude that when the hardness parameter, or η , for wheelchair, lower stamina, and visually impaired agents is increased by 150% or more the resulting evacuation times will be statistically significantly longer. In other words, repulsion probability driven by the desire to avoid injury from collision with other people and obstacles has an effect upon overall evacuation times. These results are important because they show that evacuation profiles change when heterogeneous populations are modeled more realistically at the individual agent level.

Interestingly, statistical inference tests revealed that the METs for nondisabled types were significantly different, $F(3, 96) = 4.83$, $p = 0.003$, while those for all other

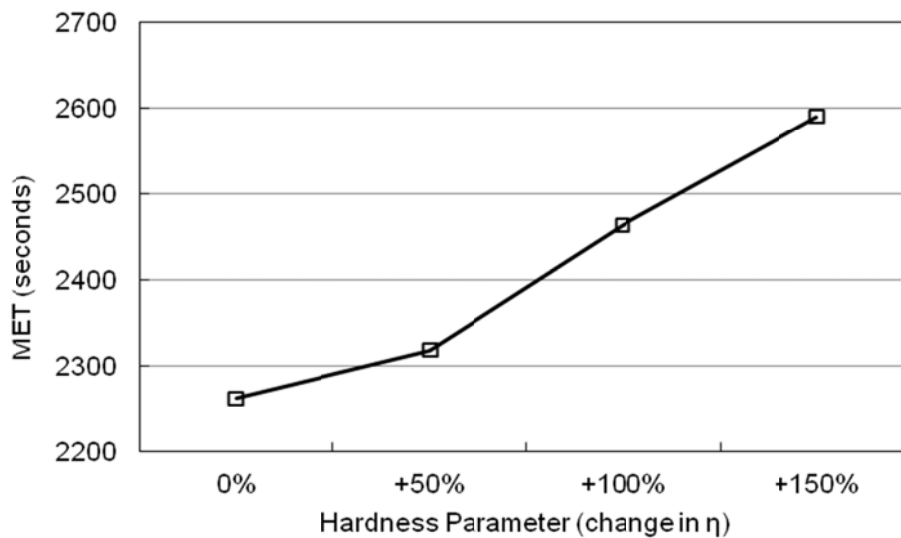


Figure 12. Sensitivity of MET to hardness parameter.

agent types were not. For nondisabled agents, significant differences were observed between scenarios D and F and scenarios D and G. This result is understandable given the potential cumulative impact of even a single agent under the right conditions. More specifically, a disabled individual who hesitantly enters a densely crowded area may force others to slow down, which is then propagated throughout the multitude. This result corroborates those of empirical studies that found that an individual using a wheelchair in a stairwell caused considerable congestion and slowing amongst other, nondisabled evacuees around them (Boyce et al., 2002). Figure 13 depicts the MET for each agent type by percent of agents evacuated for Scenario G.

The magnitude of change for nondisabled agents is also worth noting. In this case, we observed a 9% increase in MET between Scenarios D and F and an 11% increase

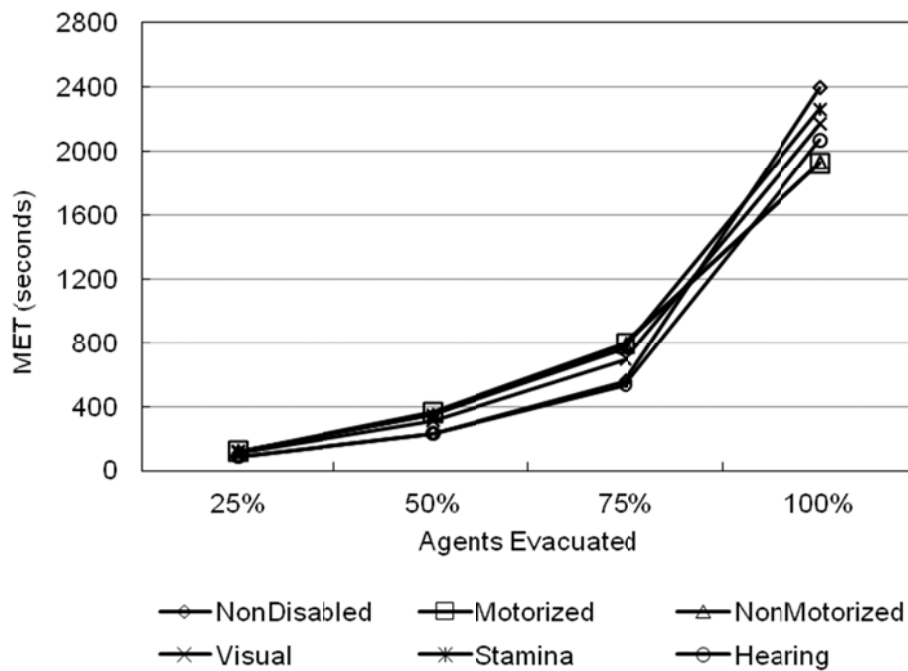


Figure 13. MET by percent of agents evacuated for 150% increase in hardness parameter.

between Scenarios D and G, which correspond to several more minutes spent in the airport. Ensuring the safety of the whole clearly requires careful consideration of the differences among individuals and specifically those with disabilities. This is an important contribution of the Exitus model considering it is the only one we are aware of which is capable of representing the interaction between the underlying characteristics of heterogeneous populations and evacuation performance in this way.

Managerial Implications

From an architectural engineering perspective the results are useful because they demonstrate a significant limitation of the pier airport design during emergency evacuations. Namely, evacuees may be required to walk long distances from the aircraft boarding gates to the exits in the terminal. Additionally, the particular ease with which piers are lengthened or added may exacerbate the situation by increasing competition for limited capacity escape routes such as stairways or narrow passageways. The effect on individuals with disabilities, specifically those with lower stamina, is especially pronounced. It is important to recognize that many large international airports are built after this design and are thus susceptible to these consequences. Chicago O'Hare International Airport, Frankfurt International Airport, London Heathrow Airport, Amsterdam International Airport, Bangkok International Airport, and Hong Kong International Airport are just a few examples. Future building projects may be wise to evaluate other designs before committing to a pier configuration. In this regard the linear airport design may provide a possible alternative. In this design passenger processing

leads directly to aircraft access resulting in significantly shorter walking distances, which is an important advantage during total evacuation scenarios such as the one presented here.

No matter what design is used it is clear that both stairway and exit capacity greatly affect evacuation performance. Under certain conditions, the stairways in Terminals 1 and 3 became bottleneck areas and were susceptible to intermittent clogging or became impassible for a short period of time. Furthermore, in this airport the majority of stairways are only wide enough to accommodate two evacuees abreast whereas one wheelchair user with a stair climbing device occupies almost the entire width. As a result, those behind them are forced to descend at the same speed that slows the evacuation rate even more. From an evacuation perspective increasing the number and width of stairways may help improve performance and ultimately the safety of those required to use them. The other important building feature to consider is the exit itself. In this case, even with several exits available in Terminal 3 evacuees clearly favored some over others resulting in a certain amount of queuing and waiting. However, the exit on the second floor of Terminal 2 was not susceptible to this problem. Evacuees were able to access this feature the moment they arrived because it was wide enough to accommodate the flow of even a large crowd. For this particular airport managers may be wise to consider routing some individuals from concourses A, B, or D to Terminal 2 where the extra capacity gained from the second floor exit negates the limitations imposed by the stairways allowing for an overall quicker escape.

From an emergency management perspective the results are useful because they

identify the most vulnerable individuals during an evacuation. In particular, evacuees with lower stamina, visual impairments, and those using wheelchairs were at the greatest risk. The results add further emphasis to the recommendations made in Chapter IV. Specifically, while individuals using wheelchairs are easily identifiable, those with other disabilities such as lower stamina may not be. Such people may include the elderly, pregnant women, those with chronic health conditions such as respiratory and other internal ailments, or temporary injuries. Consequently managers should adopt a broad approach in terms of identifying individuals with disabilities early and often to better ensure their safety. Outreach programs that involve the disabled community in an advisory role and clear service provisions for individuals with disabilities in both land and airside operations are two examples of the elements that may be included in the broad approach advocated here.

The other important item of consideration in regard to individuals with disabilities is the complexity of the interior space. Individuals with disabilities are particularly sensitive to the frequency and orientation of obstacles that may alter their escape route. For example, lower stamina and visually impaired individuals may have difficulty negotiating their way past multiple rows of permanent seating. Tables, chairs, charging stations, and counters present additional challenges especially if they are irregularly strewn about or misplaced as may occur during a panic situation. This effect of these factors was particularly evident in the variability of evacuation times for all disabled agents leaving terminal three during Scenario A. With standard population distributions this may not be an area of concern. After all, the overall evacuation times observed in this

experiment did not appear to be affected. However, managers of airports with perceptibly different population distributions may have greater reason to be concerned. For example, Miami Palm Beach Airport and Seattle-Tacoma Airport have recognizably older populations. In this situation the complexity of the interior space may indeed have an effect on the ability to evacuate passengers in an overall safe and timely manner.

From a security management perspective the results are useful because they identify the problem that arises from locating EDS machines close to passenger processing areas. In this airport portable EDS machines are located adjacent to ticketing counters in Terminals 1 and 3. In terms of operational efficiency such an arrangement makes sense. In terms of the impact response procedures have on evacuations it may not. The establishment of a 300-foot radius hot zone or impenetrable area around the location of the bomb changed the nature of the evacuations dramatically. Evacuees in concourses A and B were required to alternate stairways when the bomb was discovered in Terminal 3 even though there were fewer of them attempting to use that route. Inline EDS facilities such as the one associated with Terminal 2 offers a better alternative. In this case the EDS machines are located far from the main passenger processing area resulting in very little impact on evacuation performance. Evacuees were able to use the normal exit routes almost without restriction.

In this regard we realize yet another limitation of the pier airport design. In all cases, agents originating in a concourse were required to move towards the hot zone before exiting the terminals exposing them to further danger. The hazard faced by evacuees in doing so was demonstrated during an incident that occurred in the airport on

October 14, 1989. A Boeing 727 aircraft parked at a gate near the intersection of the concourse and terminal caught fire, forcing the passengers and crew to evacuate. The rest of the passengers waiting in the concourse shortly followed, some of them walking through the smoke from the fire as they exited toward the main terminal (D. Korzep, personal communication, April 8, 2010).

Conclusion

The research contributions of this phase of the study are twofold. First, the Exitus system was extended to include an implementation of Helbing's (1992) social force theory resulting in more realistic simulations. Second, the system was used to evaluate evacuation performance in light of a dirty bomb discovery in one of the airport's EDS machines. The results of the experiments revealed important considerations for architectural engineers, emergency managers, and security professionals alike including: (a) the inherent weaknesses of the pier airport design in terms of effecting timely evacuations, (b) who the most vulnerable groups of people are and the particular risk engendered from crowded or complex interiors for individuals with disabilities, and (c) the potential problems caused by locating EDS machines near passenger processing areas.

CHAPTER VI

SIMULATION OF A SPORTS ARENA EVACUATION

Introduction

The following chapter presents a further extension of the Exitus model. In this version of Exitus agent behaviors were modified to include an implementation of proxemic relationships, or the maintenance of interpersonal distances based on group membership, between evacuees. In this phase of the research, the model was used to simulate evacuations from a major sports arena. Several experiments based upon a likely terrorist bombing attack were conducted. The results of the experiments led to the identification of several factors that contribute to the development of optimized emergency evacuation procedures for sports arenas and heterogeneous populations in general.

System Architecture

In this phase of the research, the Exitus model's agent behavior algorithms were further expanded to consider attraction to other agents based on group membership in accordance with Hall's (1963) work on proxemics. Patrons attending sporting or other events have been shown to do so in the company of others such as friends (Irwin & Sandler, 1998) or, in the case of individuals with disabilities, family care givers (Huh & Singh, 2007). As a result, the representation of proxemic behavior or the measureable distances maintained between people as they interact with those whom they have a

relationship with is an important component that adds to the realism of the model. Hall defined four types of interpersonal distances: (a) intimate distance (0 – 0.46m) for embracing, touching or whispering, (b) personal distance (0.46 – 1.2m) for interacting with friends or family members, (c) social distance (1.2 – 3.7m) for interacting with acquaintances, and (d) public distance (3.7m or more) used for interacting with other members of the public. According to Hall, interpersonal distance is culturally defined. However, researchers have noted the interaction of other factors including gender, age and crowd density (Burgess, 1983b; Remland, Jones, & Brinkman, 1995) amongst others. For example, elderly individuals have been shown to maintain significantly closer relationships to companions than those who are younger (Burgess, 1983a). Patrons of a crowded shopping mall were observed to maintain significantly closer distances with group members while walking than compared to strangers (Burgess, 1983b). Note that at least two prior studies have presented proxemic ABMs (Beltran, Salas, & Quera, 2006; Manenti, Manzoni, Vizzari, Ohtsuka, & Shimura, 2010). In both of these works, the models were evaluated using single room scenarios with relatively sparse, homogeneous populations. While our implementation of Hall's theory is in some ways similar it is distinguished by consideration for individuals with disabilities and application to an extremely high density, complex environment (in this case a fully populated sports arena).

Within Exitus, the desire to maintain close interpersonal distances with group members was driven by a proxemic threshold parameter that differed by agent type. That is, in selecting a direction each agent a first calculated the distance d between them self

and each group member m yielding equation (12) where f is the distance to the exit obtained from the relevant floor field. If the distance between the agent and the closest other group member was within proxemic threshold p the agent reverted to the default behavior and selected the next direction based upon the smallest floor field value. However, if the distance between the agent and the closest other group member exceeded the proxemic threshold the agent was motivated to choose the direction closest to the other group member. The formal definition for these behaviors is presented in equations (13), (14) and (15). This behavior represents an important departure from previous proxemic ABM studies in which the centroid of the group was used to determine direction choice (Manenti et al., 2010). We made this decision based upon visual observations of agent behavior during preliminary simulations. During these simulations, agents frequently clung to walls as they attempted to walk through them and rejoin their group on the other side. The centroid algorithm was clearly unsuited for very complex environments where group members may be within close proximity yet separated by walls or other obstacles. The parameterization of the proxemic threshold for each agent type based on Hall's social distance follows in equation (16). Note that the model's sensitivity to changes in this parameter is the subject of the second experiment presented in this paper.

$$d(a, m) = \sqrt{(f_a - f_m)^2} \quad (12)$$

$$dir_a = \min(f) \quad (13)$$

$$dir_b = \min(d) \quad (14)$$

$$dir_{final} = \begin{cases} dir_a \rightarrow \min(d) \leq p \\ dir_b \rightarrow \min(d) > p \end{cases} \quad (15)$$

$$p = 3.7 \quad (16)$$

Verification and Validation

The model was validated by comparing the mean evacuation time of several simulations to the evacuation time of a real world exercise. Since detailed performance data from an evacuation of a sports arena was not available the model was validated using the same procedure described in previous chapters). In this case, the results of one hundred simulations using the HSRC building and same population distribution demonstrated comparable results at a mean evacuation time of 159s.

Simulation Experiments

Experiment 6: Terrorist Bomb Attack

In this experiment, the Exitus model was used to: (a) determine the impact of a terrorist attack on the evacuation performance of a sports arena, and (b) the impact of shifting population demographics on the same. Notwithstanding the capture of Osama Bin Laden and other military successes in the Middle East, the general threat of terrorist attacks against targets in the United States remains. As a result, it is important for private entities that own or operate critical infrastructure assets to continue to prepare. In this experiment, simulation scenarios were based upon a potential terrorist attack situation described in the National Planning Scenarios Executive Summary (NPS; DHS, 2005). The NPS describes 15 all-hazards planning scenarios for use in national, federal, state

and local homeland security preparedness activities. The sports arena bombing scenario is illustrated as follows:

In this scenario, agents of the Universal Adversary (UA) use improvised explosive devices (IEDs) to detonate bombs at a sports arena. . . . During an event at a large urban entertainment/sports venue, multiple suicide bombers are strategically prepositioned around the arena. They ignite their bombs and self destruct in order to guarantee mass panic and chaotic evacuation of the arena. They also create a large vehicle bomb (LVB) and use suicide bombers in an underground public transportation concourse, and detonate another vehicle bomb in a parking facility near the entertainment complex. (p. 12-1)

We also considered the impact of increasing numbers of individuals with disabilities. It is well recognized that improvements in life expectancy have resulted in a decline in mortality at older ages (Parker & Thorslund, 2006). For example, a person reaching age 65 in 1900 could expect to live an additional 11.9 years, while a person reaching the same age in 1992 could expect to live an additional 17.5 years (Kochanek & Hudson, 1995; National Center of Health Statistics, 1992). As the size of the older population grows and life expectancy continues to increase, evacuation strategies that address the functional consequences of disability in a longer-living population become increasingly important.

Four simulation scenarios were devised for this experiment. The first scenario was designed to simulate a pre-event evacuation of a sports arena. This scenario was included to establish a baseline for subsequent comparisons. The second, third and fourth scenarios were designed to simulate post-event evacuations. In these scenarios, several exits representing primary escape routes were disabled to simulate the destruction resulting from detonated bombs. The exits were chosen based on visual observations of simulations conducted during preliminary experiments (Manley & Kim, in press). The

number of individuals with lower stamina was also systematically increased to reflect the shifting population demographic previously described. The specification of all four simulation scenarios is depicted in Table 12.

The simulations were conducted using the map of a major multi-purpose sports arena located in the intermountain west region of the United States. The arena is an important venue for music concerts, basketball games, hockey games, rodeos, monster truck demonstrations, etc. and is very similar to others located throughout the United States such as the Bridgestone Arena in Nashville, Tennessee, or the Toyota Center in Houston, Texas. From a design perspective, the arena is an enclosed structure providing continuous tiered seating around an inner-bowl. Two major concourses provide access to the seating. Four additional levels provide accommodation for administrative offices, conference rooms, concessions and other services. Together, the inner bowl, tiered seating, and surrounding levels occupy approximately 69,027m² of interior space. From an evacuation perspective, 10 stairwells located on the north, south, east, and west walls of the building provide routes of egress (ROE) for evacuees from all levels of the building. A 3.7m wide ramp on the east wall also serves as a major ROE. Twenty-three

Table 12

Specification of Scenarios for Terrorist Bomb Attack Experiment

Scenario	Population distribution	Blast destruction
A	1x Lower Stamina	None
B	1x Lower Stamina	Disabled Exits on Levels 1 and 2
C	2x Lower Stamina	Disabled Exits on Levels 1 and 2
D	4x Lower Stamina	Disabled Exits on Levels 1 and 2

exits are divided amongst the lower three levels of the arena: three exits on Level One, four exits on Level Two, and 14 exits on Level Three. Due to its tiered-seating design, the arena poses a significant challenge for individuals with disabilities but especially those with lower stamina. Note that seating for individuals using wheelchairs is provided on Level Three of the building only. Thus agents using motorized or nonmotorized wheelchairs were not instantiated on any other level. Figure 14 depicts the map of the sports arena used in this experiment.

Fifteen thousand agents were evacuated during the simulations reflecting the published seating capacity for several common events including end-stage concerts, ice floor shows, and dirt floor shows such as motocross or monster truck demonstrations.

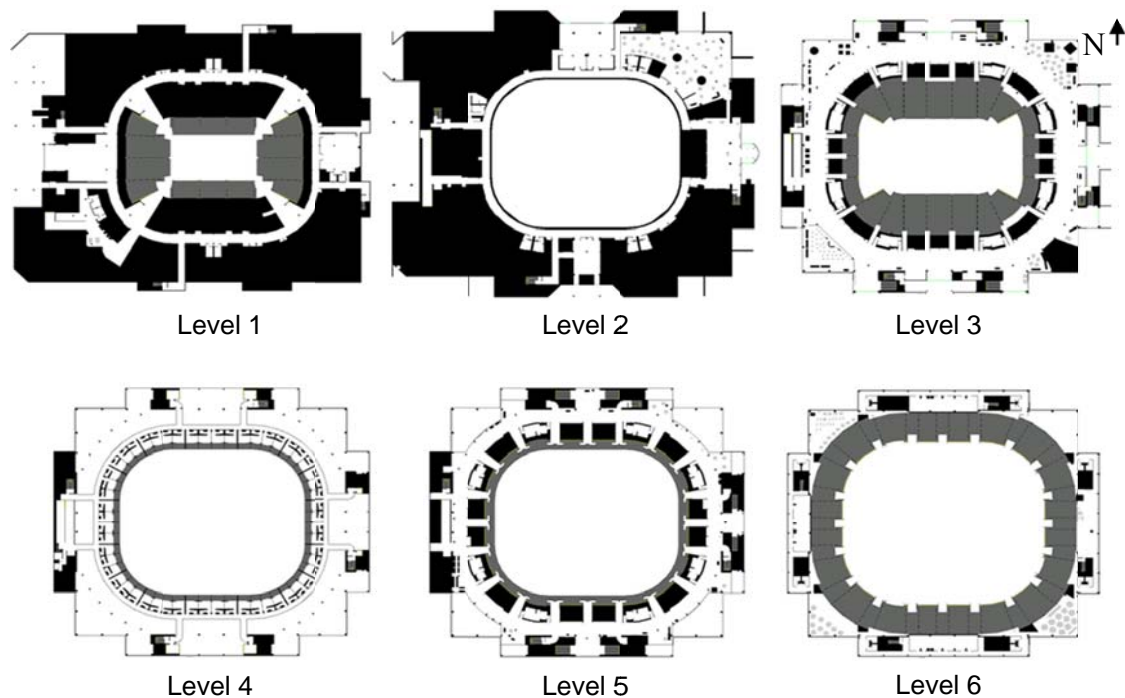


Figure 14. Map of an intermountain west sports arena.

The prevalence and diversity of individuals with disabilities in the evacuation population was assigned in a manner similar to experiments presented in Chapters IV and V. Note that agents with lower stamina were randomly associated with two nondisabled agents to form simple groups of three. We elected to only associate lower stamina agents in order to reflect available empirical literature. At least one marketing oriented study has shown that in planning trips or day excursions individuals with disabilities often travel in the company of others such as family members or caregivers (Huh & Singh, 2010) with an average party size of 3.6 individuals. Members of each group were instantiated within 15m of each other at the start of each simulation, the results of which are presented next.

Simulation performance was primarily measured by evacuation time or the time at which the last agent exited the arena in seconds. Twenty-five simulations were conducted for each scenario. Thus, results are presented in terms of the mean evacuation time or MET. We begin by comparing the results from our proxemic model with those from a preliminary experiment utilizing an earlier, non-proxemic version of Exitus (Manley & Kim, in press). The simulation scenarios devised for the preliminary experiment were identical to those presented here. Several *t* tests revealed that the proxemic results were significantly longer than the non-proxemic results for scenarios B, C, and D, $t(48) = 7.38$, $p < 0.001$; $t(48) = 4.39$, $p < 0.001$; and $t(48) = 3.07$, $p = 0.003$, respectively. Though the MET for scenario A was longer it was not significantly different. In general, longer METs for the proxemic model were expected given that a significant portion of agents were constrained by the desire to stay close to their group. Such agents were often observed moving against the general flow of the remaining population in order to do so.

These results emphasize the importance of modeling relevant social phenomenologies as realistically as possible. As we see here, doing so can result in significantly different evacuation profiles. Table 13 depicts the METs from both the nonproxemic and proxemic models.

We next consider the difference between pre and post-event evacuations by comparing the proxemic model results from scenarios one and two. A t test revealed that the MET for all agents in scenario B was significantly greater than scenario A, $t(48) = 25.5, p < 0.001$. In other words, agents took significantly longer to exit during the post-event evacuation than during the pre-event one. This outcome is expected given the extra distance agents had to travel to find a working exit in scenario two. In this scenario, massive queuing was observed at the stairwells on the bottom level as agents attempted to reach levels two and three. Those who selected a different route (i.e., upwards through the several tiers of inner-bowl seating), were able to travel relatively unhindered though at slower speeds. This result is important because it points to the need for different response procedures during pre and post-event evacuations. More specifically, participants must be able to respond to the threat environment in a dynamic fashion

Table 13

Simulation Results (in seconds)

Scenario	Nonproxemic	Proxemic
A	1446.24	1457.41
B	1689.26	1763.80
C	1822.72	1886.78
D	2076.72	2112.61

during post-event evacuations. In this case, we assumed agents had a full knowledge of the building leading to the selection of the best alternative exit based on proximity to their current location. In real-world situations this may not be the case or the most desirable strategy. Patrons may be unfamiliar with parts of the arena or unaware of damage to other areas of the building. Managers may be required to take an active role in directing evacuees to faster or safer ROEs. Table 14 depicts the METs for all agent types using the proxemic model only.

Interestingly, the change in MET for each agent type between scenarios one and two was essentially the same with the exception of motorized and nonmotorized wheelchairs, which were significantly greater (i.e., 21% nondisabled, 18% visual, 21% stamina, 17% visual, 61% motorized wheelchair, and 110% nonmotorized wheelchair). In other words, agents using motorized and nonmotorized wheelchairs were the most affected by changes that occurred during the post-event evacuation. Though no changes

Table 14

Results for Simulation of a Terrorist Bomb Attack (in seconds)

Scenario	Statistic	All types	Nondisabled	Motor ^a	Nonmotor ^b	Visual	Lower stamina	Hearing
A	MET	1457.41	1449.67	482.03	491.24	1339.34	1455.69	1369.52
	SD	45.65	41.10	92.93	115.39	78.92	46.18	62.55
B	MET	1763.80	1753.17	776.25	1031.38	1581.26	1761.22	1598.67
	SD	42.14	39.83	232.22	299.33	113.92	42.04	90.98
C	MET	1886.78	1864.12	889.36	883.94	1704.70	1885.23	1702.35
	SD	50.15	52.98	331.70	285.32	102.64	49.80	101.86
D	MET	2112.61	2091.09	908.00	911.44	1907.37	2112.30	1973.44
	SD	48.70	49.04	303.41	302.86	112.53	48.95	91.38

^aMotorized wheelchair.

^bNonmotorized wheelchair.

were made to the third level of the arena motorized and nonmotorized wheelchair agents were forced to compete for access to ROE with significantly greater numbers of individuals arriving from the first and second levels where the exits had been disabled. This result is important because it illustrates the potential for unforeseen domino effects. That is, damage in one part of a building may lead to congestion and thus longer evacuation times in an entirely different part of the building. In this case, motorized and nonmotorized wheelchair agents were particularly vulnerable.

We continue our analysis by examining the influence of population composition upon evacuation times in scenarios two, three and four. A one-way ANOVA revealed that the MET differed significantly across all of these, $F(2, 72) = 353.88, p < 0.001$. In other words, the evacuation time for populations with increasing proportions of individuals with lower stamina was significantly different. A post-hoc analysis using the Bonferroni-Holm test indicated that all pairwise comparisons were significant. These results are understandable given the interaction between agents with lower stamina and others in confined areas of the building such as stairwells or narrow passageways. With limited room to maneuver faster moving agents were required to alter their behavior to accommodate slower moving ones who often barred the way. This interagent effect was visually observed at several of the stairwells located on the outer walls of the arena. Greater proportions of agents with lower stamina would understandably lead to a greater number of similar interactions and thus overall longer evacuation times. This result is important because it demonstrates that the composition of the evacuating population has an effect on evacuation performance. The immediacy of emergency situations naturally

leads to a short term focus in terms of planning for the event. However, a long-term view may be important in mitigating the potential consequences of shifting population demographics.

We also considered the rate of evacuation. Figure 15 depicts the percent of agents who exited every minute as the evacuation for each scenario progressed. Surprisingly, all of the scenarios exhibited very similar profiles. However, we noticed a sharp decline at approximately 3 minutes on the evacuation timeline that may represent the point at which the volume of remaining agents began to exceed the capacity of important ROE such as the stairwells and the east ramp. Visual observations of the simulations after three minutes revealed massive queuing at these locations in all scenarios that seems to support this notion. In other words, as congestion became worse the number of agents able to exit the building significantly decreased. This result is important because it represents the

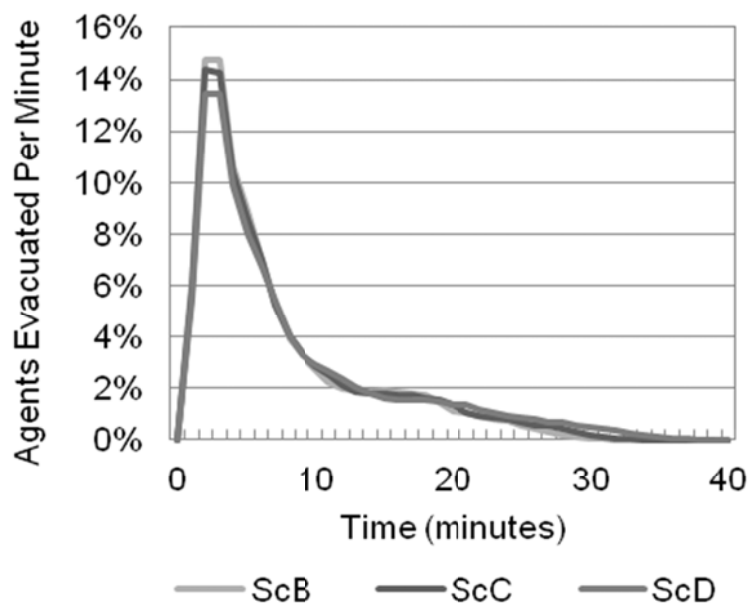


Figure 15. Percent of agents evacuated per minute.

critical point of an evacuation in terms of exposure to risk. Agents remaining in the arena longer than 3 minutes are much more likely to be adversely affected by hazards such as accumulating smoke, structural failure, and a variety of other possible conditions depending on the emergency event. Note that at the critical evacuation time approximately 55% or 8,250 agents had yet to vacate the arena.

We conclude our analysis by considering which type of agent took the longest to evacuate. A comparison of METs by agent type revealed that those with lower stamina took the longest time to exit the arena in all scenarios. Note that the METs for the lower stamina group were very similar to the METs reported for all agents collectively. This result is understandable given that MET is the mean of maximum evacuation times or the time the last agent exited in each simulation. Interestingly, the next longest evacuation times were recorded for nondisabled agents. Though counterintuitive this is understandable given that greater numbers of nondisabled agents were likely to start farther away from the exits placing them at a disadvantage in accessing highly congested ROEs. The interagent slowing effect previously described adds further credence to this explanation. Visually impaired, hearing impaired, nonmotorized wheelchair, and motorized wheelchair agents followed by descending order of MET. Taken together, these results are contrary to those reported in Chapter IV. In the prior experiment, motorized and nonmotorized wheelchair agents took the longest time to exit from a multi-story office building. The results reported here are expected, however, considering the limited amount of wheelchair accessible seating on the third floor of the arena that is also located in close proximity to major exits. As a result of the building design

motorized and nonmotorized wheelchair agents were not required to compete for access to ROE to the same degree that lower stamina and other agents were. Figure 16 depicts the differences in evacuation profile for each agent type. Note that the rate of evacuation for motorized and nonmotorized agents did not appear to change from scenario to scenario notwithstanding generally longer METs as we have described.

Experiment 7: Proxemic Distance Sensitivity

In this experiment the Exitus model was used to determine the sensitivity of evacuation performance to changes in the proxemic distance parameter. Several studies have shown that subcultural characteristics influence proxemic behavior (Little, 1968; Watson & Graves, 1966). In particular, age and familiarity with one's companions have been found to play a role in determining the amount of interpersonal distance maintained between individuals (Burgess, 1983a). Heshka and Nelson (1972) found that as the average age of a person exceeded 40 years interpersonal distance began to decrease. While this behavior was attributed to the physiological effects of aging the authors also acknowledged the possible influence of other factors such as intrusion or interference from uncontrolled distracting events. That is, individuals will increase proximity with others to ensure uninterrupted communication. Note that disruptive events do not actually have to occur during the interaction; rather, knowledge of probable interference alone is sufficient to encourage the behavior. Familiarity with one's companions has also been found to influence proxemic behavior. Strangers have been found to stand farther apart than acquaintances (Willis, 1966) and acquaintances farther than friends (Little, 1968). Most notably, Burgess (1983b) studied proxemic behaviors among pedestrian groups in a

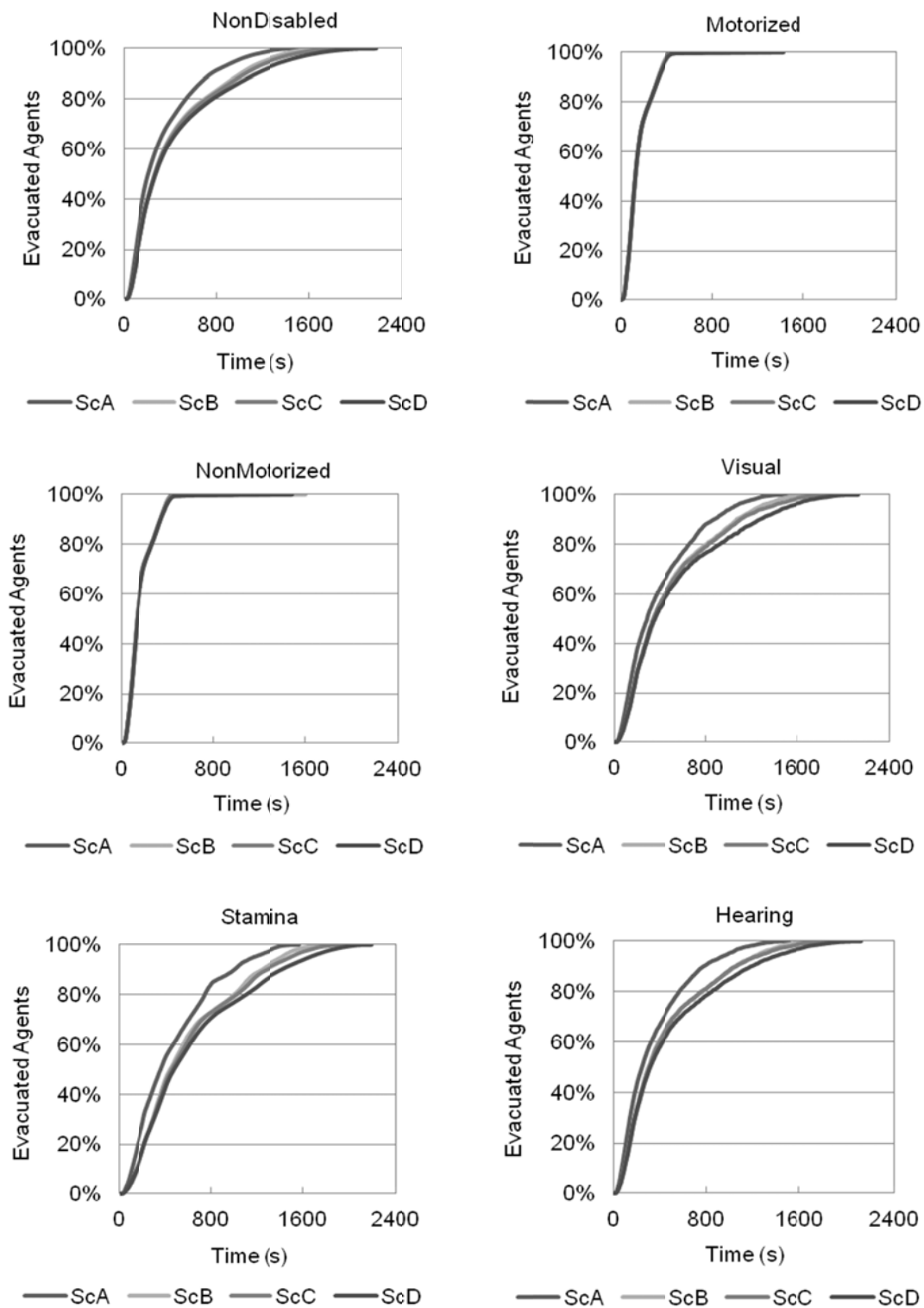


Figure 16. Mean evacuation curves for each agent type.

crowded shopping mall. The results of this study revealed that pedestrians who considered themselves friends aggregated into small groups of slightly more than two persons while maintaining close proximity with each other. Furthermore, there was a negative correlation between interpersonal distance and the density of the environment. As the density of the crowd increased interpersonal distances amongst group members decreased.

Consequently, three additional scenarios were devised for this experiment. In each scenario the proxemic distance parameter for individuals with lower stamina was decreased by an additional 25% to reflect the findings from the literature previously described. The degree of change between scenarios was arbitrarily chosen. All other parameters related to the environment and population were the same as those used in scenario four. That is, we wanted to determine the sensitivity of the evacuation performance to changes in the proxemic distance parameter using the worst-case scenario from experiment one. From a management point of view, one of the goals of this type of assessment should be to establish a hypothetical upper-bound characterization of risk during a post-event evacuation. As a result, 15,000 agents were evacuated in each scenario. The distribution of agent types was as follows: 66% nondisabled, 3% motorized wheelchair, 3% nonmotorized wheelchair, 1.5% hearing impaired, 20% lower stamina, and 1.5% visually impaired. The specification of simulation scenarios for this experiment is depicted in Table 15.

A one-way ANOVA including the results from Scenario D revealed that the MET was significantly different between decreases in p , $F(3, 96) = 8.55$, $p < 0.001$. In other

Table 15

Specification of Scenarios for Proxemic Distance Sensitivity Experiment

Scenario	Population distribution	Blast destruction	Proxemic Dist. (p)
E	4x lower stamina	Disabled exits on Levels 1 and 2	-25%
F	4x lower stamina	Disabled exits on Levels 1 and 2	-50%
G	4x lower stamina	Disabled exits on Levels 1 and 2	-75%

words, evacuation times were significantly longer when the proxemic distance for individuals with lower stamina was decreased. Post-hoc analysis using the Bonferroni-Holm test revealed that while decreases in p elicited a slight increase in MET between Scenarios E-F, F-G and E-G it was not statistically significant ($p = 0.67, 0.26$ and 0.11 respectively). However, the increase in MET between Scenarios D and E was (2112.61 vs. 2353.62, respectively), $p < 0.001$. Therefore, we can conclude that reducing the proxemic distance for agents with lower stamina below Hall's definition of social distance elicits a statistically significant increase in overall evacuation time but not for further reductions. This result is important because it indicates that the interpersonal distances preferred by individuals with disabilities have an effect on evacuation performance. Thus, ensuring the safety of all participants during emergency evacuations requires careful consideration of psychological profiles. The METs for scenarios D, E, F and G are presented in Figure 17.

As expected, the METs for nondisabled, visually impaired, hearing impaired, and lower stamina agents were longer as opposed to just lower stamina agents for whom the

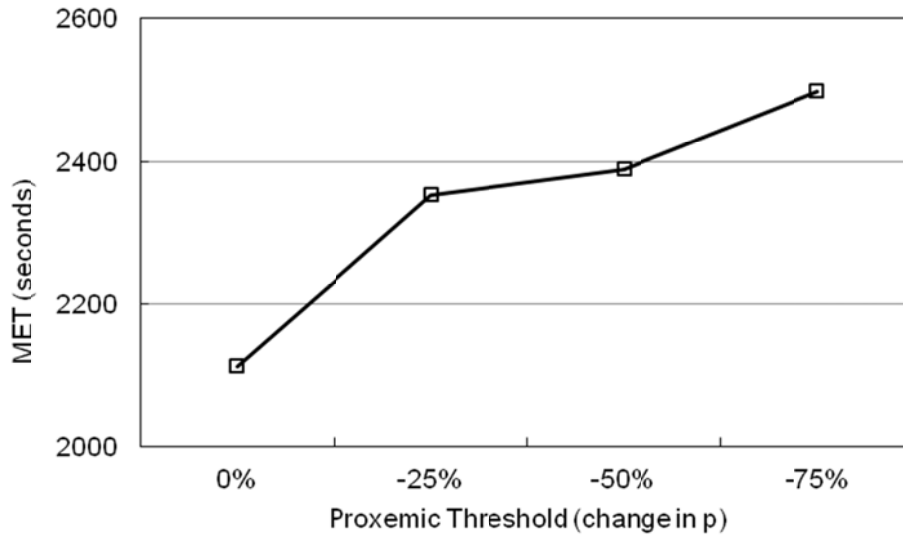


Figure 17. Sensitivity of MET to proxemic distance parameter.

proxemic parameter was modified. This result is understandable given the potential cumulative impact of even a single agent under the right conditions. Consider the agent who attempts to rejoin their group against the general flow of an evacuating crowd. Others are often forced to slow down or alter their own direction, which is then propagated throughout the remaining crowd. Note that the largest change occurred for nondisabled agents, which experienced a 10% increase in MET when the proxemic parameter was reduced. Lower stamina agents experienced a 7% increase in MET. This is important because it emphasizes the effect individuals with disabilities may have on nondisabled agents. Figure 18 depicts the MET for each agent type by percent of agents evacuated for Scenario E.

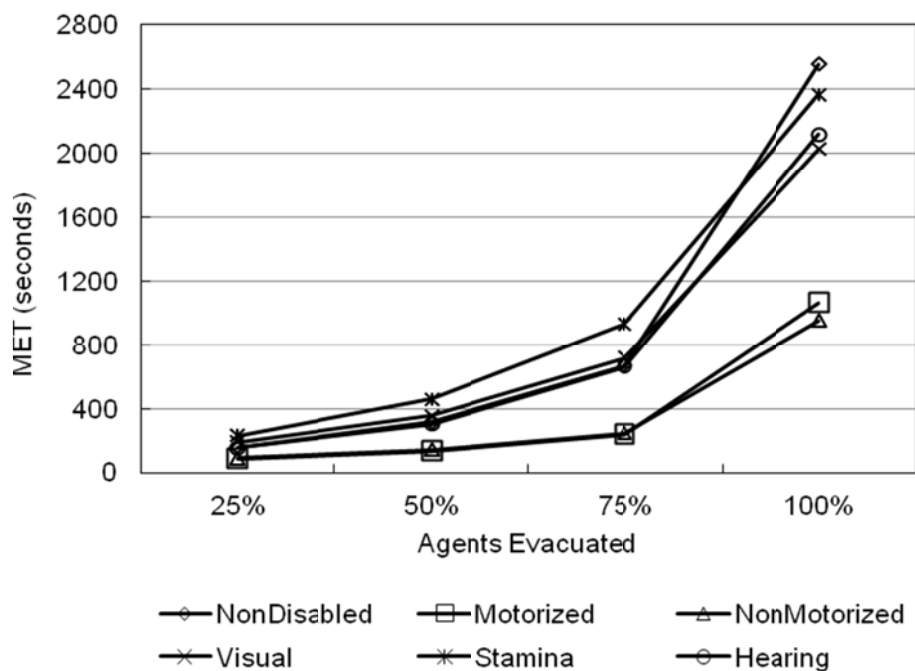


Figure 18. MET by percent of agents evacuated for 25% decrease in proxemic parameter.

Managerial Implications

From an architectural engineering perspective it is clear that the capacity of certain features such as stairways have an effect on evacuation performance. This is especially important for vertical structures such as sports arenas. In this study we have shown that agents will begin to overwhelm the arena's stairways approximately three minutes after the start of the evacuation. Unfortunately, those remaining after this period will likely take much longer to completely exit the building. This is a grave concern considering the potentially lethal effects of even short exposures to certain hazards. It is well recognized that the main cause of death during building fires is exposure to fire smoke and other gases (Barillo & Goode, 1996).

It is worth noting that the sports arena's east ramp was also subject to congestion

or overcrowding. Even though it is wider than the arena's stairways it was not sufficient to ensure an unhindered ROE. This is an important result given that ramps are often considered a more effective means of moving people up or down the vertical levels of a structure (Yeh, Robertson, & Preuss, 2005). Moreover, ramps are often purpose built to accommodate those with lower stamina, those using wheelchairs, and other mobility impaired individuals. In this case, however, the possible benefits were outweighed by the size and density of the crowd and interagent slowing effects of heterogeneous populations including individuals with disabilities. This finding is has important implications for any structure that relies on such features for vertical evacuation of large crowds.

Physical capacity is not the only concern, however. The psychological profile of evacuees also plays a role. Visual observations of the simulations revealed a clear preference for certain ROE over others. Thus, even if a structure has adequate capacity from a physical perspective other factors may cause evacuees to choose certain ROE leading to similar overcrowding situations. In light of these results, our recommendations are as follows: (a) consider increasing existing ROE capacity through building upgrades, and (b) be prepared to actively direct the flow of evacuees in response to the condition of the built environment. The latter may be more realistic than the former given the prohibitive cost of altering a structure the size of a sports arena. However, it is still difficult. Effectively directing an evacuation clearly requires an intimate knowledge of several elements including the building's physical design, patron behavior or preferences, and the interaction between the two during a wide range of emergency situations.

Similar to the results reported in Chapters IV and V, the composition of the

evacuating population had an effect on evacuation performance. This is especially relevant for sports arenas that may accommodate different population profiles depending upon the nature of the event. The ticket purchasing and attendance behavior of different age groups has been shown to be influenced by several different factors related to the event (Pan, Gabert, McGaugh, & Branvold, 1997). In this study we have shown that evacuations of populations with a greater number of individuals with lower stamina take significantly longer.

Interestingly, all agent types, with the exception of those using wheelchairs, exited more slowly, not just those with lower stamina. Even a small difference in proxemic behavior was shown to have a potentially negative impact on evacuation performance. Thus, ensuring the safety of the whole requires careful consideration of the differences among individuals and specifically those with disabilities. In light of these findings managers may consider the following: (a) installation of mobility equipment such as stair chairs or lifts, and (b) designation of special seating areas for the elderly or others who have lower stamina. Recall that individuals using wheelchairs were not affected by changes in the population distribution or proxemic parameter. We attributed this finding to the proximity of specially designated seating areas to several major exits on the third level of the sports arena.

Conclusion

The research contributions of this phase of the study are twofold. First, the Exitus system was extended to include an implementation of Hall's (1963) proxemic theory

resulting in more realistic simulations. Second, the system was used to evaluate evacuation performance in light of a terrorist bombing attack that resulted in damage to the first and second levels of the sports arena. The results of the experiments revealed several important considerations including: (a) the limitations imposed by stairwells and ramps on vertical evacuations, (b) the especial vulnerability of individuals with lower stamina, and (c) the effect of psychological profiles manifested through ROE choice and proxemic behavior.

CHAPTER VII

CONCLUSION

Summary of Findings

The results of the experiments conducted in Chapters IV, V, and VI have several important implications for management practice. First, it is important to recognize that existing ROE may not be adequate for safe evacuation at expected attendance levels. In this research we have shown that congestion is a problem in all of the environments that were studied including a multi-story office building, a large international airport, and a major sports arena. Note that back-of-the-envelope or hand calculations are often used to calculate mass evacuation rates during the design phase of such buildings (Kuligowski & Peacock, 2005). As we have already established, however, such equations cannot account for the effect of interactions among individual heterogeneous agents upon the whole. Thus, initial expectations regarding ROE capacity may be misleading.

Second, the heterogeneity of the evacuating population has an effect on evacuation performance. In this research we have shown that even relatively small changes in repulsion and proxemic distance parameters can result in significantly different evacuation profiles for environments with dense crowds. Furthermore, we have shown that evacuations of populations with a greater number of individuals with disabilities take significantly longer. Interestingly, all agent types were affected, not just those whom changes were applied to. Thus, ensuring the safety of the whole requires careful consideration of the differences among individuals and specifically those with

disabilities.

Third, effective evacuation planning requires both tactical and strategic planning. While the immediacy of disaster situations requires careful consideration of short-term response procedures, a long-term view is necessary to ensure that they address the needs of shifting population demographics. In this research we have attempted to simulate future conditions in which greater numbers of individuals using wheelchairs and those with lower stamina will be present. In both cases evacuation performance was significantly affected. Adopting a long-term view in terms of budgeting and resource allocation may be required to keep tactical response plans in line with changing evacuation requirements.

Fourth, emergency evacuation decision support systems can be an effective tool for addressing the uncertainty of the threat environment when other means are practically or financially impossible. In this research we have shown how a variety of changes to the built environment can influence evacuations. Using Exitus we simulated elevator use and disablement in an office building, the discovery of a dirty bomb at several locations within an airport, and the damage from explosions in several areas of a sports arena. Employing a systematic simulation program featuring a wide array of pre and post-event scenarios beyond these would certainly help managers to effectively establish requirement boundaries and thus target levels of response capability.

The ease with which a wide variety of evacuation scenarios can be modeled is an important feature that distinguishes Exitus from so-called first generation examples or those characterized by homogeneous populations and application in very simple

environments. The model presented in this research is an example of an emerging group of second generation models that are characterized by complex behavioral considerations, environments, and stochastic elements.

Notwithstanding these benefits, it is important to recognize the challenge facing unrestrained adoption of such systems by private organizations. While the necessary programming skill is often readily available the expertise required to meet rigorous theoretical requirements, including a deep understanding of the social dynamics involved, is typically not. The problem grows as models become more sophisticated and the range of parameters that can be investigated increases. Acceptance of this and other evacuation ABM may be furthered by establishing a standard range of scenarios and parameters to form minimum acceptance criteria.

Overall, the findings and managerial implications arising from this research can help provide a foundation for the development of best practices and policies that address the emergency evacuation needs of heterogeneous populations. In this case, the simulation of evacuations from a multi-story office building, an international airport, and major sports arena helped to highlight the key issues surrounding the development of optimized evacuation plans. Ultimately, an all-hazards or capabilities-based approach featuring both strategic and tactical planning with an eye toward the unique problems presented by individuals with disabilities is advocated.

Limitations

In terms of the limitations of this work, readers will have noted a number of

simplifying assumptions that may not fully reflect the reality of the scenarios we have attempted to simulate. While we have done our best to identify and explain our reasoning throughout the manuscript it is worthwhile to point out the following specific issues.

First, some of the assumptions underlying the implementation of assisted evacuations in Chapter IV may not reflect limitations found in the real world. In particular, we may have been overly optimistic in averaging the travel speed for individuals with and without disabilities working together. Unfortunately the lack of empirical data surrounding these issues forced the specification of certain model parameters based on rudimentary assumptions even when they may not be entirely realistic.

Second, a fifth concourse connected to terminal three of the airport was not considered in Chapter V. The concourse was not included at the time the structure was digitally mapped. Note, however, that its inclusion would result in a configuration very similar to terminal one. The expectation is that doing so would lend further credence to the findings already presented.

Third, the representation of post-detonation destruction in Chapter VI was limited to the exits on the first and second levels of the sports arena only. In reality, a wide variety of structural damage and/or hazards are likely to occur. For example, gas and electrical systems may be damaged resulting in fire and smoke accumulation throughout the building. Our decision to do so was a pragmatic one driven by the need to maintain a reasonable scope for the experiments.

Further Research

Taken together, the conclusions and limitations arising from this work suggest several possible avenues for further research. In particular, studies examining stairwells and ramps in relation to evacuations would increase our understanding of how to alleviate the problems encountered in these areas. Studies incorporating additional hazard data such as fire spread or smoke accumulation rates would enhance the realism and thus reliability of the model. Lastly, studies applying Exitus to different environments such as high rise buildings would lead to more generalized policy development regarding evacuation of heterogeneous populations including individuals with disabilities.

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PUBLICATIONS

Refereed Journal Articles

- In Press Manley, M. & Kim, Y. Exitus: Agent-based evacuation simulation for individuals with disabilities in a densely populated sports arena, *International Journal of Intelligent Information Technologies*.
- 2012 Manley, M. & Kim, Y. Modeling emergency evacuation of individuals with disabilities (Exitus): An agent-based decision support system. *Expert Systems With Applications*, 39(9), 8300-8311.
- 2011 Manley, M., Kim, Y., Christensen, K. & Chen, A. Modeling emergency evacuation of individuals with disabilities in a densely populated airport, *Transportation Research Record: Journal of the Transportation Research Board*, 2206, 36-48.
- 2009 Ugray, Z., Ellsworth, C., Manley, M., & Erickson, K. Does the use of computer-aided learning tools affect learning performance? *International Journal of Innovation and Learning*, 6(3), 275-284.

Refereed Conference Proceedings

- 2011 Manley, M. & Kim, Y. Exitus: Agent-based evacuation simulation for individuals with disabilities in a densely populated sports arena. *Proceedings of 17th Americas Conference on Information Systems (AMCIS 2011)*, Paper 61.

- 2010 Manley, M., Kim, Y., Christensen, K., & Chen, A. An agent-based model for emergency evacuation of heterogeneous populations. *Proceedings of the 41st Annual Meeting of the Decision Sciences Institute (DSI 2010)*, 691-696.
- 2007 Kim, Y., Manley, M. & Johnson, J. D. Towards an intelligent property valuation model: An exploratory and conceptual study. *Proceedings of 13th Americas Conference on Information Systems (AMCIS 2007)*, Paper 231.

Manuscripts in Preparation

- nd Manley, M. & Kim, Y. Managerial implications of dirty bomb scenarios in airports: An agent-based simulation study, Target Journal: *Decision Support Systems*.
- nd Manley, M. & Kim, Y. Agent-based simulation of terrorist attack scenarios: Implications for sports arenas, Target Journal: *Decision Support Systems*.

GRANTS AND AWARDS

- 2010 Transportation Research Board of the National Academies, Airport Cooperative Research Program #A11-04, 2009-2010, \$10,000

CONFERENCE PARTICIPATION

Papers Presented

- 2011 Agent-based evacuation simulation for individuals with disabilities in a densely populated sports arena, *Americas Conference on Information Systems*, Aug. 5-7.
- 2011 Modeling emergency evacuation of individuals with disabilities in a densely populated airport, *Transportation Research Board 90th Annual Meeting*, Jan. 23-27.
- 2010 An agent-based model for emergency evacuation of heterogeneous populations, *Annual Meeting of the Decision Sciences Institute*, Nov. 20-23.
- 2007 Towards an intelligent property valuation model: An exploratory and conceptual study, *Americas Conference on Information Systems*, Aug 9-12.

TEACHING EXPERIENCE

Principles of Management Information Systems, Instructor, 2 courses
 Microcomputer Applications, Instructor, 9 courses
 Advanced Database Systems, TA, 1 course

SERVICE TO PROFESSION

2011 Americas Conference on Information Systems, Ad Hoc Reviewer
 2010 Decision Science Institute Annual Meeting, Ad Hoc Reviewer
 2007 Americas Conference on Information Systems, Ad Hoc Reviewer
 nd ISC2 Safe and Secure Online program, Volunteer Presenter

NONACADEMIC WORK

Web Systems Engineer, Wells Fargo Bank N.A., 2005 - present
 Database Engineer, Health Care Insights, 2004 - 2005
 Software Engineer, Novell, 1998 - 2004

RELATED PROFESSIONAL SKILLS

LNG C, C++, C#, Java, VB.Net, VB, VB Script, Javascript, SQL, T-SQL, PL-SQL, XML, XSLT, HTML, XHTML
 OS Unix (FreeBSD, OpenBSD), Linux (Ubuntu, Suse), MS Windows 3.x/95/98/NET/2000/XP/Vista/7
 DB Oracle, Sql Server, MySQL, Sybase
 NW MS Windows NT/2000/2003/2008 Server, Netware 4.11/5.0
 APPS Eclipse, MS Visual Studio, PL/SQL Developer, Toad, Sql Server Management Studio, Business Intelligence Development Studio

PROFESSIONAL MEMBERSHIPS

Association for Information Systems, 2011 - present
 Decision Sciences Institute, 2010 - present
 International Information Systems Security Certification Consortium, 2007 – present