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Exitus: Agent-based Evacuation Simulation for Individuals with Disabilities in a Densely Populated Sports Arena

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ABSTRACT

In this paper we present an agent-based evacuation model which may be used to support private sector organizations with capabilities-based planning efforts surrounding likely terrorist attack scenarios. The model is distinguished by its explicit consideration of individuals with disabilities in respect to the characteristics influencing their ability to negotiate surroundings. The virtual environment is also classified according to several accessibility traits shown to have a disproportionate effect upon behavior during an emergency. The results of an experiment simulating the truck bombing of an intermountain west sports arena reveal special areas of concern for arena managers and identify those who are most at risk or individuals with lower stamina. Ultimately, the model can be used to inform policy makers of more effective, evidence-based evacuation planning methods based on a better understanding of the behavior of heterogeneous populations during emergency situations.

Keywords

Decision Support System, Agent-Based Modeling, Emergency Evacuation, Individuals with Disabilities, Simulation

INTRODUCTION

Emergency preparedness efforts since the 9/11 terrorist attacks have been overwhelmingly focused on public sector services. However, private sector organizations own 85% of the nation's infrastructure and provide employment for a vast majority of people (Kean et al. 2004). As a result, there is a compelling need for private sector organizations to protect themselves against the human and economic costs resulting from large scale disasters. Organizations owning critical infrastructure assets such as sports arenas are especially vulnerable. In July 2002 the U.S. Federal Bureau of Investigation issued a warning that individuals associated with terrorist groups were downloading stadium images from the internet (Estell, 2002).

Evacuation procedures which consider the needs of all persons, including those with disabilities, constitute a key part of effective disaster response plans. Individuals with disabilities comprise 16% of the U.S. population and have been shown to be disproportionately affected by changes in the physical environment (USFA, 1999). Yet emergency evacuation research has largely overlooked this relationship (Christensen, Collins, Holt and Phillips, 2006). As a result, studies examining evacuations of individuals with disabilities from critical infrastructure assets like sports arenas are needed to help ensure their safety and mitigate the risk faced by private sector owners.

Unfortunately, the traditional evacuation-drill approach used to prepare for emergency situations presents several practical and financial challenges at this scale and magnitude. Consequently, simulation is often employed to create a realistic environment in which the social dynamics between virtual evacuees can be fully expressed. Agent-based Modeling (ABM) is a specific simulation technique which has already been used to successfully represent a variety of social dynamic systems such as stock trading strategies (Luo, Liu and Davis, 2002). In this study, ABM is used in conjunction with geographical data to create a decision support system (DSS) capable of assessing the evacuation performance of sports arenas from several different analytical dimensions.

The remainder of the paper is organized as follows. We first review the literature surrounding evacuation simulation with an emphasis on the underlying theory of ABM. We then present our system's architecture including its organization, implementation, and underlying assumptions. This is followed by a presentation of the results of an evacuation experiment designed to simulate the sports arena truck bombing scenario described in the National Planning Scenarios Executive Summary (DHS, 2005). We then discuss the managerial implications for those charged with protecting individuals with disabilities and conclude by reviewing the limitations of the study and possible directions for future research.

LITERATURE REVIEW

Evacuation simulation models can be broadly categorized according to the specificity of the human component. From this perspective, three general approaches are evident from the literature, macroscopic, microscopic, and mesoscopic.

Macroscopic modeling is characterized as a top-down approach in which collective pedestrian dynamics such as spatial density or average velocity are related to model parameters through a closed-form formula (Lovas, 1994). Microscopic modeling is characterized as a bottom-up approach in which pedestrians are modeled as individual entities; formulae encapsulating spatial transition probabilities are repeatedly applied leading to temporal changes in state or behavior (Burstedde, Klauck, Schadschneider and Zittartz, 2001). Mesoscopic modeling is a combination of both macro and micro techniques. Though agent movement is individually specified it is still dependent on aggregate flow conditions rather than interactions with other agents (Hoogendoorn and Bovy, 2000).

In terms of pedestrian crowds, macroscopic and microscopic models are limited by their inability to explain empirically observed self-organizing behaviors (Helbing, Buzna, Johanssen and Werner, 2005). Self-organizing behaviors are those which arise naturally without external influence from signals or conventions. Microscopic models, on the other hand, have been shown to successfully reproduce a wide variety of such phenomena including lane formation, clogging, and several others (Helbing and Molnar, 1995; Helbing et al. 2005). Note that the application of this approach is made difficult by the computational intensity of continuous formulae. Recent studies, however, have used parallel computing and other techniques to overcome this obstacle (Quinn, Metoyer and Hunter-Zaworski, 2003; Song, Yu, Wang and Fan, 2006).

A particular subcategory of microscopic modeling focused on the emergent process is Agent-Based Modeling (ABM). ABMs are 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). In terms of individuals with disabilities ABM has an important advantage in the ability to incorporate multiple perspectives in a simple and flexible manner. Other modeling approaches are often forced to make limiting assumptions which contradict real-life behavior. ABM, however, is ideal for modeling problems where conflicting interests are essential.

Several commercial examples of evacuation ABM exist including EXODUS, EGRESS, SIMULEX, EXIT89, GridFlow, and others. Such models, however, do not allow users to specify the physical and psychological characteristics describing individuals with disabilities (Kuligowski and Peackock, 2005). Nor do they consider the impact of the built environment upon them during emergency situations which is why we have designed our own ABM to specifically address these considerations.

SYSTEM ARCHITECTURE AND DESIGN

The ABM developed for this study is called Exitus which is based on a design presented by Christensen and Sasaki (2008). A preliminary implementation was introduced in Manley, Kim, Christensen and Chen (2010). Two important modifications distinguish the current model from these predecessors. First, the underlying data structures were modified to accommodate large environments and populations. Second, agent behavior algorithms were modified to incorporate fundamental concepts presented in cellular automaton studies by Kirchner, Nishinari, and Schadschneider (2003) and Song et al. (2006). The following discussion primarily focuses on the unique aspects of the Exitus model. Readers are referred to Manley, et al. (2010) for a more thorough treatment of the basic elements composing the system.

From a purely technical perspective, Exitus is a custom desktop application built with C++ and the MFC library for Windows platforms. Within this framework, agents are realized using a standard object-oriented approach. That is, agents are expressed as discrete bundles of data and behavior in the form of state transformers which differ by agent type. The unique aspects of the Exitus architecture, however, are embodied in three logical components: (1) environment; (2) population; and (3) simulation.

The environment component is responsible for creating an abstraction of the real world in which spatial data is expressed as a two-dimensional grid of cells having a finite length and width. As a result, the virtual environment in Exitus is a discretized version of the real world and similar to other cellular automata. Unlike other models, however, Exitus classifies the environment in terms of accessibility characteristics including exit character, route character, and obstacle character, each of which refers to the functional demand imposed by the environment upon an individual’s competency to meet it in relation to their disability.

The population component is responsible for creating populations specified in terms of six different types of people: (1) non-disabled; (2) motorized wheelchair users; (3) non-motorized wheelchair users; (4) visually impaired; (5) hearing impaired; and (6) stamina impaired. Each type is distinguished by physical and psychological characteristics which address several established criteria for describing the functional competency of people with disabilities in the general population. For example, speed, size, ability to negotiate terrain, and others (Christensen et al. 2006).

The simulation component controls the progress of the evacuation by sending movement signals to agents at regular time intervals. Upon receiving a signal an agent calculates the probability for movement p as their velocity modified by the accessibility of the current location va_{ij} in relation to the signal interval *T* which is then compared to a real-valued random number generated from a uniform distribution or *u*. The formal definition of this algorithm is presented in equations (1) and (2).

$$p = \frac{va_{ij}}{T} \tag{1}$$

$$move \rightarrow p \geq u[0,1] \tag{2}$$

Given the decision to move, agents then select the next prospective location based on the accessibility characteristics of each cell corresponding to the set of four directional choices, {*d* | *north, south, east, west*}. If a cell is impenetrable it is removed from the set of available choices. Thereafter, the agent selects from those remaining and updates their location accordingly. The agent's final selection and movement is influenced by three essential forces: (1) attraction; (2) repulsion; and (3) friction.

Attraction refers to the desire to move toward a destination. Attraction is quantified by means of static floor fields (Kirchner, Nishinari and Schadschneider, 2003) expressed as a spatial grid for each exit and connecting feature on each level of the virtual environment. Floor field cells contain values indicating the time to destination from their location. For example, an exit cell will contain a value of 0 while one further away is greater. Agents choose the one with the lowest value in an effort to reach their destination by the shortest route possible.

Repulsion refers to the desire to avoid injury resulting from collision with obstacles or other agents. Repulsion is expressed as 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*. If an agent is repulsed a penalty is applied to the cell's time to destination *t* to reflect its undesirability in relation to its neighbors. Equations (3), (4), and (5) depict the formal definitions for hardness, repulsion probability, and the time to destination penalty where η = hardness of an individual cell.

$$h_{ij} = \sum_{d=1}^{D} \eta_d \tag{3}$$

$$r_{ij} = \frac{1 - e^{-hv}}{1 + e^{-hv}} \tag{4}$$

$$t_{ij} = t_{ij} + \begin{cases} 0 \rightarrow u[0,1] < r_{ij} \\ 1 \rightarrow u[0,1] \geq r_{ij} \end{cases} \tag{5}$$

Friction refers to the necessity of physically slowing down when an agent is in contact with an obstacle or other agents. Friction is realized in terms of the probability of movement from the current location to the destination cell f_{ij} in a manner similar to repulsion probability modified by the intent to move. The intent to move is expressed in terms of a coefficient, $\theta \in [0,1]$, applied to the result from equation (4). The application of friction probability to agent movement over time results in slower speeds through narrow passageways, congested areas, etc. Equations (6) and (7) depict the formal definitions for friction probability and the final movement decision.

$$f_{ij} = \theta \times r_{ij} \tag{6}$$

$$move \rightarrow f_{ij} \geq u[0,1] \tag{7}$$

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

$$\eta = \begin{cases} 1(agent) \\ 2(wall) \end{cases} \tag{8}$$

$$\theta = 0.7 \tag{9}$$

CALLIBRATION AND VALIDATION

Since detailed performance data from the evacuation of a sports arena was not available the model was validated using a four story office building on the university campus. The results of one hundred simulations demonstrated comparable results at a mean evacuation time of 159 seconds (s) compared to 155s recorded for a real world exercise. The correctness of the model was also visually validated by observing individual agent motion through the building which demonstrated realistic path-finding behavior.

SIMULATION OF A TERRORIST ATTACK SCENARIO

Objective

The objective of the simulation experiment was twofold: 1) estimate the impact of a truck bombing on the evacuation performance of a sports arena, and 2) estimate the impact of greater numbers of individuals with disabilities on the evacuation performance of the same venue. It is generally recognized that mortality rates in elderly age groups have decreased due to medical advancements and improvements in living conditions. At the same time, chronic disease and functional impairments have increased (Parker and Thorslund, 2006). Therefore, management practitioners should also consider respond and recover capabilities in light of this shifting demographic.

The simulation experiment was conducted using the map of a major sports arena located in the intermountain west region of the United States as depicted in Figure 2. The arena is an enclosed structure comprising six levels which occupy 743,000 square feet. From an evacuation perspective the building is unique in that it is designed around two major concourses which provide access to continuous tiered seating around an inner-bowl. The tiered seating arrangement poses a significant challenge for those using wheel chairs or with lower stamina. Four additional levels provide accommodation for administrative offices, conference rooms, concessions and other services.

Ten major 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 12 foot wide ramp on the east wall provides similar access. Twenty-three exits are divided amongst the lower three levels of the arena: three exits on level one, four exits on level two, and fourteen exits on level three. Two of the exits on the second level are only accessible by individuals without disabilities.

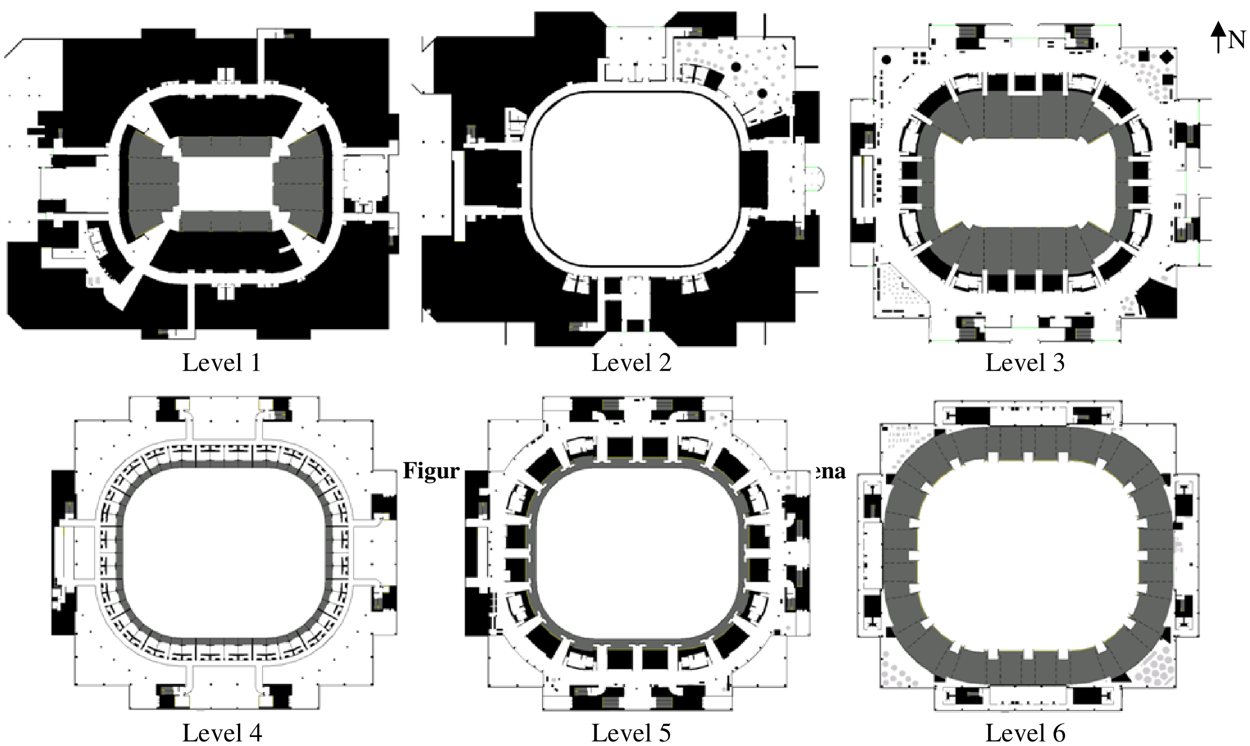

Figure 2. Map of an Intermountain West Sports Arena

Fifteen thousand agents were evacuated during the simulations. This value represents the seating capacity available for several common events including end-stage concerts, hockey or ice floor shows, and dirt shows such as motocross and monster truck demonstrations (Energy Solutions Arena, n.d.). The prevalence and diversity of individuals with disabilities was assigned based on distributions defined by U.S. Census Bureau values (2003), i.e. 86% non-disabled, 3% motorized wheel chair, 3% non-motorized wheel chair, 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 and Silcock, 1999; Wright, cook and Webber, 1999) and accessibility axioms when not. Note that seating for individuals using wheel chairs is provided on the 3rd level of the building only. Thus agents using motorized or non-motorized wheel chairs were not instantiated on any other level.

Four simulation scenarios were devised based upon the sports arena truck bombing attack described in the National Planning Scenarios Executive Summary (DHS, 2005) 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. (p 12-1)*

The first simulation scenario was conducted without any changes to building condition to establish a baseline for subsequent comparisons. For the remaining three scenarios, exits located on the first and second levels of the arena were disabled to simulate the destruction resulting from the detonated bombs. These exits were chosen based on visual observation of baseline simulations which revealed them to be primary escape routes for agents originating in the inner bowl. The number of individuals with lower stamina was also systematically increased to reflect the shifting population demographic described in Parker and Thorslund (2006). Fifty simulations were conducted for each scenario. Simulation performance was primarily measured by evacuation time or the time at which the last agent exited the arena in seconds. The full specification of scenario parameters is depicted in table 1.

Scenario	Population Distribution	Blast Destruction	Simulations
1	1x Lower Stamina	None	50
2	1x Lower Stamina	Disabled Exits on Levels 1 - 2	50
3	2x Lower Stamina	Disabled Exits on Levels 1 - 2	50
4	4x Lower Stamina	Disabled Exits on Levels 1 - 2	50

Table 1. Specification of Simulation Scenario Parameters

Results

The mean evacuation time (MET) for all agents in scenario two was significantly greater than scenario one, $t(49) = 4.48$, $p < 0.001$. That is, agents took significantly longer to completely exit the building after the bombs had been detonated than during the baseline exercise. This outcome is expected given fewer exits to choose from as a result of the blast's destruction. Agents originating on level one or two of the building were required to walk farther than they otherwise would have to find an exit on level three. The METs for the simulation scenarios are depicted in table 2.

Scenario	Statistic	All	Non Disabled	Motorized	Non Motorized	Visual	Low Stamina	Hearing
1	MET	1489.62	1422.73	510.06	549.33	1317.46	1489.50	1280.98
	SD	307.32	40.55	204.98	192.72	85.16	307.33	72.48
2	MET	1689.26	1672.88	719.30	718.93	1565.43	1688.25	1560.42
	SD	30.75	34.33	214.97	212.68	74.87	31.67	79.00
3	MET	1822.72	1801.26	669.60	773.81	1656.89	1822.43	1638.59
	SD	45.03	44.97	189.40	249.29	95.76	45.32	118.13
4	MET	2076.72	2054.19	740.51	1601.40	1947.56	2076.12	1745.95
	SD	46.02	47.92	255.56	576.81	84.53	45.93	151.41

Table 2. Simulation Results for all Scenarios in Seconds

This result is important because it indicates that post-detonation evacuations are different than preventative ones triggered by an impending emergency event. Different response procedures may be required. In this case agents automatically selected the best alternative exit based on proximity to their current location. In practice, managers may assign employees to direct evacuees in the same manner. However, the best locations for deployment may change from one situation to another. Several different simulations could be conducted to support the establishment of a balanced response procedure which addresses the most likely range of post-detonation destruction.

The MET for all agents in scenario three was significantly greater than scenario two, $t(49) = 16.99$, $p < 0.001$. Agents took significantly longer to exit the building when there was twice the number of agents with lower stamina. Likewise, the MET for all agents in scenario four was significantly greater than scenario three, $t(49) = 27.78$, $p < 0.001$. These results are explained by the interaction between agents with lower stamina and others in confined areas of the building such as narrow passageways. With limited room to maneuver faster moving agents were required to adjust their speed to accommodate slower moving ones who often barred the way. This effect was visually observed at several of the stairwells located on the outer walls of the arena.

These results are important because they demonstrate that the composition of the evacuating population has an effect on evacuation performance. Consequently, long term planning which addresses the concerns arising from shifting population demographics should be conducted. For example, managers may plan to acquire additional personnel and equipment, such as wheel chairs or oxygen, to help individuals with lower stamina evacuate quicker. These parameters and several others could be introduced into a systematic simulation program to help focus planning efforts on the most promising solutions.

The MET differences are also reflected in the mean evacuation curves for each scenario as depicted in figure 3. The early divergence and gradually distancing of the curves demonstrate the slowing effect caused by the experimental treatment conditions over time. Just as important, however, is the dramatic change in the slope of the curve for all scenarios occurring at approximately 300 seconds on the evacuation timeline. This represents the time at which the volume of remaining agents began to exceed the capacity of key ROE such as the stairwells and the east ramp resulting in spending much longer periods of time in the building. Visual observations of the simulations after 300 seconds revealed massive queuing at these locations as agents waited to use them.

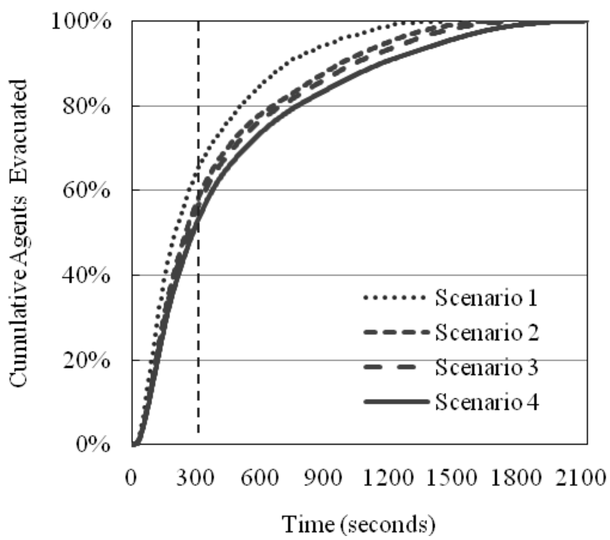

Figure 3. Mean Evacuation Curves for all Agents

This result is important because it represents the critical point of an evacuation in terms of exposure to risk. Agents remaining in the arena longer than 5 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. In this case, approximately 6,000 agents had yet to evacuate. Simulations incorporating flame spread and other hazard-related data could be used to confidently quantify response plans with evidence-based goals or standards.

A comparison of METs by agent type revealed that those with lower stamina took the longest time to exit in all scenarios. Note that the METs for the lower stamina group were almost identical to the METs for all agents in each scenario. This is expected given that MET is based on the time the last agent exited the arena which is the same as the slowest. The next slowest group to exit was non-disabled agents. Though counterintuitive this is understandable given the potential combined effect of several factors such as initial position, response delay, and ratio of non-disabled to other agent types. That is, non-disabled 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. Visually impaired, hearing impaired, non-motorized wheel chair, and motorized wheel chair users were the next slowest to exit in order of MET.

This result is contrary to prior evacuation research which found that non-motorized and motorized wheel chair agents evacuated slowest from a multistoried office building (Manley et al. 2010). However, wheel chair accessible seating within the arena is limited and in close proximity to major exits. No such restrictions exist for those with lower stamina forcing them to compete for access to ROE with all other agent types alike. The effect of this situation is further demonstrated in the differences between scenarios for each agent type. Specifically, the MET for non-disabled agents in scenario three was significantly different from the MET for those in scenario two, $t(49) = 15.80$, $p < 0.001$. Lower stamina agents exhibited a similar result, $t(49) = 16.85$, $p < 0.001$. The METs for all other agent types were not significantly different.

MANAGERIAL IMPLICATIONS

A number of important managerial implications may be drawn from the findings. Based on the evacuation curves ROE capacity was not enough to support a timely evacuation at normal attendance levels. In this case, agents began to overcrowd the stairwells and ramps five minutes after the evacuation started. This finding corroborates those of other studies which identified stairwells and landings as particular problem areas in other kinds of buildings (Manley et al. 2010). However visual observations revealed that some of these routes were favored heavily over others. Managers may need to deploy employees to direct the evacuation, even in undamaged areas, to ensure that all ROE are used to their fullest extent. Note that doing so may still not be enough to overcome excessive crowding. Arena managers may need to establish new ROE or increase the capacity of existing ones to accommodate patrons.

Another implication arises from the intra-agent slowing effect derived from the inclusion of greater numbers of individuals with lower stamina. The METs in scenario three were significantly slower for both non-disabled and lower stamina agents than scenario two. Managers may consider installing mobility aids such as wheel chairs, stair chairs, or lifts to help minimize this effect. Note that the effective use of such equipment requires managers to clearly identify those who may need them. Unfortunately individuals with lower stamina are not always immediately identifiable. People with chronic health conditions, those taking certain medications, or those with minor injuries may all fall into this category, emphasizing the need for a broad approach in terms of identifying those who need assistance early and often as conditions change to ensure their safety during emergency situations.

From a broader perspective the findings suggest that managers can use Exitus to effectively address the uncertainty of the threat environment when other means are practically or financially impossible. In this case, rescue evacuations incorporating damage to the first and second levels of the arena were found to be significantly different from preventative ones. Expanding the simulations to consider a wider range of post-event consequences would help managers to effectively bound response requirements thereby allowing the establishment of target levels of capability which meet them in a balanced manner. The ease with which important aspects of the evacuation were identified and quantified, such as the critical time threshold for escape, is an important feature of the Exitus model which can further help in the planning endeavor.

A strategic evacuation planning approach which considers the specific requirements engendered by shifting population demographics may also be warranted. In this case, evacuations of populations containing twice as many people with lower stamina were found to be significantly different from those with a standard population distribution. The trend towards higher numbers of individuals with disabilities in the population is well recognized among those studying the phenomenon (Parker and Thorslund, 2006). 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.

CONCLUSION

The findings and managerial implications presented in this study can help provide a foundation for the development of best practices and policies which address the emergency evacuation needs of heterogeneous populations. Specifically, evacuation of sports arenas, one of several national critical infrastructure asset categories, was examined using simulation scenarios which highlighted 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.

A particular limitation of this study resides in the modeling of post-detonation destruction which was limited to the first and second levels of the arena. Modeling destruction on other levels of the arena may affect evacuation performance for specific agent-types further. Incorporating additional hazard data such as fire spread or smoke accumulation rates may also have an impact on evacuation performance.

Lastly, the findings presented in this study suggest two important avenues for further research. First, studies examining the design of stairwells in relation to evacuation speed for heterogeneous populations would increase our understanding of how to alleviate the problems encountered in these areas. Second, evacuation simulation studies of different structures like airports may help to highlight further similarities and differences leading to more generalized policy development regarding evacuation of individuals with disabilities.

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