COMPUTATIONAL MODELING OF HUMAN AND SOCIAL BEHAVIORS FOR EMERGENCY EGRESS ANALYSIS

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THE DEGREE OF DOCTOR OF PHILOSOPHY

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Abstract

This dissertation addresses the problem of bringing the perspectives of psychology and sociology about human behavior in emergencies into computational models for egress analysis. Efficacious analysis of emergency egress is facilitated by incorporation of diverse human behavior into a Multi-Agent Simulation System for Egress analysis (MASSEgress). MASSEgress adopts a multi-agent based simulation paradigm to model evacuees as individual agents equipped with sensors, brains and actuators. Individual behavior is simulated through modeling of sensing, decision-making, behavior selection and motor control. Social behavior is simulated through modeling of individual behavior and interactions among individuals. Competitive, queuing, herding, and leader-following behaviors are modeled. MASSEgress is a computational framework; its modular design allows easy extensions to include additional behavior types.

A set of computational methods including point-test and ray-tracing algorithms, and decision-trees are incorporated into MASSEgress to simulate the sensing, decision-making, behavior selection, and motor control of evacuees. A Grid Method is utilized to perform collision detection among large number of agents with an O(N) time complexity, and K-Means clustering algorithm is utilized to develop statistical procedures for drawing evacuation patterns from multiple simulations.

Comparisons of MASSEgress with other evacuation models have been performed to demonstrate its capabilities as well as to validate the computational framework with prior

results. Simulation to replicate a historical event—evacuation at a Rhode Island nightclub has also been carried out. Finally, an application of MASSEgress to simulate emergency evacuation of a multi-story university building is performed to illustrate the potential utilization of the simulation system for egress design analysis.

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Dedication

To my son, Leo Long Pan.

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Chapter 1

Introduction

1.1 Motivation

Design of egress for places of public assembly is of significant importance to facility and safety engineering. Although the regulatory provisions governing egress design are prescribed in building codes, the actual performance of the evacuation systems is difficult to assess. There have been numerous incidents reported regarding overcrowding and crushing during emergency situations. They occur in sport stadiums (for example, the stampede incident in a soccer stadium that killed over one hundred twenty people in Ghana, Africa, 2001), schools (for example, the incident due to power outage that killed twenty-one children and injured forty-seven in Beijing, China, 2002), social gathering places (for example, the incident at a nightclub in Chicago, IL in 2003 that killed twenty-one people) and other facilities. In addition to injuries and loss of lives, the accompanying post-disaster psychological suffering, financial loss, and adverse publicity have long-term negative effects on the individuals and organizations—the survivors, the victims' families, and the communities (Lystad, 1988).

Studies to improve safety in places of public assembly involve many disciplines: architectural design for safe egress (Greenwood, 1990; ICBO, 2000), crowd planning and management (City of Cincinnati, 1980), crowd simulations (Musse et al., 1998; Goldenstein et al. , 2001), evacuation simulations (Stahl, 1975; Berlin, 1982; Fahy, 1991; Helbing et al., 2000; Still, 2000; Fire Safety Engineering Group, 2003), emergency planning, leadership training and many others (Chertkoff and Kushigian, 1999). Even for well planned events in well designed facilities, an undeniable fact is that real danger lies within the crowds. In a crowded environment, it has been observed that most victims were injured or killed by the so called "nonadaptive" behaviors of the crowd, rather than the actual cause (such as fire or explosion) of the emergency. For example, during the Hillsborough English FA Cup Stampede (in 1981), there were no real causes of emergency but still ninety-five people died and over four hundred people were injured. As another example, a Hajj stampede occurred in Saudi Arabia (in 2006) killed three hundred forty-five people, and nonadaptive crowd behaviors were the primary cause of the incident.

Nonadaptive crowd behavior is the type of crowd behavior that does not adapt to an emergency situation and often leads to destructive consequences, which range from clogging at exits, to stampede, pushing, and trampling, etc. (Bryan, 2003). To study nonadaptive behavior in a crowded environment, we need to gain an understanding of human and social behavior in emergency situation from both psychological and sociological perspectives. On a microscopic level, individuals in a crowd act and make decisions differently than when they are alone or in a small group. On a macroscopic level, nonadaptive crowd behaviors are collective phenomena triggered by some external crises or emergencies (e.g., fire, smoke, or explosion).

Building codes contain "means of egress" provisions designed to ensure building safety (ICBO, 2000). However, these codes only provide basic guidelines and are not exhaustive and often insufficient for many practical situations (Still, 2000). First, current codes and guidelines contain ambiguity which may lead to misinterpretations. For example, in the International Building Code (ICBO, 2000), Section 1004.2.2.2 states, "Additional exits or exit access doorways shall be arranged a reasonable distance apart so that if one becomes blocked, the others will be available" (p. 231) — the meaning of the phrase "reasonable distance" is ambiguous and can be easily misinterpreted. An effective computational tool can test whether a specific guideline is appropriate for a particular situation. Second, each building is unique, and compliance with design guidelines does not automatically ensure safety. Often, local geometries — shapes and sizes of spaces and obstacles — can have significant influence to egress, albeit in a subtle way. To date, very few studies can be found in existing literature in terms of understanding how environmental constraints and local geometries impact crowd evacuation behaviors and movements. Such studies are difficult since it often requires exposing real people to the actual and possibly dangerous environment. A good computational tool which takes into consideration human and social behavior of a crowd could serve as a viable alternative.

Computational tools are now commercially available for the simulation and design of emergency egress. However, most current computational tools focus on the modeling of spaces and occupancies but rarely take into consideration of human and social behaviors. On the other hand, the usefulness of a simulation tool is dependent on its ability to properly and correctly model the crowd that occupies the facility and the crowd behaviors. Understanding human and social behaviors in emergency situations is essential to the development of effective egress strategies and models for achieving safety. Current computational models are unable to cover the range of scenarios suitable for safety engineering purposes (Still, 2000), mainly because most of these models have largely ignored insights regarding human and social behavior from the fields of social psychology and social organization (Santos and Aguirre, 2004). Therefore, the research questions raised from the above discussions are:

1. How do human behave during emergency evacuations?

2. How can human behaviors be taken into consideration during design of safe egress for buildings?

3. How can human behaviors, which vary widely depending on emergency situations and the environment, be incorporated in an egress simulation tool?

1.2 Dissertation Goal and Methodology

The main goal of this dissertation is to investigate human individual and social behaviors under emergency situations and to incorporate such behaviors in a dynamic computational model suitable for safe egress analysis. Specifically, this dissertation includes the following two objectives:

1. To research and document human individual and social behaviors in emergency situations;

2. To develop a computational framework that can model some aspects of human individual and social behaviors for egress analysis.

In order to achieve the first objective, we conduct comprehensive literature studies in the fields of psychology, sociology, safety engineering, and egress design, in addition to performing interviews with field experts such as fire marshal, police chief, and crowd control educators. Although human behavior has long been a subject of study in the psychology and sociology, and some efforts have been taken to consider human psychology into crowd simulation (Pelechano et al., 2005), incorporating the insights from these fields into engineering is still underdeveloped. This view also is echoed by Santos and Aguirre (2004) in their reviews of current evacuation models. Our efforts of bringing the psychological and sociological perspectives of human behavior into the perspective of safety engineering has resulted in a theoretical framework, where factors that impact human behaviors in emergency situations are recognized and formalized for developing computational models.

Regarding the second objective, in order to represent human individual and social behaviors computationally, we adopt a multi-agent system paradigm to develop a simulation framework. Multi-agent systems are particularly suitable for exploring complex emergent macro phenomena through studying interactive parts, the phenomena that usually are not reducible to or understandable in terms of the micro properties of the parts. By following a multi-agent system approach, we represent each human evacuee as a virtual agent equipped with sensors, brain, and actuators. The behavior of an individual agent is simulated through modeling the process of sensing, decision-making, and motor control of the agent thus creating a modeling process that is able to integrate psychological and sociological factors to drive the agent's behavior. Human social behaviors are thereafter simulated through modeling individual agent's behavior and the agent's interaction among agents. Since the totality of human behavior can never be modeled completely, we only selectively model a set of commonly observed human behaviors during evacuations. The main emphasis has been to develop a computational framework that is flexible enough to allow new behaviors to be dynamically integrated into the system.

In order to apply behavior-based computational models to safe egress analysis, our approaches are to:

1. Integrate the modeling of evacuees' behavior with the modeling of building geometries, so that virtual agents interact directly with building geometries and egress components, such as obstacles, exits, staircases and assembly points; and

2. Develop visualization tools that allow a simulation to be observed in 2D and 3D views, or capture the simulation as video clips for visual analysis purposes; and

3. Develop a set of methods that present and analyze simulation output in ways that are suitable for design analysis, methods such as creating crowd density map, tracking individual escape routes, tracking egress times, and deriving evacuation patterns using statistical methods.

Once the multi-agent based framework is developed, a set of experimental tests are conducted to validate the framework. The tests include comparing the framework with other evacuation models, employing the framework to perform case studies on replicating a historical case, and conducting egress design analysis on a multi-story building involving over two thousand five hundred occupants.

1.3 Contributions

Primary contributions of this dissertation are as follows:

- *A theoretical framework to facilitate study of human egress behavior and integrate psychological and sociological perspectives into the context of safety engineering*. The theoretical framework developed in this dissertation studies human behaviors in emergency situations at three interdependent levels: individual, interaction among individuals, and group. Factors with significant influence on human behavior in emergency situations can be recognized and formalized in order to be modeled computationally. Such an effort is among the very first in the field of evacuation simulation studies.
- *A computational framework that is capable of simulating human and social behaviors for safe egress analysis.* Capturing human behaviors computationally is difficult and challenging, partly because the complex nature of human behaviors is difficult to understand and formalize, and partly because human behavior cannot be simply represented as mathematical equations. MASSEgress, the computational framework developed for this dissertation, adopts a multi-agent based simulation paradigm, which models a human evacuee as an individual agent equipped with sensors, brain, and actuators. The behavior of an individual evacuee is simulated through modeling the sensing, decision-making, and motor control of an agent. The social behaviors of evacuees are simulated through modeling individual behaviors and interactions among agents.
- *The incorporation of a set of efficient computational methods suitable to simulate the sensing, decision-making, motor control of human evacuees and other utilities*

such as collision detection and statistical analysis of evacuation patterns drawn from multiple simulations. Specifically, the computational methods implemented in MASSEgress include the following:

- Point-test and ray-tracing algorithms are adopted to provide a visual sensing capability for virtual agents in MASSEgress;
- Decision-trees are employed to model agent decision-making processes;
- A hierarchical structure involving different behavioral layers (i.e., locomotive, steering, high-level (decision), and social) is designed and implemented to model the selected human and social behaviors;
- A grid method is adopted to perform collision detection among large number of agents with an O(N) time complexity;
- A statistical procedure which employs K-Means clustering algorithm to draw evacuation patterns from multiple simulations is developed; the method is shown suitable for conducting design analysis for buildings.

1.4 Dissertation Overview

This dissertation is organized as follows:

Chapter 2 documents human behavior during emergency situations, research from which the dissertation draws. Human behavior, social behavior, crowd dynamics, nonadaptive crowd behavior during emergencies from the perspectives of psychology and sociology, a review of current evacuation models are included.

Chapter 3 describes a theoretical framework to facilitate understanding and formalize human and social behavior during emergencies from the perspectives of psychology and sociology. The framework examines human behaviors at three levels: individual, interactions among individual, and group. Process models which describe emergence of social behavior from individual behavior and interaction among individuals are developed for selected behaviors.

Chapter 4 describes Multi-agent Simulation System for Egress Analysis (MASSEgress), a computational framework capable of modeling and integration of human behavior into evacuation simulations for emergency egress analysis. The structure of the framework, computational methods, and essential algorithmic procedures related to representation of physical environments, sensing, behavior modeling, and collision detection are described.

Chapter 5 describes utilization of MASSEgress to simulate behavior through capture of sensory data, decision making, and behavior selection and implementation, and describes an application of MASSEgress to a hypothetical egress analysis.

Chapter 6 describes the validation of MASSEgress by comparing simulation results with other evacuation models which have been extensively validated, as well as with prior reported incidents. This chapter also includes an emergency evacuation simulation for a multi-story university building to illustrate the potential application of the simulation tool for egress design analysis.

Chapter 7 summarizes the contributions of the dissertation and presents potential areas for future research.

Chapter 2

Background

2.1 Human and Social Behavior and Crowd Dynamics

The study of the "crowd" has a long history in sociology. Traditionally, the crowd has been seen as a dangerous phenomenon, in which individual identities, motivations, and rationalities dissolve into a collective mind. Modeling of crowd behavior using fluid dynamics and particle systems thus has a firm basis in sociological thinking about mass assemblies. In terms of the history of social theory, the traditional view of crowd behavior echoes Durkheim's (1995) identification of socially induced religious ecstasy as the cause of a social phenomenon that transcends the individual. The secular analogue of religious ecstasy is panic, the yielding up of individual rationality to an overwhelming collective force, albeit fear rather than joy.

This view of the crowd as unitary and overwhelming of its individual constituents has been eroded over the last two decades by contrary propositions that:

1. View individuals as at least partially retaining their rationality (Simon, 1982); and

2. Identify social structures of interaction below the level of the crowd, including both preexisting structures (e.g., family and friendship groups) and other structures such as queues, arcs, and rings which serve a particular function in the context of gathering (Tucker et al., 1999).

If such features of crowds and other gatherings are operative in both "normal" events and those in which emergencies occur, then these propositions have some clear implications for modeling emergency egress.

Studies of collective action in crowds, including studies of collective locomotion, have demonstrated that preexisting social relationships play a very significant role in structuring behavior (Aveni, 1975; McPhail, 1991; McPhail and Wohlstein, 1986). People who come together to a gathering tend to move in concert with each other, orient their actions to each other, and to leave together. This means that gatherings have a "lumpy" quality—an event with a thousand people, for example, might be composed of several hundred constituent groups moving as internally self-regarding and coordinated units. This has some obvious modeling implications, for example:

1. Flow through exits is likely to be smoother if the path through the exit can accommodate groups as a whole, rather than requiring the group to disperse or string out;

2. If group (for example, family) members become separated from each other, individual members may seek to reconstitute the group before exiting, producing contrary movements and impeding the flow of the crowd as a whole; and

3. Groups that are hierarchically organized (e.g., parents plus children) will probably behave differently than those that are not.

The state of individual rationality defines a second broad set of issues in modeling crowd behavior. If crowd members retain purposive rationality, even under conditions of emergency and panic, then two questions arise:

1. How should this rationality be modeled?

2. What are the relevant aspects of the situation that affect decision-making?

The simplest model of rationality is to assume that group members assess all of the available options and select the alternative that maximizes their utility — in the case of emergency egress, their likelihood of exiting safely. One possibility is to use a game theoretic approach to capture the fact that an important part of the decision environment involves other actors who are themselves making rational decisions. An interesting line to pursue might be the extent to which altruistic behavior appears, and how it manifests itself. For example:

- Is there a mix of selfish and altruistic actors?

- How do they behave differently?

- Are there classes of actors that are more likely to be the target of altruistic behavior, for example children or the elderly?

- Does altruistic behavior actually work?

Another model of rationality, and one that is probably more realistic, is referred to as bounded rationality (Simon, 1982). Models of bounded rationality assume that people are purposively rational, but that they are limited by the extent of their information and by their cognitive capacities for calculation, prediction, and action. To compensate, people:

1. Satisfice rather than optimize;

2. Pursue courses of action until they fail, rather than constantly scan for better alternatives; and

3. Search for alternatives that are in the neighborhood of the problem, and that represent smaller rather than large deviations from current practice.

These assumptions allow for many alternative descriptions of behavior. For example, people may be strongly disposed to exit the same way that they entered, rather than evaluate all possible exits. This suggests that directing flows of people into a space through varying pathways would make it more likely that they would use the full range of exits in an emergency. Another modeling issue is how people decide that there is a problem and that they should exit, or alternatively that the exit process is presenting problems, and that they should do something differently. Bounded rationality would suggest that:

1. The perception of a problem will lag its appearance; and
2. The local state will predominate over distant states in guiding behavior.

Bounded rationality could also explain reinforcing behavior that produces negative consequences. For example, if a queue stops moving, it is difficult for most queue participants to identify the cause. For them, it manifests itself as a sudden slowing of the person immediately in front of them. This slowing might well produce a pushing reaction in order to resolve the immediate problem. This action could easily produce a chain reaction. A design which compensates for this problem could take several directions:

1. Distribute information about the queue to its members, perhaps through displays;
2. Provide or introduce interruptions in the queue, to limit the extent of the chain reaction; and
3. Prevent the formation of queues, through some other mechanisms.

2.2 Theories on Nonadaptive Crowd Behaviors

> "Nonadaptive behavior ranges from the single act of leaving a room of fire origin without closing the door, thus allowing the fire to spread throughout the structure and endanger the lives of all the occupants, to the more generalized behavior of fleeing

> from a fire without regard for others and perhaps injuring others in what is often termed 'panic'" (Brayn, 2003, p.4-14).

Nonadaptive crowd behaviors refer to a broad range of human behaviors that can lead to non-constructive consequences, for examples, behaviors causing the delay of an evacuation or blockage of an exit. Stampede and trampling are the extreme cases caused by nonadaptive crowd behaviors. Although the study of crowd behavior can be dated back to the 1800s, relative few studies about nonadaptive crowd behaviors have been reported in the literature. Most of the fundamental studies on behavioral models were conducted prior to the 1960s before computers were commonly used as simulation tools.

Generally speaking, existing theories on nonadaptive crowd behaviors in emergency situation can be classified into three basic categories: (1) panic (La Piere, 1938; Le Bon, 1960; McDougall, 1920; Smelser, 1963), (2) decision-making (Brown 1965; Mintz, 1951), and (3) urgency levels (Kelley et al., 1965):

1. Panic theories deal primarily with factors that may cause panic during emergencies. The basic premise is that when people perceive danger, their usual conscious personalities are often replaced by the unconscious personalities which in turn lead them to act irrationally unless there is a presence of a strong social (such as a leader) influence.

2. Decision-making theories assume that a person, even under a dangerous situation, can still make (albeit limited) rational decisions, attempting to achieve good outcomes and objectives in the situation (Mintz, 1951). In a situation such as a fire, cooperating with others and waiting one's own turn can likely be beneficial to the group and, in turn, increasing the individual's likelihood of exiting a facility. On the other hand, if some people are pushing, then an individual may feel that his/her chances of exiting safely are threatened if he/she does not react; the best course of action for the individual may be to join the competition and push, in order to maximize the chance of exiting safely.

3. Another theory suggests that the occurrence of (human) blockages of exiting space depends on the levels of urgency to exit (Kelley et al., 1965). There are three crucial factors that could lead to such situations: the severity of the penalty and consequence for not exiting quickly, the time available to exit, and the group size. A problem arises when the urgency to leave reaches a high level of anxiety—for example, too many people try to exit quickly at the same time. Thus, any effort that can reduce the number of people having a high urgency to leave will cause a decrease in jams and less entrapment.

Although these theories have provided many insights into human behavior and reactions in an emergency situation, as pointed out by Chertkoff and Kushigian (1999), to date, a coherent and comprehensive theory about nonadaptive crowd behaviors has not emerged. One common shortcoming of existing theories is that the factors considered are incomplete. Another problem is the inconsistencies among the different theories. For example, panic theories and decision-making theories have opposite assumptions regarding whether or not people are rational under emergencies. Proulx (2001) argues that the difficulties of developing comprehensive theories about human behavior in emergency situations are caused by:

1. Missing data in a number of areas, such as the response time of evacuees and the social interactions among evacuees that influence their response to an emergency;

2. The complex nature of human behavior. Researchers in the field are reluctant to provide equations to predict human behavior in emergencies, because they realize that an oversimplification of this phenomenon would provide unreliable results.

2.3 Evacuation Models

A variety of computational tools for the simulation and design of exits are now available. To review all existing computational models for egress analysis is beyond the scope of this dissertation. Generally speaking, most existing models can be categorized into (1) fluid or particle systems, (2) matrix-based systems, and (3) emergent systems.

2.3.1 Fluid and Particle Systems

Many researchers have considered the analogy between fluid and particle motions (including interactions) and crowd movement. One example of fluid or particle systems is the panic simulation system built by Helbing et al. (2000) (see Figure 2-1). Coupling fluid dynamic and "self-driven" particle models with discrete virtual reality simulation techniques, these systems attempt to simulate and to help design evacuation strategies. Another example is the Simulex (Thompson et al., 2003), which utilizes "distance maps" — a technique that is similar to "potential field" in motion planning (Latombe, 1991) — to simulate crowd movement in buildings. "Distance maps" are pre-computed to represent the "elevations" of spaces, and people then can flow from higher grounds to lower grounds following "gravitational pulls".

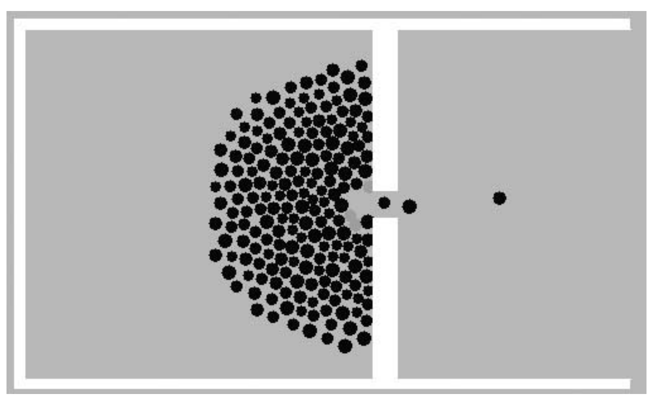


Figure 2-1: Particle simulation in Helbing's model (Helbing et al., 2000)

Recent studies have revealed that the fluid or particle analogies of crowd are untenable. As noted by Still (2000):

> "The laws of crowd dynamics have to include the fact that people do not follow the laws of physics; they have a choice in their direction, have no conservation of momentum and can stop and start at will (p. 16)."

Fluid or particle analogies also contradict with some observed crowd behaviors, such as herding behavior, multi-directional flow, and uneven crowd density distribution. For example, herding behavior is often observed during the evacuation of a crowd in a room with two exits — one exit is clogged while the other is not fully utilized (Low, 2000). However, a fluid or particle analogy would likely predict that both exits were being used efficiently. Furthermore, it is difficult for fluid or particle systems to properly model bi-directional flows (with people moving in opposite directions) in a very crowded environment (Still, 2000). Earlier "self-driven" particle models, such as Exodus (Fire Safety Engineering Group, 2003), are now enhanced to capture behavioral characteristics of occupants. Exodus is now considered by some as an agent-based system (Santos and Aguirre, 2004).

2.3.2 Matrix-Based Systems

The basic idea of a matrix-based system is to discretize a floor area into cells. Cells are used to represent free floor areas, obstacles, areas occupied by individuals or a group of people, or regions with other environmental attributes (see Figure 2-2). People transit from cell to cell based on occupancy rules defined for the cells. Two well known examples of the matrix-based systems are Egress (AEA Technology, 2002) and Pedroute (Halcrow Group Limited, 2003), which have been applied to simulate evacuation in buildings as well as train (and underground) stations. It was suggested that existing matrix-based models suffer from the difficulties of simulating crowd cross flow and concourses. Furthermore, the assumptions employed in these models are questionable when compared with field observations (Still, 2000). Moreover, because the size of cells and the associated constraints need to be adjusted when creating new models, the output of these models depends highly on the modeler's skill.

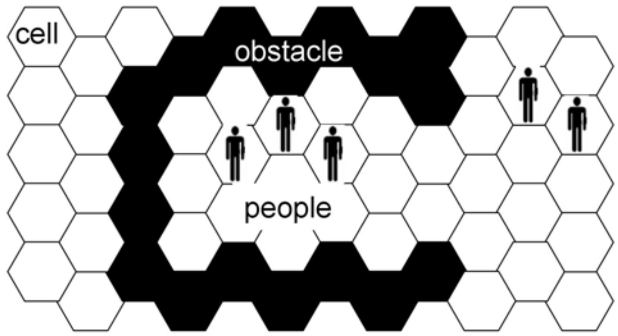


Figure 2-2: Cells in a matrix-based system (Adapted from AEA Technology, 2002)

2.3.3 Emergent Systems

The concept of emergent systems is that the interactions among simple parts can simulate complex phenomena (Epstein, 1996; Johnson, 2001) such as crowd dynamics. One example of the emergent systems is the Legion system (Still, 2000; Legion International Ltd., 2004). It should be noted that Legion was not designed as a crowd behavioral analysis system but an investigation tool for the study of large scale interactive systems. Current emergent systems typically oversimplify the behavioral representation of individuals. For example, the Legion system employs only four parameters (goal point, speed, distance from others, and reaction time) and one decision rule (based on assumption of the least effort) to represent the complex nature of individual behaviors. Furthermore, all individuals are considered to be the same in terms of size, mobility, and decision-making process. Finally, the model ignores many social behaviors such as herding and leader influence. Nevertheless, the emergent concept is intriguing since it has the notion that crowd behavior is a collection of individuals'.

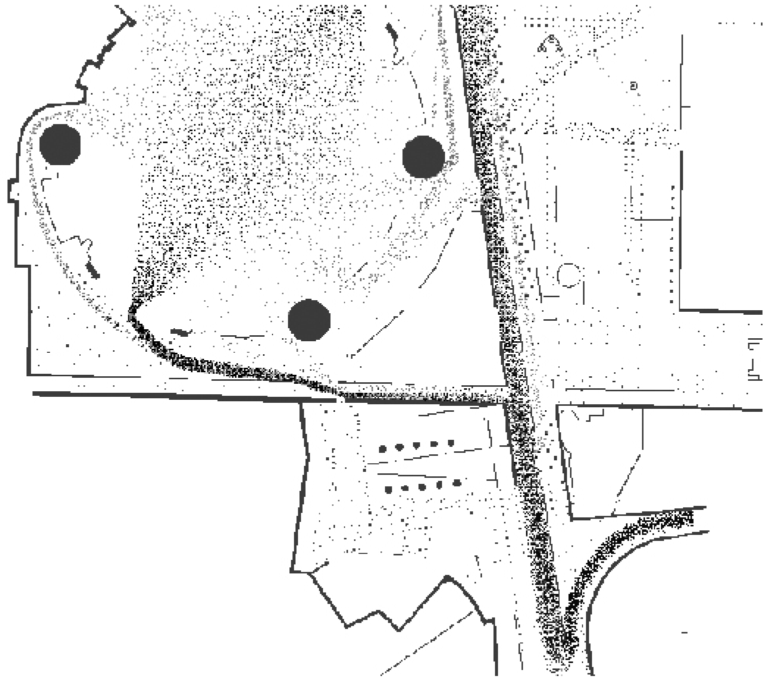


Figure 2-3: Emergent system (Still, 2000)

2.4 Summary

Regarding the theoretical development about nonadaptive crowd behaviors in emergencies, no coherent and comprehensive theory has emerged. Regarding the development of evacuation models, as noted by the Society of Fire Protection Engineers (2002):

> "[Computational] models are attractive because they seem to more accurately simulate evacuations. However, due to the scarcity of behavioral data, they tend to rely heavily on assumptions and it is not possible to gauge with confidence their predictive accuracy (p. 52)."

There has been increasing interests in studying human factors in emergencies (Bryan, 2003; Shields and Proulx, 2000; Proulx and Richardson, 2002). However:

> "the fundamental understanding of the sociological and psychological components of pedestrian and evacuation behaviors is left wanting (Galea, 2003, p. VI)."

This view is also echoed by Santos and Aguirre (2004), who point out that current models have largely ignored insights regarding human and social behaviors from the fields of social psychology and social organization. Therefore, it is evident that incorporating psychological and sociological insights about human behavior into evacuation models is crucial to safety engineering purposes but has yet to be accomplished.

Chapter 3

Human and Social Behaviors in Emergency Egress

Human and social behaviors are complex phenomena. Characteristics impacting human and social behaviors in emergency situations can be categorized into:

1. Human physical characteristics,
2. Environmental characteristics; and
3. Psychological and sociological characteristics.

While many research studies related to the first two categories have been conducted, relatively little work has been conducted related to the third. Psychological and sociological characteristics have also been largely overlooked in most computer-based evacuation models (Santos and Aguirre, 2004). This chapter provides brief overviews of human physical characteristics and environmental characteristics, and follows with investigation of psychological and sociological characteristics of human behaviors during emergency egress.

3.1 Human Physical Characteristics

The physical characteristics of individual humans have significant effect on individual and crowd behavior. Literature research identifies the following relevant physical characteristics: body dimension, mobility, and age and gender.

3.1.1 Body Dimension

Body dimension directly relates to the design of spaces and the measure of crowd density, which, in turn, influences crowd movement. Fruin (1971) defines a fully clothed male body measuring 22.8 inches by 13 inches. Still (2000) defines an average human body as measuring 19.7 inches by 11.8 inches. The model by Thompson et al. (2003) assigns varying body measurements to varying population types through the use of three circles (see Figure 3-1, where Rb, Rt, and Rs represent, respectively, the radii of whole body circle, torso circle, and shoulder circle). The three circle model also is the representation used in our simulation system. For example, the values of Rb, Rt, and Rs are 10.6, 6.3, and 3.9 (in inches) respectively for the body of an adult male, and 8.3, 4.7, and 2.8 (in inches) for the body of a child.

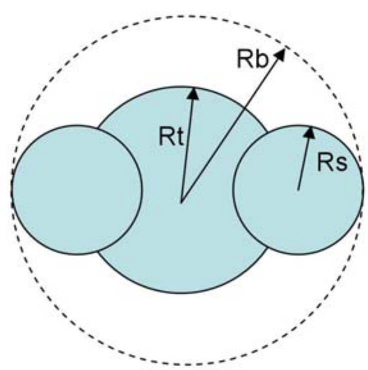


Figure 3-1: Representation of a human body

3.1.2 Mobility

Mobility impacts egress time and physical interaction among individuals. Individuals of varying age and gender may also vary in quality and degree of mobility. For example, females generally move slower than males, and adults move faster than children (Fruin, 1971; Bryan, 2003). In addition to moving speed, mobility often has relation to whether or not an individual is disabled or impaired (Pauls, 1977; Klote, 1992; Juillet, 1999). Individuals with disabilities bring forth a set of different constraints, and they usually have special needs and/or require the assistance from others during an evacuation.

3.1.3 Age and Gender

Age and gender often correspond to individual's body size and mobility. Age may relate to quality and degree of alertness. For example, elderly individuals are generally less alert than younger individuals (Bryan, 2003).

Another characteristic, energy (i.e., potential forces generated by human bodies (Fruin, 1984)), is mentioned by researchers but is less frequently studied and is seldom employed in simulation models.

3.2 Environmental Characteristics

Environmental characteristics represent a set of environmental conditions that confine and/or influence human behaviors during an emergency evacuation. These characteristics can be categorized as geometric constraints, emergencies, and emergency egress systems.

3.2.1 Geometric Constraints

Geometric constraints are imposed by spaces and obstacles with which evacuees interact, such as rooms, walls, exits, and furniture. Evacuees need to comply with these constraints in order to maneuver in the environment. In building science, tremendous efforts, including the development of building codes, have been conducted to produce safe environment for the occupants. For example, the Means of Egress (ICBO, 2000) include specific requirements and equations to calculate the quantity and width of exits to facilitate safe emergency egress. Nevertheless, much work still needs to be done in terms of understanding how local geometries influence the flow of egress crowds. For example, as illustrated in Figure 3-2, a widening in a corridor could actually exacerbate crowd flow, rather than, as one would assume, allowing people to move faster (Helbing et al. 2000).

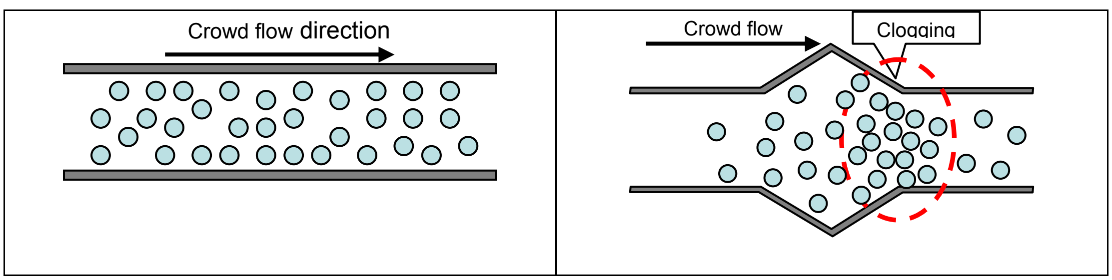


Figure 3-2: Possible negative effects on widening a corridor

3.2.2 Emergencies

Emergencies refer to specific events, typically urgent and life-threatening, which can trigger emergency evacuation, such as fires, explosions, earthquakes, and terrorist attacks. Emergencies cause widespread perception that negative consequences could result from failure to exit within a certain amount of time. Such a perception drives occupants to evacuate. It is also worth noting that it is the perception of an emergency that impacts the perceiver's behaviors, not the actual emergency itself. For example, upon witnessing the same event, one occupant may perceive it as a life-threatening emergency and therefore evacuate immediately, while another may perceive it as of significantly less severity and therefore choose not to evacuate.

3.2.3 Emergency Egress Systems

Emergency egress systems provide guidance to evacuees during an evacuation. These systems include, but are not limited to exit signs, alarm system, emergency communication system, and emergency illumination system. Such systems may be essential to successful emergency egress, particularly to those unfamiliar with the facility. Uncertainty and confusion during initial stages of an emergency, for example, might cause individuals to (1) delay evacuation from a deadly threat, which could prove ultimately fatal, or (2) behave nonadaptively and trigger a stampede. Exposure to an effective emergency communication system, on the other hand, which provides information about the emergency and safe egress, could decrease uncertainty and confusion.

The abovementioned characteristics are interdependent, and may simultaneously impact occupants' behaviors during an emergency. Much development on the subject can be referred to the work of Sime (1984), Bryan (1997), Proulx and Sime (1991), and Shields and Proulx (2000).

3.3 Psychological and Social Characteristics

Human and social behaviors in emergency situations may be described psychologically and sociologically at three levels: individual, interaction among individuals, and group. These three levels of categorization are intimately related and interdependent.

3.3.1 Individual

A crowd is a collection of individuals. In order to understand crowd behaviors, we need to first study the individual's behaviors. From a human cognitive psychological perspective, individual's behaviors can be viewed as the outcomes of the individual's decision-making processes. We conjecture that an individual's decision-making processes follow three basic conventions: instinct, experience, and bounded rationality. An individual may select one or a combination of these basic conventions when faced with emergencies, depending on the specifics of the situation.

- *Instinct*. Instinct refers to inborn patterns of behavior responsive to specific stimuli. Executing an instinct does not require conscious thought process. Examples of human instincts are fear, death and survival. While human infants typically function by instinct, Wills (1998) claims that adult behavior can also be largely explained in terms of instinct, and that human adults can experience and act on instincts without being conscious of them. Adult knowledge learned through life experience can be viewed as extension of instinct. When there is a need to make decisions under high stress, following one's instincts is the most primitive way that an individual relies on in making instantaneous and quick decisions. According to Quarantelli (1954), if an individual perceives that he/she is in an extreme life-threatening situation, his/her behaviors are likely to be driven by the fear instinct such as fight or flight. Behaviors, such as pushing others down, jumping out of windows, and fleeing towards deadly blocked exits, occur because of fear.

- *Experience*. An individual often relies heavily on his/her personal experiences in making decisions. Because many life events are highly repetitive, an individual usually develops a set of relatively standard routines over time or from past experience and then applies them to similar situations in the future. In the case of emergency egress, it is widely recognized that an individual's experiences can significantly impact his/her behavior (Bryan, 2003; Society of Fire Protection

Engineers, 2002; Horiuchi et al., 1986; Sime, 1986), such as the familiarity of the surroundings, safety procedures, and fire drills. However, "using prior evacuation experience to guide future evacuation decisions, may or may not produce better outcomes" (Averill et al., 2005, p.146). One observed phenomenon is that most people tend to exit a building following the route with which they are most familiar and ignore alternate routes. Decision-making in terms of following experience is usually straightforward and quick. The process typically follows three basic steps: (1) recognize a situation that is the same as or similar to an experience in the past; (2) retrieve the routines that were successful according to prior experience; and (3) carry out the routines.

- *Bounded rationality*. The idea of bounded rationality has been integrated into many conventional social theories and come to dominate most theories of individual decision making (March, 1994). Rational decision-making assumes decisions are based on evaluation of alternatives in terms of their consequences for preferences. The process involves four basic steps: (1) search for possible options; (2) anticipate consequences of each option; (3) weigh each consequence against preferences; and (4) choose the most favorable option. Such a decision process is bounded because typically, not all options are known, not all consequences are considered, and not all preferences are evoked simultaneously. Decision-making in terms of bounded rationality is concerned with combining new facts with existing knowledge for problem-solving, and it is one of the fundamental characteristics that constitute human intelligence. The resulting solution usually is more appropriate for the given situation compared to a solution obtained through either following instinct or experience; but the "rational" decision making process does require a longer processing time. In an emergency situation where decisions need to be made instantly, an individual may opt for a faster method by simply following instincts or experiences, resulting at times to what is referred to as irrational behaviors (Le Bon, 1960). On the other hand, altruistic and prosocial behaviors are commonly observed in emergencies (Bryan, 2003; Horiuchi et al. 1986) which would seem to imply rational thinking during emergencies. Rational or irrational behaviors, thus depend significantly on time and severity as perceived by each individual.

Emergency decision-making differs from other types of decision-making in at least three ways: (1) higher stakes, (2) higher uncertainty, and (3) limited time (Proulx, 2002). According to the crisis model developed by Billings et al (1980), these would lead to increased stress. Making decisions under severe stress is different from normal situations, and different levels of stress usually give rise to different decision patterns. According to Sime (1997), when an individual is under increasing stress, there is a decrease in productive thoughts and an increase in distractive thoughts. When stress reaches a certain level, an individual may only consider immediate survival goals. Such observations are supported by the Inverted-U Hypothesis and the Signal Detection Theory (Welford, 1972). The Inverted-U Hypothesis states that as stress increases and the resulting arousal rises, human ability in decision-making performs well until the stress reaches an optimum point, but thereafter one's decision-making ability declines. According to the Signal Detection Theory, stress level increases as signal and noise increase and the ability in decision-making varies with the level of useful signals perceived by the individual. Behavior among individuals in a crowd may vary even though similar levels of stress are experienced. For individuals whose optimum levels of stress are higher than others, they may behave more rationally (e.g., altruistically and adaptively) while others may behave nonadaptively.

In summary, at the individual level, nonadaptive behaviors in emergency situations are the outcome of an individual's decision-making process under severe stress when perceiving a situation as highly important, highly uncertain, and highly urgent. As perceived stress increases, an individual may shift decision-making mechanisms from following experience, bounded rational thinking, to following instincts.

3.3.2 Interaction among Individuals

From the perspectives of social interaction, an individual's social behaviors are shaped by social structures through following social identities (March, 1994). Other crucial factors that also strongly influence human social interaction include the respect of personal space (Ashcraft and Scheflen, 1976) and the principle of social proof (Cialdini, 1993).

- *Social identity*. An individual in a crowd usually acts differently than when he/she is alone or in a small group (Braun et al., 2003). An individual is also a social being. Being part of a society is one essential aspect of a person. Societies are organized through various social structures. Social structures impose rules on individuals in the form of laws, regulations, cultures, and norms. Social structures are composed of diverse identities (i.e., social roles), and each identity has a set of associated rules, which define how it interacts with other identities. As noted by March (1994), "social systems socialize and educate individuals into rules associated with age, gender, social positions and identities. Decisions are shaped by the roles played by decision makers (p. 58)." Depending on an individual's identity, his/her behaviors are strongly shaped by these rules. Individual's identity is also "internalized,"—"accepting and pursuing it even without the presence of external incentives or sanctions (March, 1994, p. 65)." Thus, a decision-making process based on social identity involves four basic steps: (1) recognize a situation; (2) know the identity of the decision maker in the situation; (3) find the appropriate behavioral rules associated with the identity; and (4) follow the rules. In other words, individuals follow rules or procedures that they see as appropriate to the situation and with which they identify themselves. While social identity is crucial in daily decision process, during an emergency, an individual who demonstrates nonadaptive behaviors often appears to be highly individualistic and nonsocial (Chertkoff and Kushigian, 1999). On the other hand, it has been observed that during emergencies, many people (such as trained officers) do behave according to their social identities appropriate to the emergency situations.

Therefore, whether or not individuals remain consistent with their social identities depends on their stress levels and tolerance. Stress levels, in turn, are determined by a combination of perceived value of loss, time available, and uncertainty of a situation (Billings et al., 1980).

- *Personal spaces*. From a human psychological perspective, one very important factor that influences an individual's social behaviors and decision-making is the notion of personal space. According to Ashcraft and Scheflen (1976), "Man is a territorial animal very much like his fellow creatures. He defines a space and marks it out for his particular use. He draws visible and invisible boundaries which he expects others to respect. He will defend a territory against the intrusions of others (p. 3)." Under normal circumstances, an individual seeks social interaction with others; at the same time, the individual also tries to avoid intruding others' privacy as well as to defend intrusions. For example, people who are engaged in face-to-face conversation define a space that others outside the group are expected to respect; an outsider shows such respect by not hearing or pretending not to hear the conversation, by not looking into the occupied space, and by not cutting into the space surrounded by the group. Even though the actual definition of personal space varies among different cultures, genders, and social structures, social norms tend to be respected and maintained by engaged parties except under anomalous situations such as confrontation, overcrowding and emergency. Respect of personal space functions as a social rule to keep safe distances among individuals. When this rule is violated in a crowded environment, involved individuals would likely experience more stress and agitation than in a non-crowded environment (Sommer, 1969). Even so, individuals continue to attempt to regain their personal space and avoid physical contact with others (Bryan, 2003). When crowd density reaches a certain magnitude such as the safety limit suggested by Still (2000), maintenance of personal space may become practically impossible, which could lead to nonadaptive crowd behaviors.

- *Social proof.* Social proof is a phenomenon in which individuals, when faced with perceived uncertainty, for example insufficient information about new situations, follow the actions of others to guide behavior. The dominant factor that leads people to seek social proof is the perceived uncertainty of a situation. As noted by Cialdini (1993), "we seem to assume that if a lot of people are doing the same thing, they must know something we don't… those people are probably examining the social evidence, too (p. 129)." One well known example of social proof in emergency situations is herding behavior: when under highly uncertain and stressful situations, individuals tend to follow others almost blindly. Herding behavior sometimes facilitates safe egress, and sometimes not. Herding behavior may lead people to a dead end, for example, or cause blockages of some exits while others are not fully utilized. This phenomenon is particularly interesting in crowd dynamics and has now been incorporated into some computational models (Helbing et al. 2000). Other instances in this category include social inhibition and diffusion of responsibility (Latane and Darley, 1968; Bryan, 2003). Social inhibition refers to the phenomenon in which individuals first turn to each other for social cues rather than take initiative. "No one wishes to appear foolishly excited over an event that is not an emergency, so each individual reacts initially with a calm outward demeanor, while looking at others' reactions (Batson, 1998, p.285)." Diffusion of responsibility usually prevents individuals from taking altruistic actions. Individuals often hesitate to initiate action to offer help in emergencies in the presence of others. If no one makes the first move, it is less likely that any one would. However, when one offers help, others are more likely to follow. Therefore, initial reactors in an emergency have significant influence in a crowd. If the actions of initial reactors appear calm and orderly, then others would likely to remain calm and orderly. On the contrary, if initial reactors start to push, then others would likely to react similarly.

In summary, at the level of interaction among individuals, nonadaptive behaviors emerged from emergency situations in a crowded environment likely occur if (1) individuals fail to comply with their social identities and act non-socially, (2) individuals lose their personal spaces and perceive a necessity to move urgently, and/or (3) due to a highly uncertain and stressful situation, individuals tend to follow others blindly to seek social proof.

3.3.3 Group

By viewing a crowd or a group within a crowd as an entity, we can identify many significant factors that may contribute to crowd behaviors. Examples of such factors may include: crowd density, environmental constraints, and perceived emotion and tension.

- *Crowd density*. The higher the crowd density the more likely it is that comfort is diminished and the risk to the individual increases (Society of Fire Protection Engineers, 2002; Bryan, 2003). People movement can be highly restricted in a crowd of high density. As pointed out by Chertkoff and Kushigian (1999), "[At high crowd density,] people are swept along with the flow, completely unable to free themselves from the direction of that flow (p. 117)." Under such a situation, it becomes difficult for an individual even to keep his/her feet on the ground in a stable way. People may not deliberately knock others down or trample them but such actions could more easily occur accidentally because of the crowded situation. However, people movement also tends to follow and keep in a group, as opposed to being freely moving as an individual. For example, members of hierarchically structured groups (such as families) tend to remain together and follow the leader. Crowd density is an important factor that can affect individual as well as group behaviors.

- *Environmental constraint*. Crowd movement can also be restricted due to environmental constraints imposed by spatial geometries. Such constraints can be inherent in facility design or can be caused by improper usage of the space. A building may have aisles and stairs too narrow to accommodate easy exit by a large crowd, inadequate number of exterior exits, obstructed passageways, locked exterior doors, stairs or doors obscured by dim lighting or confusing signs. When considering crowd dynamics, we need to consider the environmental constraints and their impacts on individual and group behaviors. Shields and Proulx (2000) point out that current design practice has primarily focused on emergency exit identification and escape route illumination, but has ignored the cognitive and perceptual processes associated with movement and spatial behavior of crowds under emergency conditions.

- *Perceived emotion and tension*. Emergency can cause widespread perceptions among individuals that failure to exit quickly could result in negative consequences. Field observations have shown that individuals do not shove or trample until such perception becomes widespread (Chertkoff and Kushigian, 1999). As more individuals attempt to exit simultaneously, fewer may be successful due to congested or blocked routes. During emergency, because of the time pressure and the lack of information, individuals normally judge the severity of the emergency based primarily on observation of the behavior of others. In other words, regardless of the nature of an emergency, how it impacts an individual depends on the way that he/she perceives the situation and the environment, even though such a perception can be inaccurate or misguided. Varying perceptions of emergencies result in varying emotions and mental stress levels, which can in turn invoke varying decision-making mechanisms. Even in non-emergency situations, nonadaptive crowd behavior can occur, as long as the situation creates high emotional arousal among the crowd, such as false alarm, group fight, confrontation between a furious crowd and police, and power outage.

In summary, at a group level, nonadaptive crowd behavior can occur if a crowd holds the characteristics of high crowd density, severe environmental constraint, and high emotional arousal. The emotional arousal may or may not be originated from an actual emergency.

The above discussion is not meant to be exhaustive. Nevertheless, it establishes a framework to dissect the complex nature of human and social behaviors into simpler components, which can be better understood for the purpose of computational modeling. For example, Figure 3-3 illustrates a generalized process model about the emergence of nonadaptive crowd behavior. Modeled conditions which might result in nonadaptive crowd behavior include: (1) based on environmental cues (such as smoke and fire), the crowd perceived that a need to evacuate is highly important, highly uncertain, and highly urgent, (2) severe environmental constraints (such as insufficient number of exits), and (3) high crowd density.

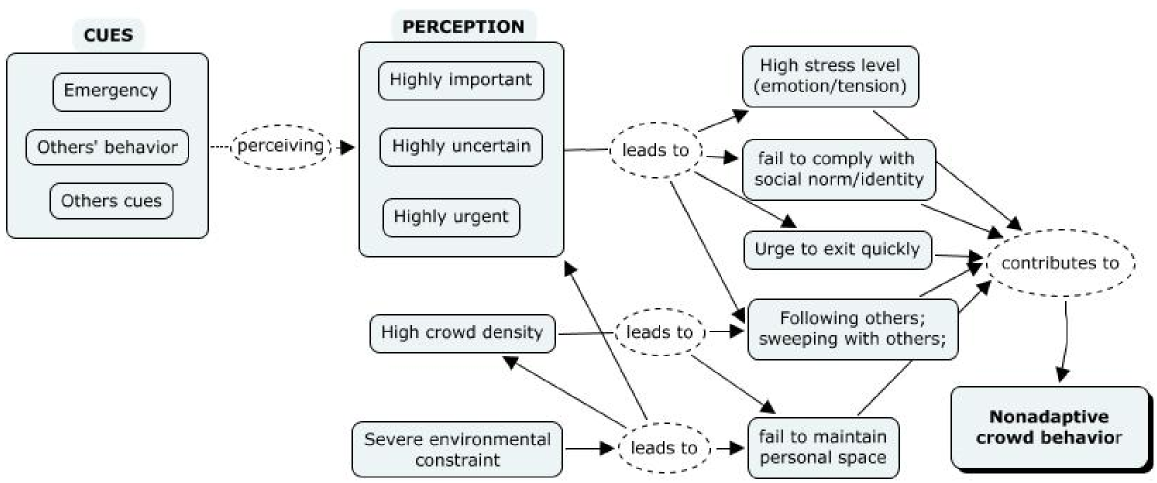


Figure 3-3: A process model of the emergence of nonadaptive crowd behavior

3.4 Process Models of Some Evacuation Behaviors

Based on the analysis provided thus far, now we can look into some observed evacuation behaviors more closely—to identify some crucial parameters and processes involved in each behavior, so that it is possible to model these behaviors computationally. The selected instances to be discussed are competitive behavior, queuing behavior, herding behavior, altruistic behavior, and leader-following behavior. A generalized process model that integrates these evacuation behaviors is presented at the end of this section.

3.4.1 Competitive Behavior

Competitive behavior is often observed in emergency situations, when individuals compete to exit, and can likely lead to inefficient evacuation and nonadaptive crowd behaviors. As illustrated in Figure 3-4, emergence of competitive behavior is relatively complex with a variety of factors, and many scenarios can potentially lead to competitive behavior.

From a modeling perspective, some typical parameters include:

- *Perceived importance*: this parameter refers to the severity of a situation that is perceived by an individual, and it is measured by the value of loss from the individual's perspective. The importance of the situation determines how much mental pressure the individual will generate to pursue a solution. High importance implies increased pressure and willingness to react to the situation. For example, individuals usually choose to react to situation only when an actual and significant threat is perceived.

- *Perceived uncertainty*: this parameter implies the question "is there a way to avoid loss?" and is measured by quality of solutions available to individuals. The level of uncertainty determines the amount of mental pressure that can be released. For example, a high quality solution implies decreased uncertainty, which in turn leads to a high degree release of the pressure.

- *Perceived urgency*: this parameter refers to time available to make a decision related to a situation. High urgency implies high pressure for immediate action.

- *Stress level*: this parameter refers to the amount of stress experienced by an individual during perception of a situation.

- *Stress threshold*: this parameter is a boundary condition which measures effect of stress. Individuals may think and behave differently when stress threshold is exceeded.

- *Personal space*: this parameter represents minimum distance individuals prefer to maintain from others.

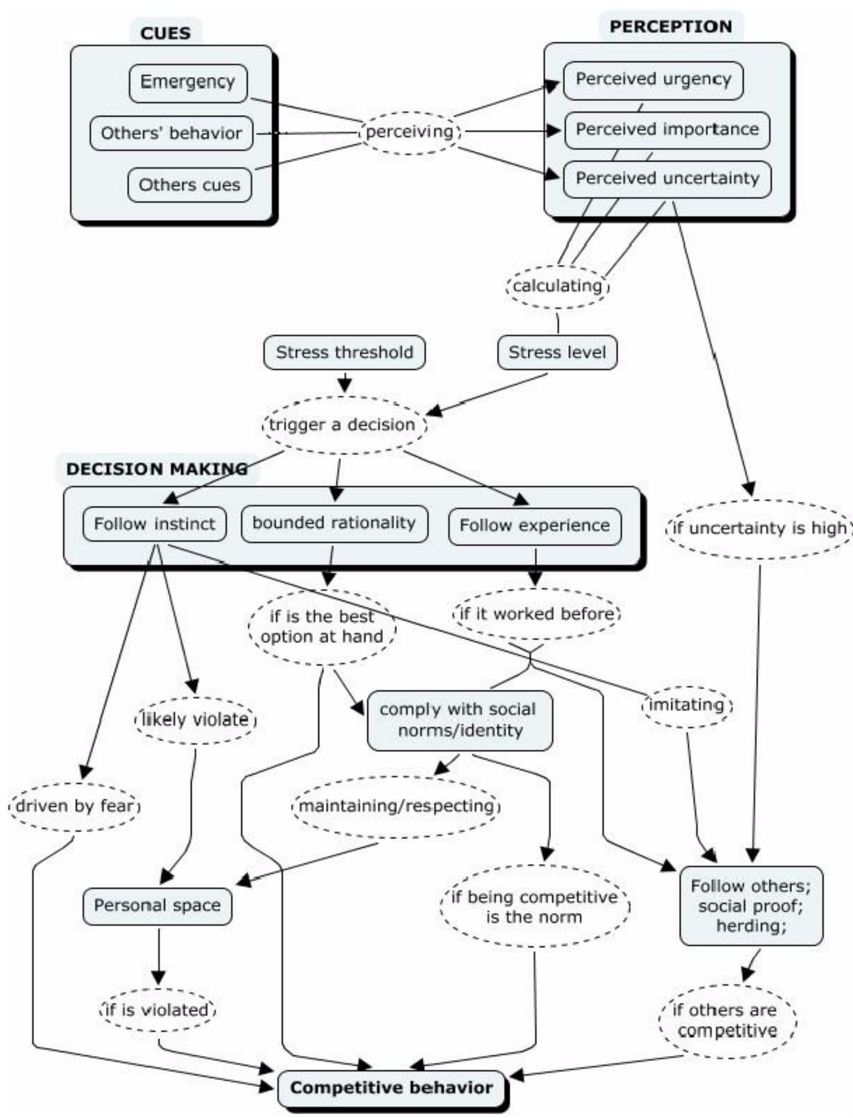


Figure 3-4: A process model describing the emergence of competitive behavior

Furthermore, some typical processes include:

- *Perceiving*: a process through which individuals obtain information from an environment through sensors such as eyes and ears.

- *Matching a perception with a specific stress level*: a process in which individuals evaluate their perception of situations and experience a specific mental stress level. Generally, if an emergency is perceived as highly important, highly uncertain, and highly urgent, then a high level of stress will be experienced which then influences decision-making processes. Moderation, on the other hand, of any of the three factors (i.e., perceived importance, certainty, and urgency) may decrease the stress level. For example, individuals may feel less or no stress if they perceive that: (1) the emergency is already under control (i.e., perceived importance is moderated), (2) they will evacuate safely (i.e., uncertainty is moderated), or (3) there is sufficient time to exit safely (i.e., urgency is moderated).

- *Decision-making*: processes by which individuals choose actions in response to assessment of perceived situations. Based on the discussion in Section 3.3.1, individual decision-making processes follow three basic conventions: instinct, experience, and bounded rationality. Individuals may select one or a combination of these basic conventions in response to stress level and threshold.

Many scenarios can lead to competitive behavior. The followings are some examples derived from Figure 3-4:

- An individual perceives a situation as highly uncertain and therefore chooses to follow the action of others; the individual behaves competitively because others are evacuating in a competitive manner (the scenario corresponds to the social proof theory (Cialdini, 1993)).

- An individual perceives that there is an urgent need to evacuate. Upon rational assessment of the situation, the individual decides that competitive action is the best option and therefore evacuates competitively (the scenario corresponds to the decision making theory (Mintz, 1951)).

- An individual perceives a highly important, urgent, and uncertain situation, which causes a high level of mental stress. Driven by fear, the individual flees in a competitive manner, driven by fear, toward the nearest exit (the scenario corresponds to the panic theory (Le Bon, 1960)).

3.4.2 Queuing Behavior

Queuing behavior often emerges spontaneously when a crowd gathers at exits, permitting the crowd to stream out in an orderly fashion. Formation of queues is largely a manifestation of self-organization. Unlike competitive behavior, queuing behavior does not typically lead to blockages at exits but often leads to more effective evacuation. Queuing behavior is also impacted by the parameters and processes as described in Section 3.4.1 and social identity as described in Section 3.3.2. Similar to competitive behavior, many scenarios can lead to queuing behavior (see Figure 3-5). For examples:

- An individual perceives a situation as highly uncertain, and therefore chooses to follow others in response to the situation; the individual joins a queue because he sees others queuing at an exit (a scenario corresponds to the social proof theory (Cialdini, 1993)).

- A school teacher perceives a need to evacuate. She organizes her students to queue and exit in an orderly manner (a scenario corresponds to the social identity theory (March, 1993)).

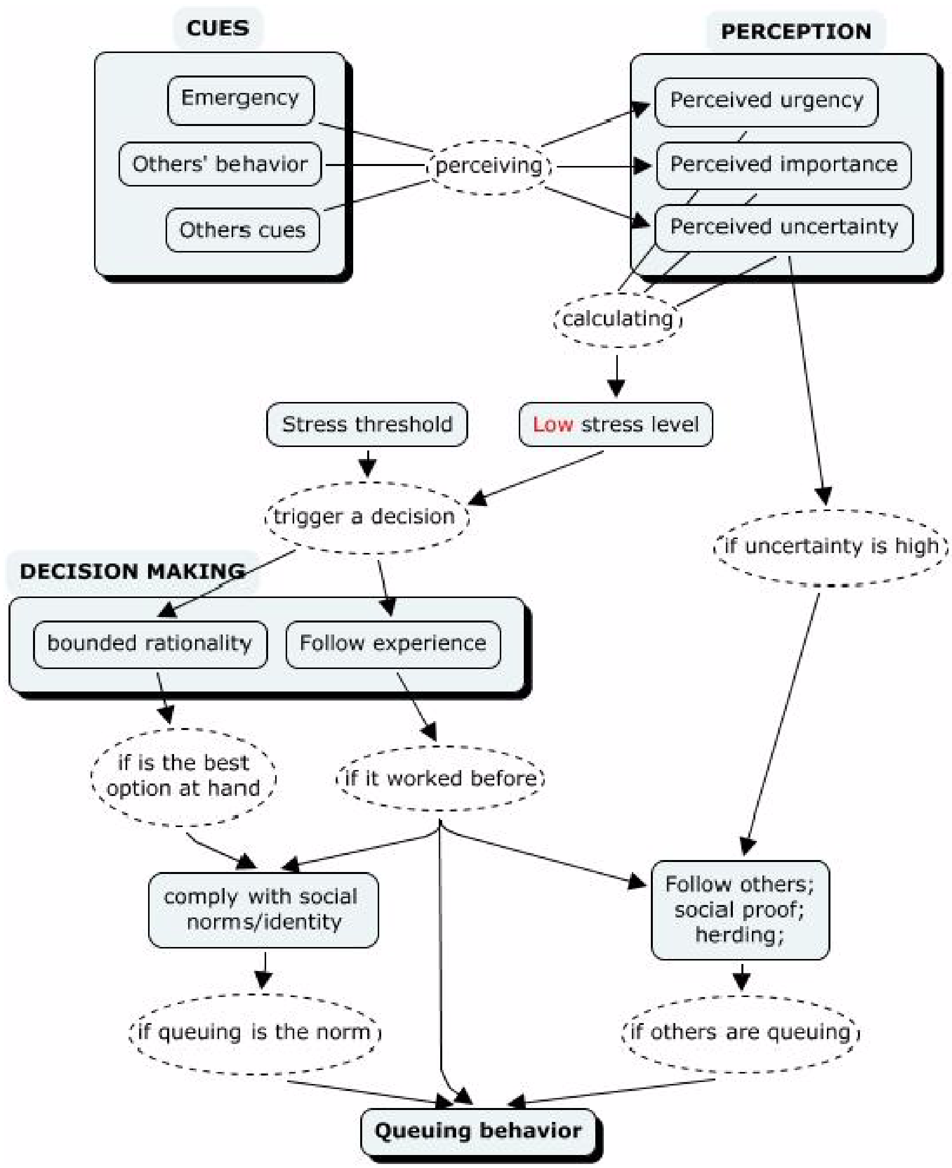


Figure 3-5: A process model describing the emergence of queuing behavior

3.4.3 Herding Behavior

Herding behavior is often observed during the evacuation of a crowd in a room with two exits—one exit is clogged while the other is not fully utilized. Building designers often assume that a crowd would exit evenly among multiple exits of a room in case of an emergency; however, herding behavior contradicts such an assumption. According to the social proof theory (Cialdini, 1993), the primary parameter contributing to herding behavior is perceived uncertainty. That is, when individuals have insufficient information regarding what to do, they tend to follow the actions of others. Another parameter relevant to herding behavior is perceived importance (see Section 3.4.1), which provides incentives for individuals to herd. Two processes are also involved in herding behavior: perceiving and decision-making (as described in Section 3.4.1). A process model describing the emergence of herding behavior is shown in Figure 3-6. Some example scenarios that could lead to herding behavior include:

- An individual perceives a situation as highly uncertain. The individual notices that most people are evacuating through the main exit and follows them (a scenario corresponds to the social proof theory (Cialdini, 1993)).
- An individual perceives a need to evacuate. The individual previously evacuated successfully by following the crowds and therefore chooses to follow the crowds—individuals' experiences can significantly impact their behavior (Bryan, 2003).

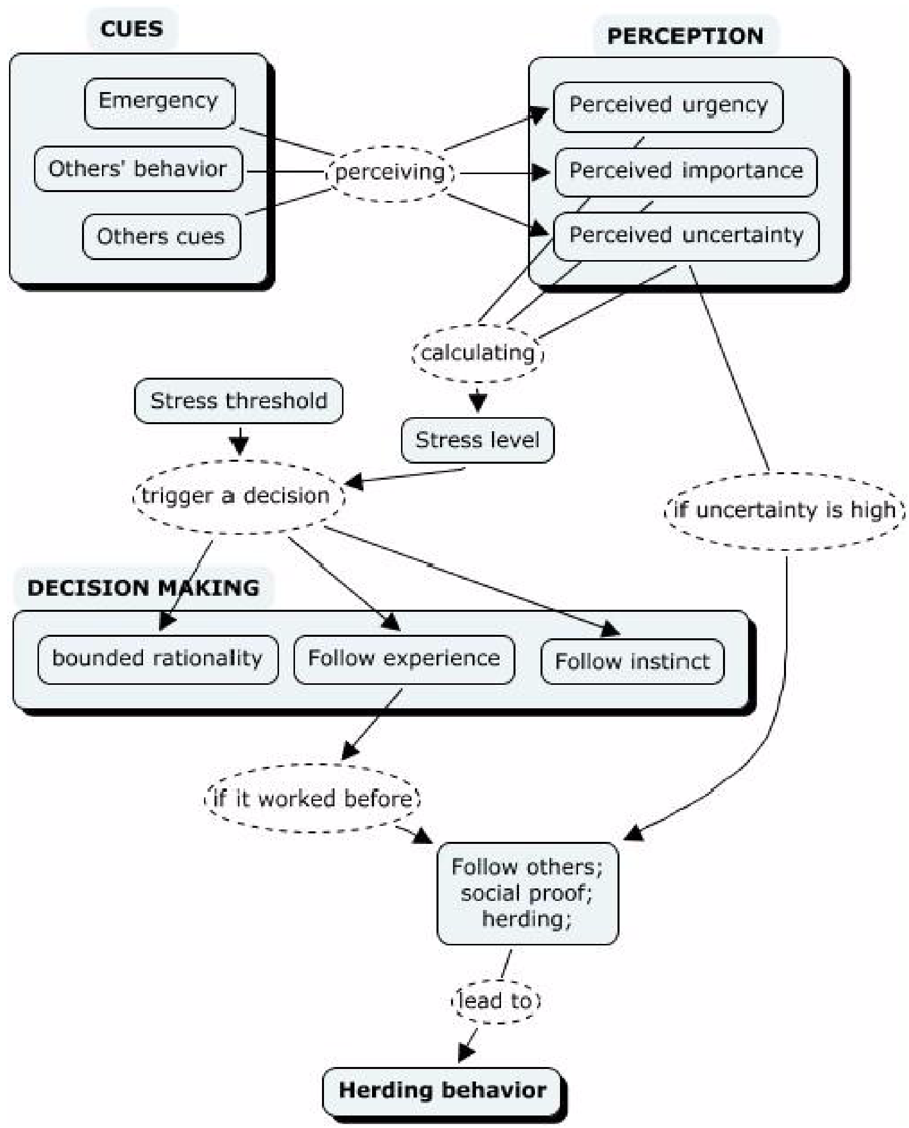


Figure 3-6: A process model describing the emergence of herding behavior

3.4.4 Altruistic Behavior

Altruistic behavior is commonly seen in emergency situation. For example, during the "September 11" evacuation, "[an] occupant from a floor in the 60s, confined to a wheelchair, was being assisted by four previously unknown occupants down the stairwells in WTC 1 (Averill et al., 2005, p. 109)." As discussed in Section 3.3.2, altruistic behavior can be a result from social proof — individuals are more willing to help those in need, if they observe that others initiate help. Altruistic behavior can be a result from people following social norms and considering it as being ethical. For example, a group of individuals help each other, because they share a belief that "good citizens should treat each other as brothers and sisters". Also, according to the empathy-altruism hypothesis (Batson, 1997), if individuals feel empathy towards a person who needs help, they are likely to help them without selfish thoughts.

A process model describing the emergence of altruistic behavior is shown in Figure 3-7. Two relevant parameters that could impact altruistic behavior are: perceived uncertainty (see Section 3.4.1) and social identity (see Section 3.3.2). Processes involved are perceiving and decision-making (see Section 3.4.1). Scenarios that could be derived from Figure 3-7 include:

- During an evacuation, an individual notices some disabled people are in need of help, and is uncertain what to do. When other evacuees offer help, the individual then decides to help (a scenario corresponds to the social proof theory (Cialdini, 1993)).
- A firefighter carries an injured occupant out of a burning building (a scenario corresponds to the social identity theory (March, 1993)).
- Two evacuees carry a disabled individual going down the staircase in a high-rise building (a scenario corresponds to the empathy-altruism hypothesis (Batson, 1997)).

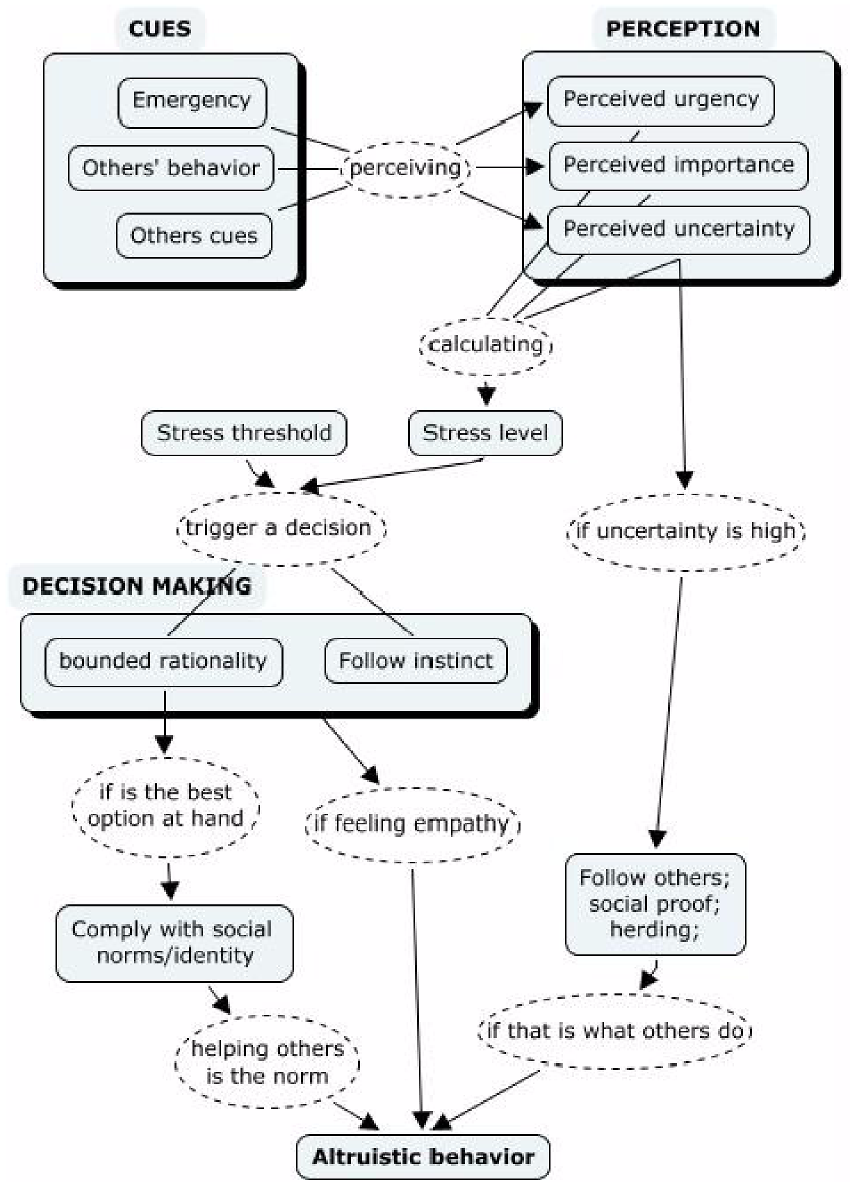


Figure 3-7: A process model describing the emergence of altruistic behavior

3.4.5 Leader-Following Behavior

During an evacuation, members of hierarchically structured groups (such as families) tend to remain together and follow the leader. Sometimes, a leader can also emerge out of a group of individuals when a situation seems to be uncertain to most people. Therefore, two parameters that can contribute to leader-following behavior are social identity (see Section 3.3.2) and perceived uncertainty (see Section 3.4.1), and two relevant processes are perceiving and decision-making (see Section 3.4.1). Figure 3-8 shows a process model describing the emergency of leader-following behavior. Scenarios that could be derived from Figure 3-8 include:

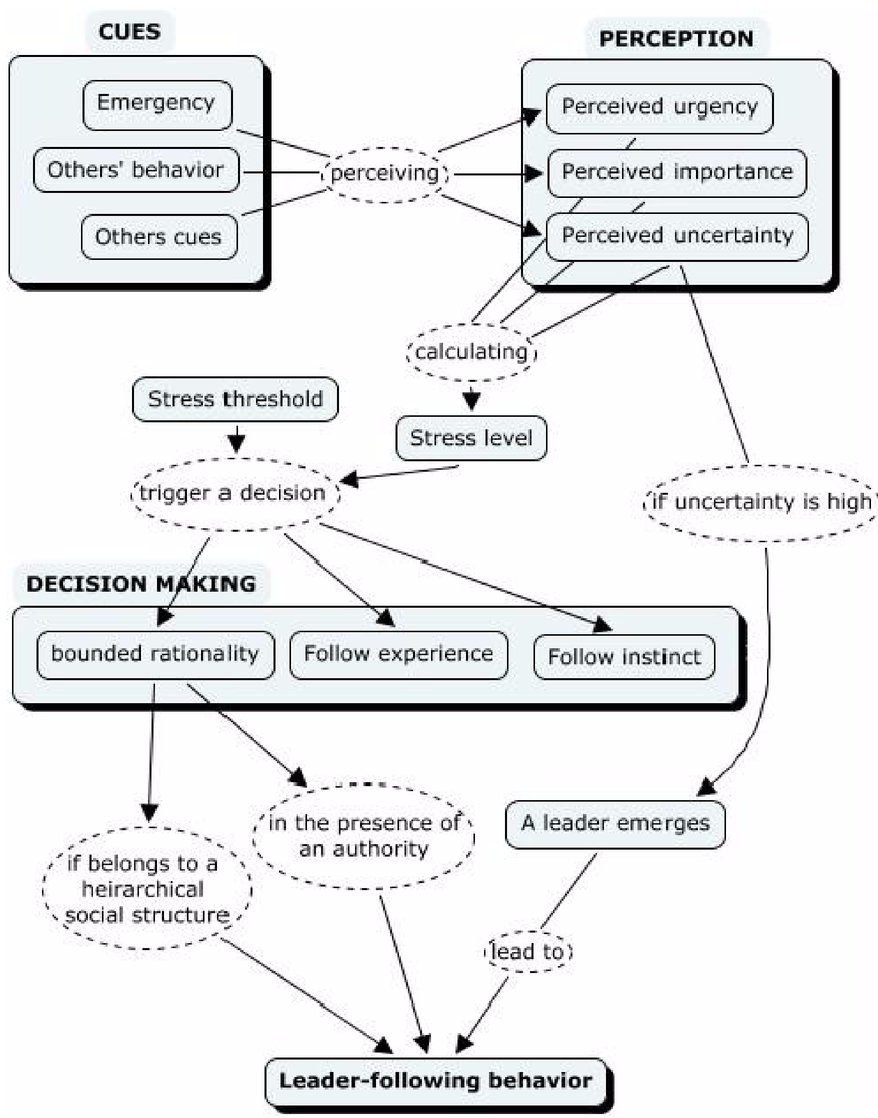


Figure 3-8: A process model describing the emergence of leader-following behavior

- Shortly after the siren goes off, the museum manager shows up and leads people to evacuate from the building (a scenario corresponds to the social proof theory (Cialdini, 1993)).
- In the situation where no one knows what to do, when one person proclaims to know the way out of the building, others would follow that person to evacuate — a leader emerges out of an uncertain situation.

3.4.6 Integrated Behavior Models

An overall process model that integrates multiple evacuation behaviors (Figure 3-9) is developed and presented based on the research from the fields of safety engineering, psychology, and sociology. Human behavior is impacted by a broad range of factors, variation of which creates significant diversity of human behavior. Different situations may provoke varying behaviors among individuals. An individual may behave differently when confronted with similar situations at different times. For example, when the uncertainty of a situation is high, an individual may tend to follow others in response to the situation. However, depending on his perception of the actions of others at the time, the individual may queue, compete, behave altruistically, or even self-exploring. Additionally, individuals are often sensitive to the change of perceived cues and may change their behavior accordingly. For example, during an evacuation caused by a fire, an individual may initially queue up with others, and wait for his turn to exit. Perception of increased intensity of the fire, however, may trigger a change to competitive behavior. That is, an integrated model that includes different evacuation behaviors to be selected dynamically by different individuals based on their perception of the situation is necessary. In this work, evacuation behaviors included in the integrated process model are: competitive behavior, queuing behavior, herding behavior, altruistic behavior, and leader-following behavior.

3.5 Summary

In this chapter, characteristics that impact human behavior during emergency egress are discussed in three categories: human physical characteristics, environmental characteristics, and psychological and sociological characteristics. The discussions have been focusing on developing better understanding of human and social behaviors in emergencies from psychological and sociological perspectives. Process models which incorporate selected behavior have been developed and presented as theoretical foundations for development of computational model(s) which will be discussed in Chapters 4 to 6.

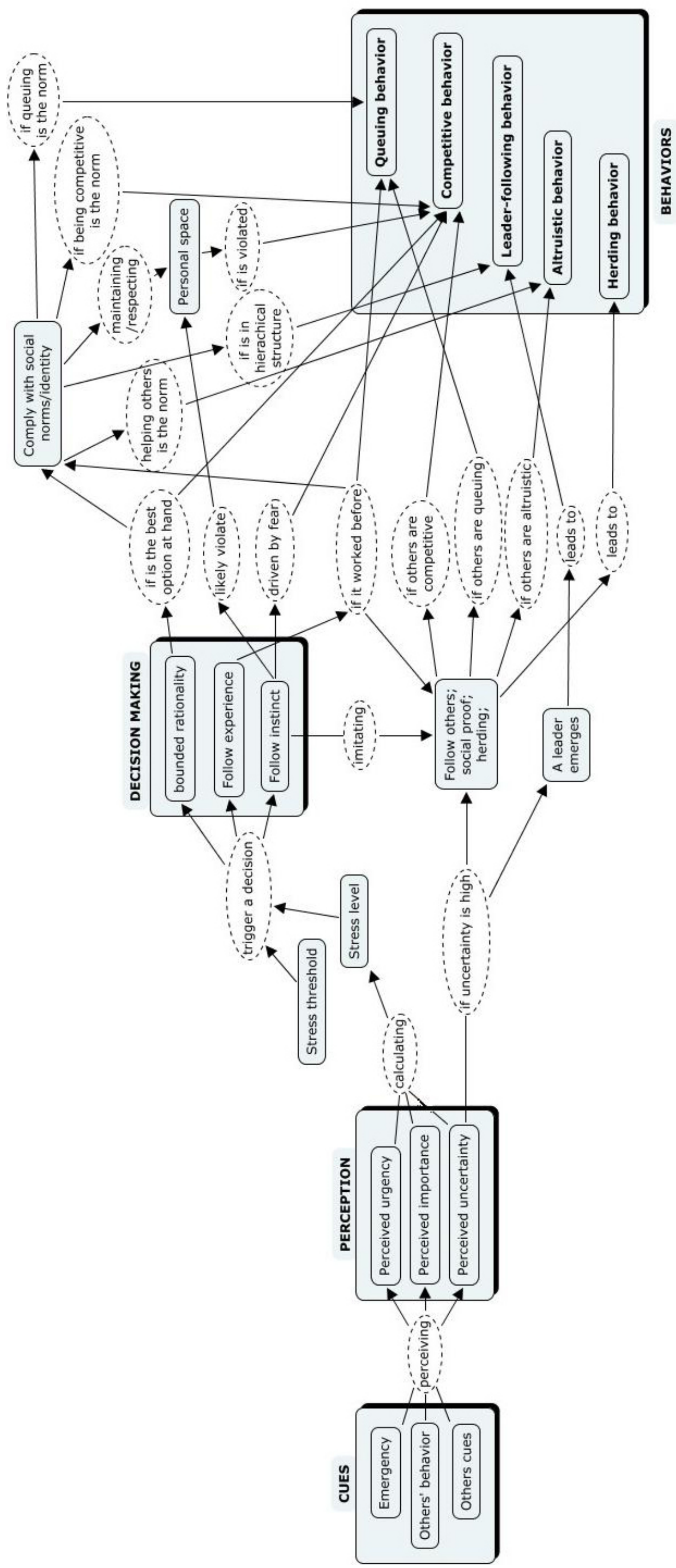


Figure 3-9: A process model that integrates a set of evacuation behaviors

Chapter 4

A Computational Framework—MASSEgress

This chapter describes a computational framework, Multi-Agent Simulation System for Egress analysis (MASSEgress), which is capable of modeling human and social behaviors for emergency egress analysis. The descriptions include the structure of the framework and some essential algorithmic procedures involved in sensing, behavior modeling and collision detection. Utilization of the framework to model some specific behaviors will be described in Chapter 5.

4.1 Framework Architecture

The system architecture of MASSEgress is schematically depicted as shown in Figure 4-1. The system consists of six basic modules: a Geometric Engine, a Population Generator, a Global Database, a Crowd Simulation Engine, an Events Recorder, and a Visualizer.

- The *Geometric Engine* generates the geometries representing the physical environments (e.g., a building or a train station, etc.). Spatial information, including obstacles, exits, spaces, spatial layouts, exit signs, etc., is most conveniently defined using CAD tools such as AutoCAD or Architectural Desktop (ADT).

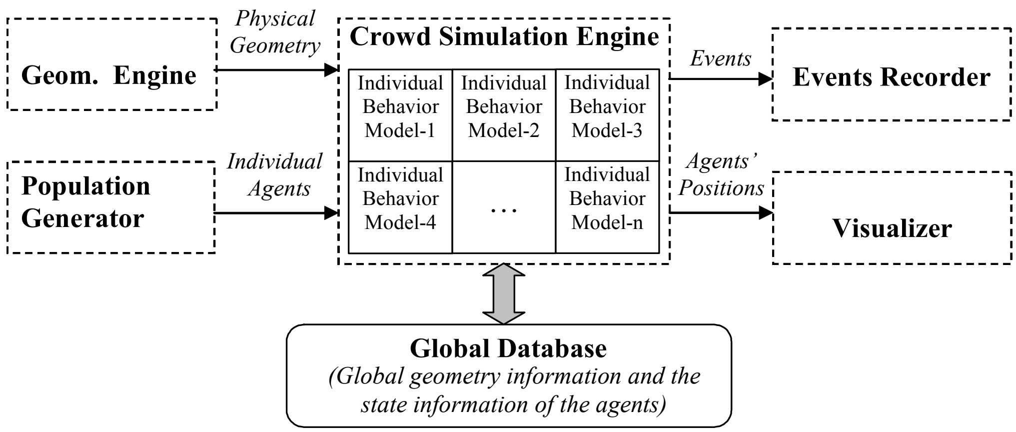


Figure 4-1: Framework Architecture

- The *Population Generator* generates virtual agents to represent a crowd based on a distribution of age, mobility, physical size, type of facility (hospital, office building, train station, stadium, etc.) and other human factors. The population, its composition, and occupants' behavior would be different for different facility types. This module allows the user to easily generate occupants and specify space assignments.

- The *Global Database* maintains all the information about the physical environment and the agents during the simulation. It maintains the state information (mental tension, behavior level, location) of the individuals. The database is also used to support the interactions and reactions among the individuals.

- The *Events Recorder* captures the events that have been simulated for retrieval and playback. The simulated results can be recorded for further analyses, for example, to derive evacuation patterns and statistical information. The events captured can also be used to compare with known and archived scenarios.

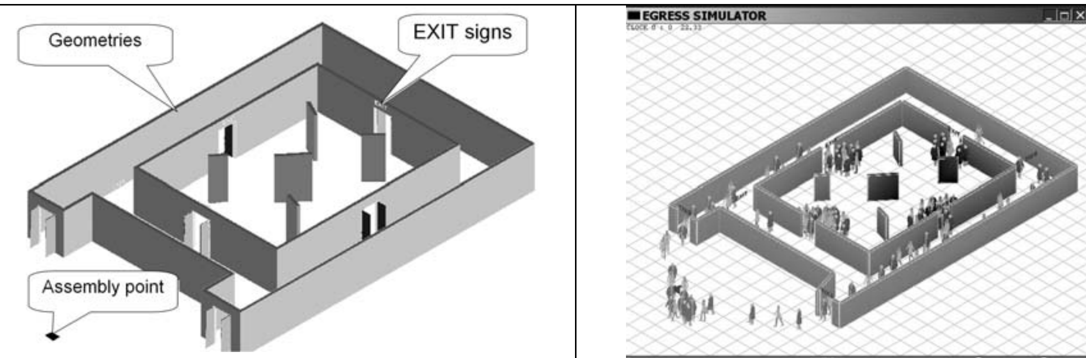
- Visualization is important to display the simulation results. The *Visualizer*, which is implemented using OpenGL, receives the positions of agents, and then dynamically generates and displays 2D/3D visual images.

- The *Crowd Simulation Engine* is the key module of the multi-agent simulation system. Based on the behavior models and classified rules, each agent is assigned with an Individual Behavior Model based on the data generated from the population generator. An Individual Behavior Model is composed of three subsystems — a Perception System, a Behavior System, and a Motor System, which will be discussed in details in the later sections. The basic algorithmic steps of the Crowd Simulation Engine are shown in Figure 4-2.

Such design allows sufficient modularity for further investigation of crowd dynamics and incorporation of new behavior patterns and rules.

```
PROCEDURE (Crowd Simulation Engine):
Create virtual environment based on information imported from the Geometric Engine;
Instantiate agents by calling the Population Generator;
WHILE not all agents are evacuated,
    FOR each agent (chosen in a random fashion),
        Update perception;
        Make a decision;
        Select a behavior and then execute it;
    END FOR;
    Send events to the Visualizer to generate visual output;
    Record events using the Events Recorder;
    Check to see if all agents are evacuated;
END WHILE;
```

Figure 4-2: The basic algorithmic steps of the Crowd Simulation Engine



Geometric information in ADT	A virtual environment as shown in Visualizer

Figure 4-3: Construction of a virtual environment.

4.2 Representation of the Physical Environment

To represent a physical environment in MASSEgress, a set of geometric information of the physical environment is selected to construct a virtual environment. Selected geometric information includes obstacles, spaces, exits, exit signs and assembly points. The geometric engine (a software component implemented in Visual LISP) extracts the model built using ADT and exports the results to the Crowd Simulation Engine (see Figure 4-3).

- *Obstacles*. Obstacles refer to walls, furniture, and any objects that are inaccessible. Each obstacle has definitive boundaries. Agents detect the obstacle through their sensors.

- *Spaces.* Spaces are the areas in which agents may maneuver freely. Examples are corridors, lobbies, and rooms. The shapes and dimensions of spaces are obtained based on the arrangement of obstacles.

- *Exits.* Exits, such as doors, connect spaces and allow an agent to transit from one space to another.

- *Exit signs.* Exit signs are devices which label exiting routes to exterior openings. They usually are unidirectional. A human agent can sense an exit sign if (1) there are no obstacles between the eyes of the agent and the sign, and (2) the sign is within a visible range.

- *Assembly points.* Assembly points are locations to specify the destinations upon evacuating from a facility. Assembly points are commonly used in evacuation plans to indicate safe gathering locations in case of an emergency.

The characteristics listed above represent a set of the most common components of a building.

4.3 Autonomous Agent

In MASSEgress, a human occupant is represented as an autonomous agent who interacts with the virtual environment and with other agents. The heterogeneity of agents is characterized by variations in Population Type and the Individual Behavior Model. An Individual Behavior Model is composed of three subsystems: a Perception System, a Behavior System, and a Motor System; these subsystems implement how each agent senses the situation and the environment, makes decision and acts according to its behavior model (Figure 4-4). A similar design was proposed by Tu (1996) for simulation of the behavior of artificial fish.

4.3.1 Population Type

Human individuals vary by age, body dimension, mobility, and personality. Rather than modeling each agent individually, MASSEgress currently includes five population types, similar to Simulex (Thompson et al. 2003): Median, Adult Male, Adult Female, Child, and Elderly. Table 4-1 shows the differences between the five population types in terms of body dimension and mobility. Body dimensions are represented by **Rb**, **Rt**, and **Rs** (as shown in Figure 3-1). Each population type represents a typical segment of the human population. Personality differences are represented by decision-making type and stress threshold type (to be discussed in Section 4.3.3).

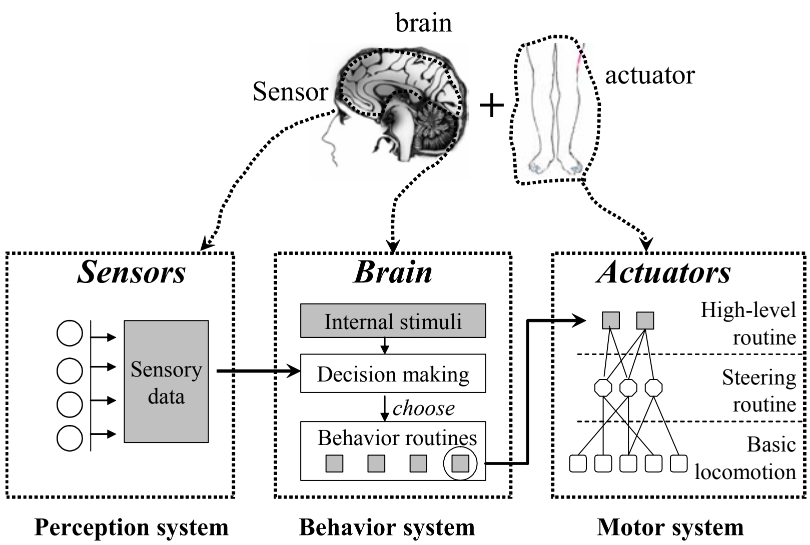


Figure 4-4: The three systems of an autonomous agent

Table 4-1: The body dimensions and moving speeds of typical population types (data sources: Thompson et al. (2003) and Eubanks and Hill (1998))

Population Type	Rb	Rt	Rs	Va	Vm
Median	9.843	5.906	3.937	51.181	168.110
Adult Male	10.630	6.299	3.937	53.150	168.110
Adult Female	9.449	5.512	3.543	45.276	168.110
Child	8.269	4.724	2.756	35.433	133.858
Elderly	9.843	5.906	3.543	31.496	107.874

Rb – radius of whole body circle (inch)
Rt – radius of torso circle (inch)
Rs – radius of shoulder circle (inch)
Va – average walking velocity on a level surface (inch per second)
Vm – maximum running velocity on a level surface (inch per second)

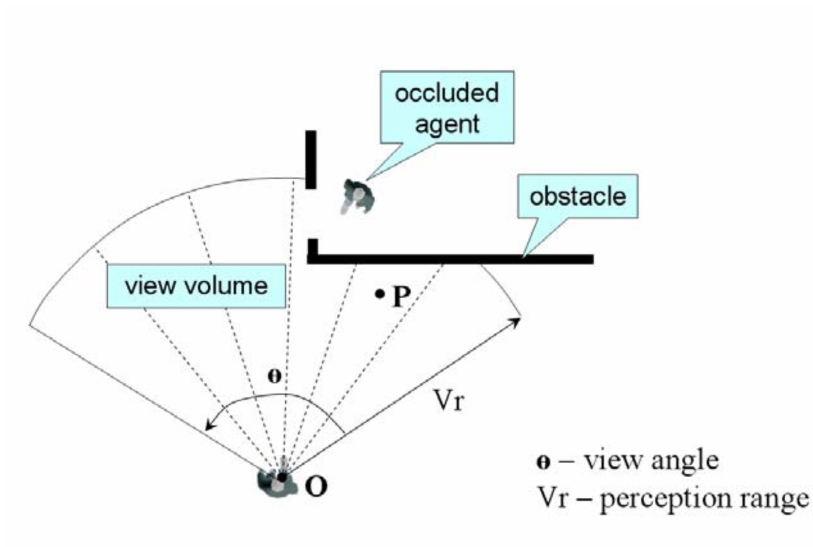


Figure 4-5: View volume

4.3.2 Perception System

The perception system of an agent consists of one or more sensors. A sensor contains three components: a set of input parameters, a sensory mechanism, and a set of output parameters which hold sensory data. Input parameters represent some aspects of the environment to which a sensor attends. The sensory mechanism is an algorithmic procedure that processes the input parameters and then produces sensory data for further processing by the behavior system.

There is multiple sensory information such as visual, audio, emotions or tensions, and others that could affect individuals' decision making in an evacuation situation. Currently, MASSEgress has implemented a set of computational methods to simulate the visual sensor of an agent. The input parameters of the visual sensor include exits, assembly points, other agents, and obstacles. As for the sensory mechanism, we have adopted the concept of view volume (Figure 4-5) which is a visual cone defined by a perception range and a view angle. The view volume represents the basic constraint of an agent's visual perception — an object is visible only if it falls within the view volume and is not occluded by any obstacle.

PROCEDURE (Point Test):
IF (the distance |**P** – **O**| ≤ **Vr**) **AND**
(the line **OP** lies within the view volume spanned by angle **θ**) **AND**
(the point P is not occluded)
THEN P is visible;
ELSE P is not visible;

Figure 4-6: Point test procedure

Computing the visibility of a virtual agent has been a subject of research in computer graphics and the modeling of digital actors, where many efficient methods have been developed. Based on experimental results, a hybrid approach which combines a point test algorithm and a ray tracing algorithm is adopted. The point test algorithm is used to determine whether or not an exit or an assembly point is visible to an agent. Given the eye position **O**, the view angle **θ** and the perception range **Vr** as shown in Figure 4-5, the procedure in testing the visibility of a point **P** is described in Figure 4-6. The point test algorithm is simple and effective because it is used in this case to test against relatively small quantities of points (i.e., exits and assembly points are relatively small in quantity for a typical facility).

The ray tracing algorithm is designed to compute the visibility of static obstacles. One observation is that individuals do not always see all objects within their view volume simultaneously. Individuals more typically focus on one object at a time, depending on what draws their attention. It is not therefore necessary to compute the visibility of all objects that fall within an agent's view volume, but rather only those objects that are relevant at the time. When surrounded by a large number of objects, those objects closest to an agent are to be tested first. Given the eye position **O** and the perception range **Vr**, and let $\mathbf{m} \in \mathbf{(0, 1]}$ be a real number and **ε** be a small positive constant, the ray tracing algorithm for computing the visibility of obstacles is described in Figure 4-7.

This algorithm works well for agents to detect nearby obstacles in order to avoid colliding with them while moving in a space (see Figure 4-8). The algorithm is efficient and also helps mimic human-like micro behaviors in its emulation of the attention-switch aspect of the human cognitive system.

```
PROCEDURE (Ray Tracing):
Initialize m = 1;
WHILE the agent has not reached an assembly point, for each time step:
    From position O, cast three rays (left, middle and right) with length LR = m*Vr;
    IF any ray intersects with an obstacle
        THEN  record the intersection;
              set m = m/2;
        ELSE IF m + ε ≤ 1
              THEN set m = m + ε;
END WHILE;
```

Figure 4-7: Ray tracing procedure

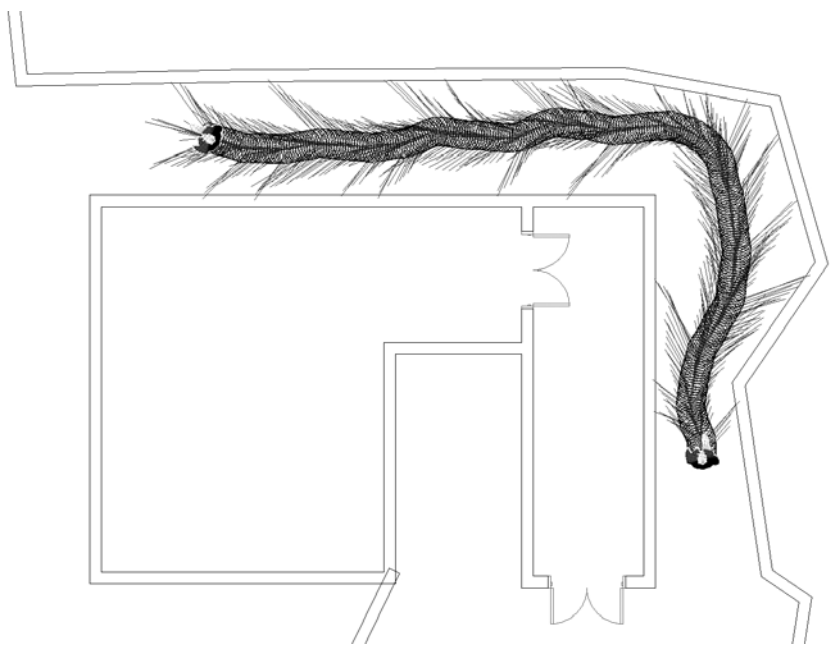


Figure 4-8: Using ray tracing procedure to detect obstacles

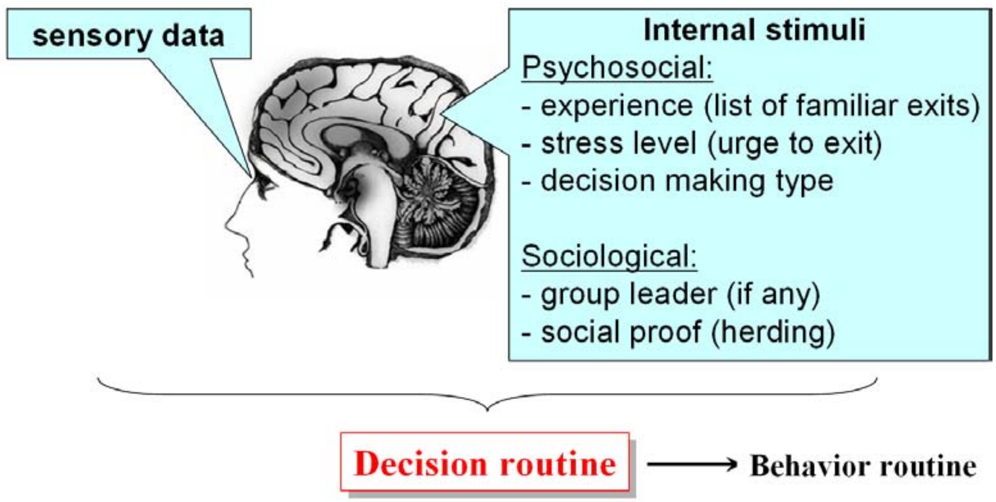


Figure 4-9: Parameters involved in a decision making process

4.3.3 Behavior System

The behavior system acts as the brain of an agent. Based on the sensory data received from the perception system, the agent then takes into consideration of some internal stimuli (i.e., psychological and sociological factors) and makes specific behavior decisions. The primary components of the behavior system are decision-making rules which are organized as decision trees. A set of complex decision-making rules can be organized as a single decision tree, in which a non-leaf node represents either a condition or some operations, and a leaf node represents a behavior decision. Different decision trees can be developed to represent different decision making types.

Psychological and sociological factors involved in a decision-making process in MASSEgress (Figure 4-9) are described as follows:

- *Familiarity*. This factor is represented as a list of exits stored in an agent's memory space. A general rule is that agents tend to evacuate through these exits over others.

- *Decision-making type*. Different decision-making types exist among heterogeneous agents due to different personal traits such as personality and experience. Each decision-making type is represented as a typical decision tree.

- *Urge to exit*. This factor represents how stress level influences agent behavior. In principle, increased *urge to exit* increases agent willingness to exit quickly, which in turn may lead to more competitive behavior. In MASSEgress, *urge to exit* is modeled as a floating point number between 0 and 1, where 1 corresponds to the highest urge.

- *Stress threshold type*. This parameter reflects how different stress levels can influence an agent's decision making which in turn would lead to different behaviors. For example, when the stress level of an agent is below a certain threshold, it is assumed that the agent would perform queuing behavior otherwise competitive behavior. Based on the fact that different humans usually respond to stress differently, in MASSEgress, the stress thresholds are modeled differently from one agent to another.

- *Herding factor*. This factor represents the aspect of social proof of human behavior—an individual tends to follow others when not knowing what to do. When an agent detects multiple exits, under the influence of herding factor, it heads towards the one with the most crowds; otherwise it goes to the closest exit.

Due to the modularity of MASSEgress, it should be pointed out that the decision-making rules and behavior routines can be tested independently before integrated into the system—a decision-making rule or a behavior routine can be assigned explicitly to an agent for testing purpose. The design has the flexibility and extensibility that allows modeling the psychological and sociological aspects of an agent's behaviors and incrementally incorporating them into the system.

PROCEDURE (Behavior Routine):
1. **IF** A goal point is chosen
2. **THEN** Compute a steering angle toward the goal point;
3. Choose a steering behavior;
4. Execute the steering behavior;
5. **ELSE** Explore the space randomly;

Figure 4-10: Algorithmic steps of a behavior routine

4.3.4 Motor System

The motor system executes the behavior routine, which corresponds to a behavior decision selected by the behavior system. A behavior routine is composed of one or more steering behaviors, each of which consists of a sequence of basic locomotion.

Behavior decisions represent the intentions of agents, in MASSEgress, such as "identify and select an exit, and then move toward it". Execution of a behavior routine, in the form of its algorithmic steps, is outlined in Figure 4-10.

The concept of steering behavior has been studied in robotics and artificial life. Steering behaviors are essential for an autonomous agent to navigate its virtual environment in a realistic and improvisational manner. Combinations of steering behaviors can be used to achieve higher level goals (Reynolds 1999), such as moving toward a selected destination while avoiding obstacles. For each time step, the main function of a steering behavior is to "compute and execute a legitimate move" which can be described in Figure 4-11. Note that the number of search steps for a legitimate move is restricted to some constant ***k***, because sometimes a legitimate move might not be possible (e.g., when an agent is surrounded by a dense crowd). The selection of a locomotion routine is done according to the decision tree representing the logical steps of a particular steering behavior.

A particular steering behavior is made up of a sequence of locomotion. A basic locomotion represents the simplest movement that an agent can conduct through its actuators, such as "moving forward one step." The basic steps of locomotion are described in Figure 4-12.

Eight types of locomotion are defined in MASSEgress in accordance with selected basic human movements relevant to egress simulation: move forward, turn left, turn right, reverse direction, shift left, shift right, move backward, and stop.

```
PROCEDURE (Steering):
FOR i = 1, …, k (some constant integer)
    Anticipate a move by calling a basic locomotion routine;
    IF the move is legitimate
        THEN  Execute the move;
        EXIT;
END FOR;
ABORT operation;
```

Figure 4-11: Algorithmic steps of a steering routine

```
PROCEDURE (Locomotion):
Update agent speed;
Compute agent body orientation according to the direction of a goal point;
Compute the coordinates of the new position;
```

Figure 4-12: Algorithmic steps of a behavior routine

4.4 Collision Detection Using Grid Method

Unlike the simulation of one or a few digital actors in computers, crowd simulation poses a challenge on developing efficient algorithms for computing collisions among hundreds or even thousands of agents. A simplistic approach is to iterate through all pairs of agents for collision detection; however such method is quite expensive since it results an $O(N^2)$ time complexity, where N is the total number of agents. Improved method, such as Sphere Tree (Palmer and Grimsdale, 1995) and Oriented Bounding Box Tree (Gottschalk et al., 1996) methods, usually involve two phases:

- Broad phase — eliminating objects that are far away using the hierarchical representations of entities; and

- Narrow phase — perform more accurate collision test on the remaining objects from the broad phase.

These methods save time by not having to perform accurate collision test against all object pairs, so the time complexity of the algorithms can be improved to be as good as O(N.logN). Upon the development of MASSEgress, the Grid Method is found to be an ideal solution for computing collisions among large number of moving entities with an O(N) time complexity.

The Grid Method was presented by Halperin and Overmars (1998) as a fast method to compute the intersection of large numbers of three-dimensional molecules. Its incorporation into MASSEgress consists of two phases: grid construction (at pre-computation time, see Figure 4-13 and Figure 4-14), and grid maintenance and querying (at real time).

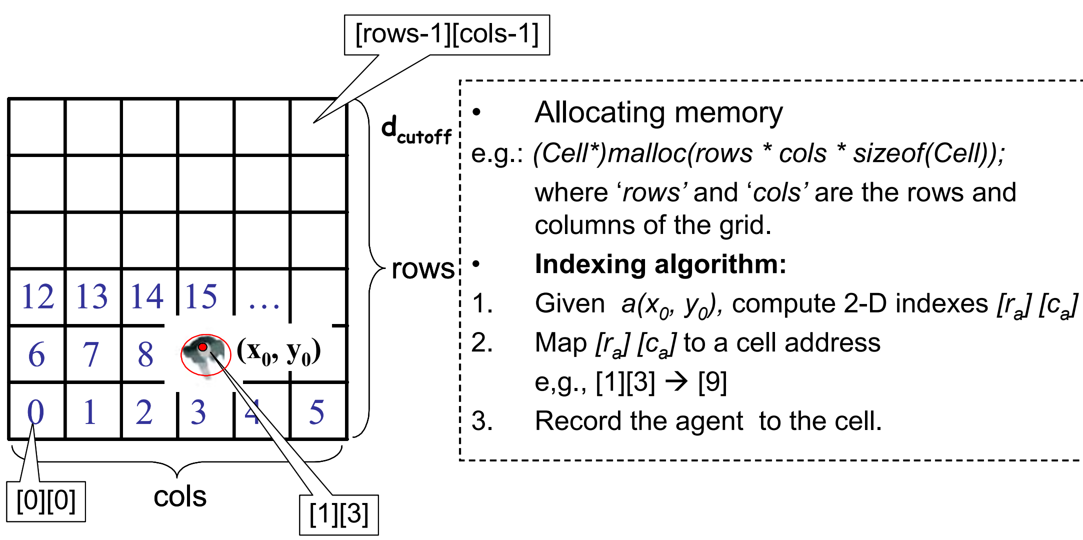


Figure 4-13: Construction of a 2D grid in C++

PROCEDURE (Constructing grid)**:**
1. Subdivide space into square-shaped cells. The size of each cell is defined by the length of its edge d_{cutoff} , and $d_{cutoff} = k*r_{max,}$ where $k \geq 1$ and r_{max} denotes the maximum diameter of an agent (with respect to its physical dimension);
2. Compute the coordinates of each agent's body center;
3. Register each agent to the cell that it resides;
4. Represent all the cells as a 2-dimentaional array;

Figure 4-14: Procedure for constructing a grid

PROCEDURE (Querying grid)**:**
1. Look up the cell to which the agent is registered;
2. Go through the agent's neighboring cells, and find a list of agents that are registered in the neighboring cells;
3. Conduct collision check for the agent against the list of agents found in step 2.
4. **IF** a collision is detected
5. **THEN** Return true;
6. **ELSE** Return false;

Figure 4-15: Procedure for querying a grid

The operation for maintaining a grid is straightforward: whenever an agent changes its position, deregister it from the cell that corresponds to its old location, and then register it to the cell that corresponds to its new location. When an agent needs to query a grid for collision detection, the procedure is shown in Figure 4-15.

Because (1) for each agent, if a 2D grid is used, there are eight neighboring cells at the most, and (2) the maximum number of agents that a cell can contain is bounded by a constant, the total time that takes to check collision for one agent is O(1). Therefore the time complexity of completing collision check for N agents is O(N).

4.5 Representation of a Staircase

For a multi-story building, different floors are connected through staircases. In order to perform egress simulations for multi-story buildings, in MASSEgress, each staircase is represented as a 'transition' function, which can transfer occupants from one floor to another. Three factors of a staircase are considered by the 'transition' function:

- *Occupant load capacity*. It is determined by the floor area of a staircase multiplied by the maximum allowed crowd density (i.e., 4 people per square meter (Still, 2000)).
- *Travel distance*. It is the distance that an occupant needs to travel in the staircase.
- *Occupant velocity*. It is the travel speed of an occupant in the staircase, which is calculated by the average walking velocity of the occupant (refer to Table 4-1) multiplied by 0.55 (Thompson et al., (2003)).

The procedure of a 'transition' function is shown in Figure 4-16. Although the "transition" function shown above is a simplified representation of how a crowd may move through a staircase, it allows MASSEgress to conduct egress simulations for buildings with multiple stories (Figure 4-17).

```
PROCEDURE ('Transition' function):
FOR Each agent,
    IF Agent wants to enter staircase AND staircase is not full
        THEN Transit agent into staircase;
    ELSE IF Agent travels in staircase
        THEN Update the distance that is left for agent to travel;
    ELSE IF Agent wants to exit staircase AND A space is available on the exiting floor
        THEN Transfer agent from staircase to exiting floor;
END FOR;
```

Figure 4-16: Transition function

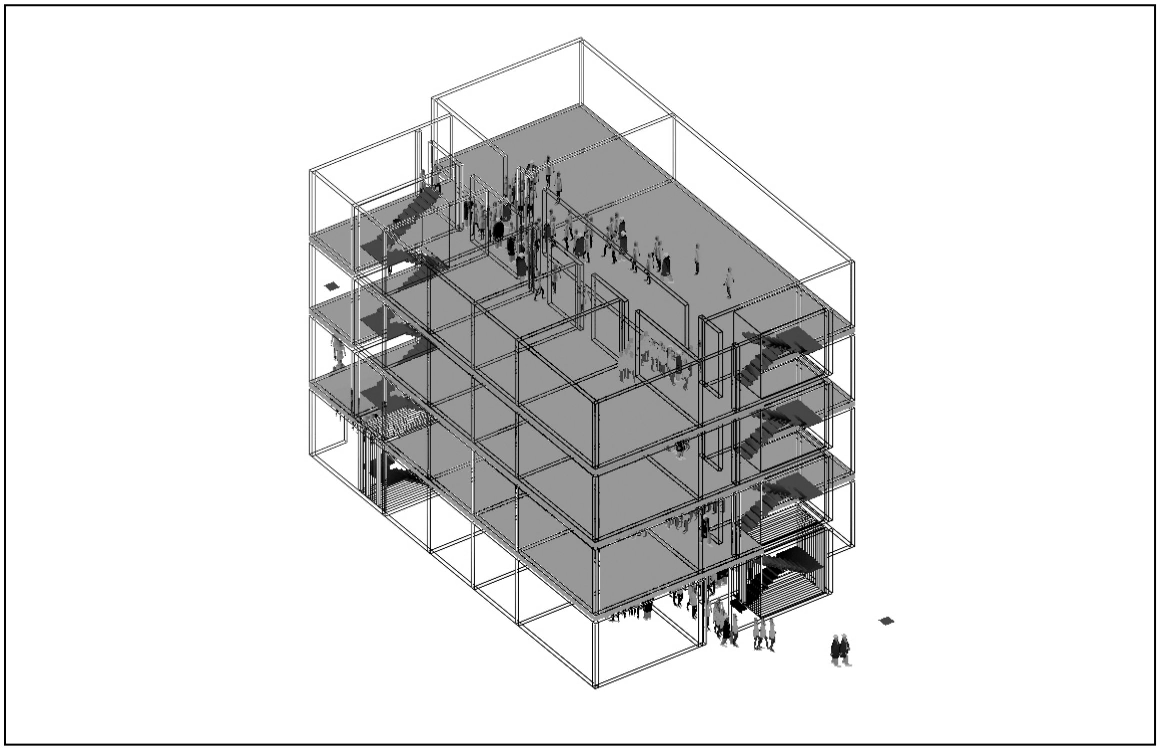


Figure 4-17: Egress simulation for a multi-story building

4.6 Summary

MASSEgress consists of six basic modules: a Geometric Engine, a Population Generator, a Global Database, a Crowd Simulation Engine, an Events Recorder, and a Visualizer. Its design allows independent implementation of these modules, and therefore provides significant extensibility. Autonomous agents are equipped with sensors, brains, and actuators which correspond to their perception, behavior, and motor systems. Diverse agent behaviors can be modeled through manipulation of the three systems to simulate the processes of sensing, behavior selection (decision-making), and behavior execution.

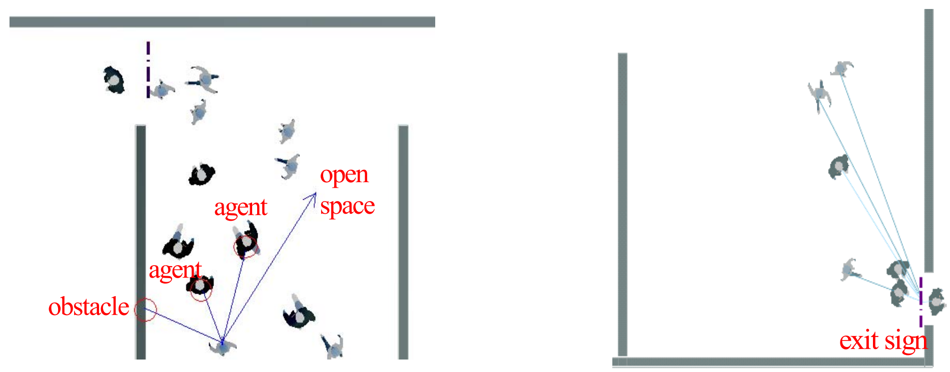
Chapter 5

Agent Behavior Simulation

Agent behavior simulation in MASSEgress involves three key steps: (1) receiving sensory data relevant to behavior through use of the Perception System, (2) modeling the process of behavior selection and decision-making through use of the Behavior System, and (3) implementing the behavior through use of the Motor System. This chapter describes agent's individual and social behavior simulation, and application of MASSEgress to egress design analysis.

5.1 Capture Sensory Data

Each agent in MASSEgress is equipped with a visual sensor with which to analyze the environment. Visual sensors adopt the concept of view volume and are implemented using a hybrid approach that combines a point test and a ray tracing algorithms (as described in Chapter 4). Sensory data relevant to an agent's behavior include: positions of obstacles, other agents, exit signs, and assembly points (Figure 5-1). In addition to visual sensing, agents can recognize the location and type of object which they encounter. Sensory data is being used by decision rules to perform behavior selection.



Sensing objects in a virtual environment | Sensing an exit sign

Figure 5-1: Sensory data that are relevant to modeling agent behaviors

5.2 Behavior Selection

An agent is capable of executing a wide range of different behaviors. From time to time, along with the change of perceived situations, an agent may switch from one type of behavior to another. Determining which specific behavior to execute is referred to as behavior selection, a process controlled by the Behavior System of an agent. The main components of a Behavior System are decision rules (Figure 5-2). Decision rules are modeled in the form of decision trees, which choose a particular behavior type based on sensory input and internal psychological and sociological factors (as discussed in Section 4.3.3). Different decision trees are constructed to represent different decision-making styles. In the decision trees, non-leaf nodes represent either a condition or an operation, and leaf nodes represent behavior decisions. An example of a very simple decision tree is: “if an assembly point is seen, then set it as a goal and go to the goal point; otherwise explore the space”. In this example, “if an assembly point is seen” is a condition, “set it (the assembly point) as a goal" is an operation, and "go to the goal point" and "explore the space" are two behavior decisions (see Figure 5-3).

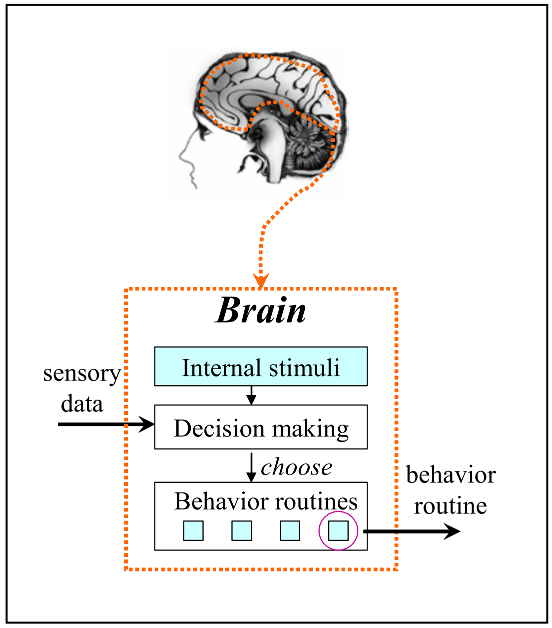


Figure 5-2: Behavior selection

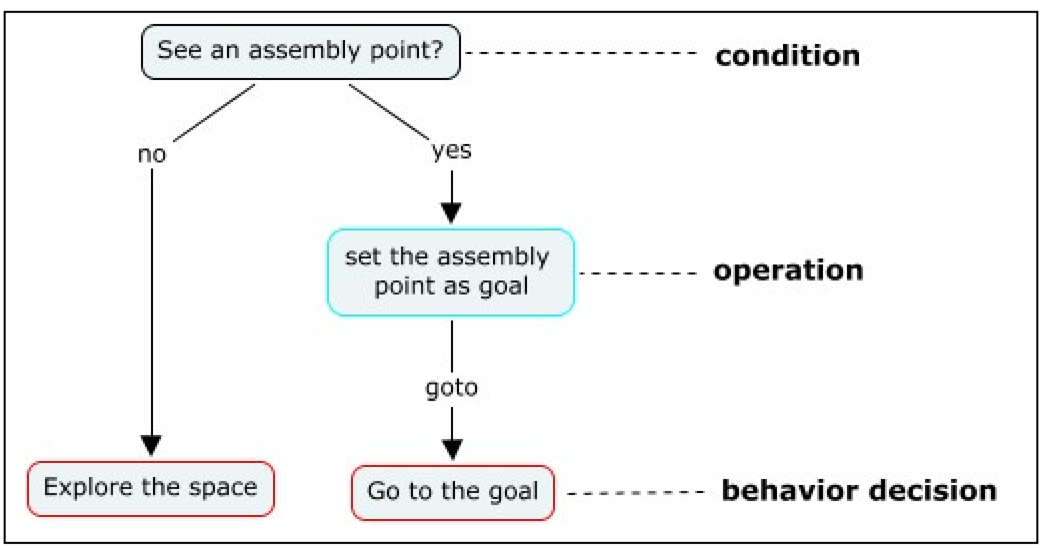


Figure 5-3: A simple decision tree

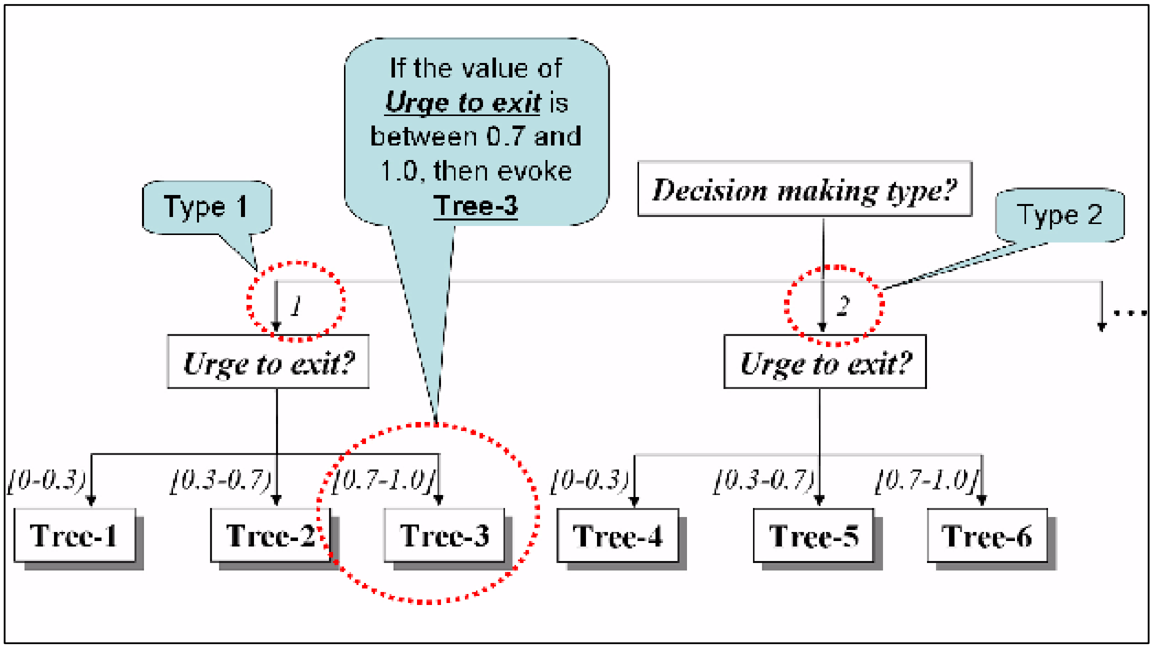


Figure 5-4: *Decision making type* and *urge to exit* determine which tree to evoke

Complex decision rules can be systematically organized as one or more decision trees, and an agent's brain can contain one or more decision trees. For a particular situation, how an agent chooses one tree instead of the others is determined by two other factors: decision making type and urge to exit. Decision making type is a positive integer value (e.g., 1, 2 or 3) assigned to an agent to simulate human personality types, and *urge to exit* is a floating point value between 0 and 1, representing stress level of an agent (which can change over time). Figure 5-4 illustrates the effect of these two factors on agent decision tree selection.

Many decision trees can be constructed to simulate personality differences among agents and to simulate the influences of various stress levels on agent decision-making. Therefore, integration of a broad range of scenarios is thus possible. Constructing a decision-making tree is essentially to define the decision-making process to be undertaken by the agent. Figure 5-5 illustrates a decision tree that represents decision-making by a "type 1" agent under low stress (i.e., *urge to exit* between 0 and 0.3). As shown in the figure, the tree has combined a set of decision rules into a systematic reasoning structure.

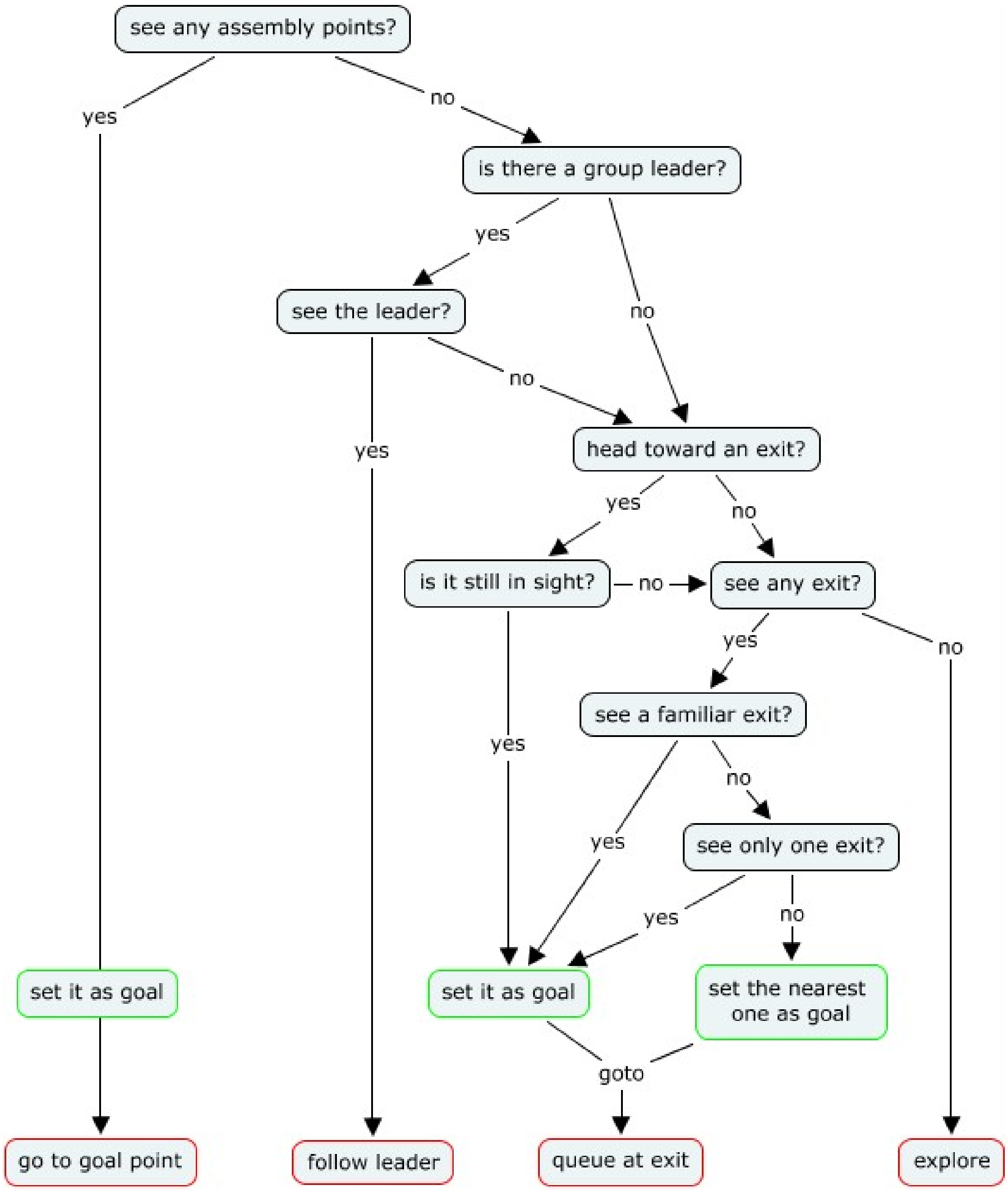


Figure 5-5: Decision making under low stress

The rules encoded in the decision tree shown in Figure 5-5 include:

- If the agent sees an assembly point, then it goes toward the assembly point;
- If the agent is with its leader, then it follows the leader;
- If the agent sees a familiar exit, then it goes toward the exit;
- If the agent sees multiple exits, then it goes toward the nearest one;
- If the agent does not see any exits, then it continues to explore the space;
- If the stress level of the agent is low, then it queues at an exit.

When the decision tree is evoked, the agent will check the various conditions and then select one of the four behavior decisions: “go to goal point”, “follow leader”, “queue at exit”, and “explore”.

Figure 5-6, for comparison, illustrates another example on how a “type 1” agent makes decisions under high stress (i.e., *urge to exit* between 0.7 and 1.0). The basic differences of the two decision trees shown in Figure 5-5 and Figure 5-6 are that under high stress:

- The agent will not care about following its leader even if there is one, because high stress leads to more individualistic action;
- If the agent sees multiple exits, then it goes to the one with the most people—the process that potentially leads to herding behavior; and
- The agent will exit in a competitive manner because it is under high stress.

If the decision tree shown in Figure 5-6 is evoked, the agent will choose one of the four possible behavior decisions: “go to goal point”, “compete at exit”, “herding”, or “explore”.

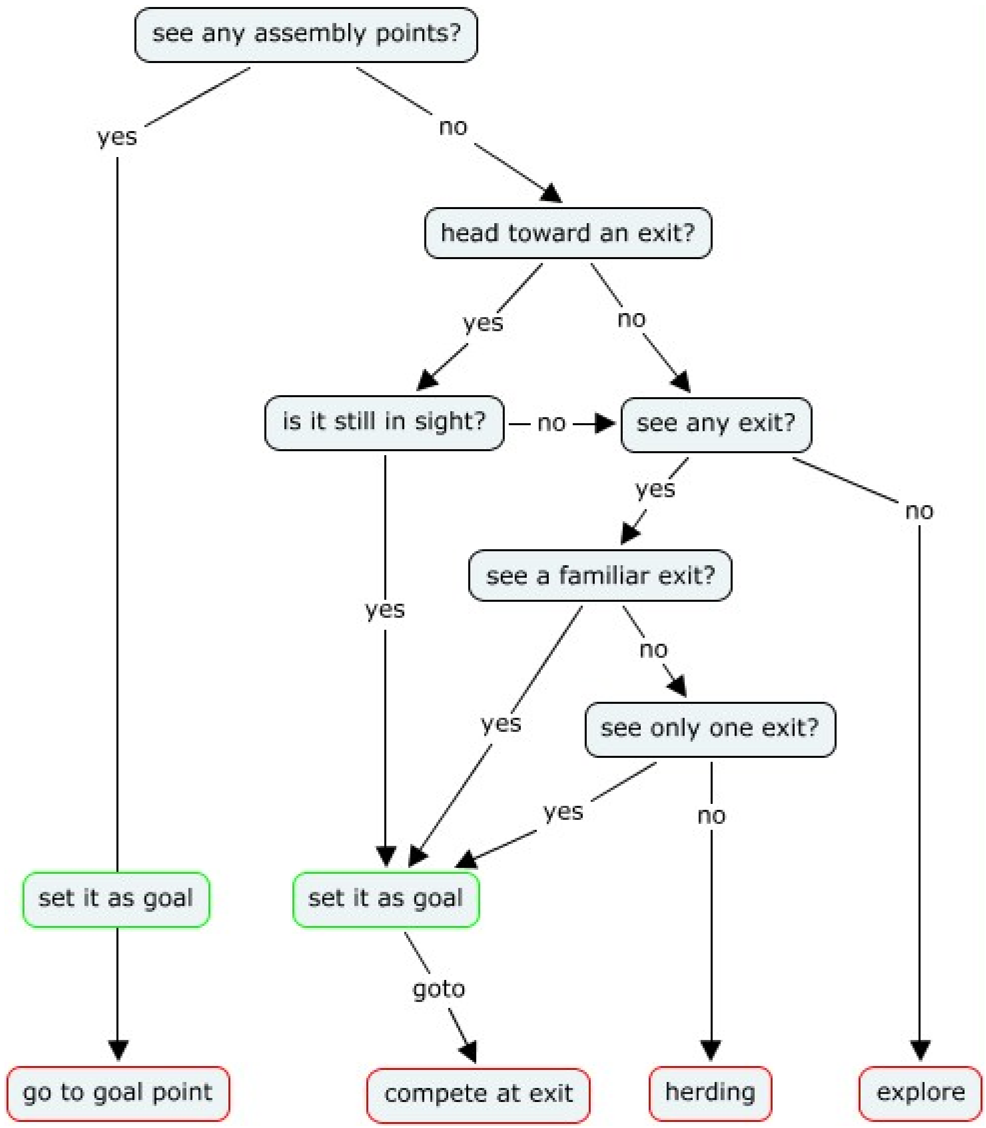


Figure 5-6: Decision making under high stress level

The decision trees represent a set of hypotheses about human decision making in emergencies. The hypotheses can be derived from the analyses presented in Chapter 3. As described, decision trees allow a broad range of assumptions about human behavior to be modeled and tested.

MASSEgress currently includes seven behavior decisions; each behavior decision will trigger execution of a specific behavior routine:

- "explore" → EXPLORE_RANDOM();
- "go to goal point" → GO_TO_GOAL_PT();
- "compete at exit" → COMPETE_AT_EXIT();
- "queue at exit" → QUEUE_AT_EXIT();
- "herding" → HERDING();
- "follow leader" → FOLLOW_LEADER();
- "follow an agent" → FOLLOW_AGENT();

At a microscopic level, the above behavior routines are all what an agent can do individually. The next section describes how some of these behavior routines are implemented in MASSEgress.

5.3 Behavior Implementation

As depicted in Figure 5-7, through the use of the Motor System of an agent, a behavior routine is implemented in a hierarchical manner. A behavior routine is composed of one or more steering behaviors, and each steering behavior in turn consists of a sequence of basic locomotion. We first give descriptions of a set of locomotion and steering behaviors implemented in MASSEgress.

Behaviors at the layer of locomotion are directly controlled by the actuators of an agent, corresponding to the simplest movements an agent can execute, such as "turn left 35 degrees." MASSEgress has implemented eight different types of agent locomotion—move forward, turn left, turn right, make a U-turn, shift left, shift right, move backward, and stop. To choose a locomotion type at a particular time step is determined by the decision logic encoded in a steering routine.

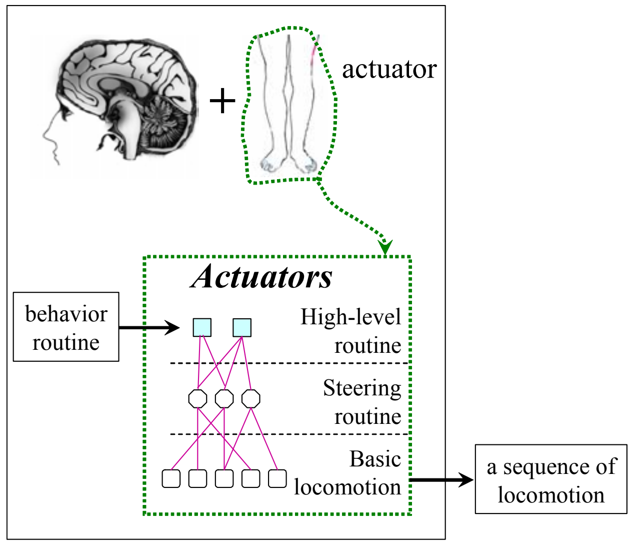


Figure 5-7: Behavior implementation

The following steering behaviors are included in the MASSEgress:

- *Random walk*. This behavior enables an agent to walk randomly in the virtual environment.

- *Collision avoidance*. This behavior gives an agent the ability to maneuver in the virtual environment without colliding with obstacles or other agents. Its implementation is achieved by monitoring an agent's sensory input and reacting to possible collisions. For example, if an agent detects obstacles both in front and on the right but not on the left, then it steers toward the left.

- *Seek*. Seek acts to steer an agent toward a goal point. When a goal point is detected, an agent adjusts its orientation and traveling speed toward that goal. The agent also alters its orientation randomly by a small magnitude and then re-aligns it, producing a life-like motion while approaching the goal (it is interesting to note that from field observations, human individuals do not usually walk along a straight line toward a goal point (Brogan and Johnson, 2003)).

- *Negotiation*. Negotiation enables an agent to exchange information and reach agreements with others. For example, when a group of agents forms a queue at an exit, they negotiate with each other to determine their positions in the queue. The agents achieve this by informing each other of their distances to the exit, and the ones who are closer to the exit get higher priority in the queue.

- *Target following*. This behavior allows an agent to follow a moving target. A typical example is that an agent moves forward in a queue by following another agent who is in front.

These steering behaviors serve as basic building blocks for constructing behavior routines at the top level (see Figure 5-7). Steering behaviors can be combined by (1) switching between different behaviors in response to perceived situation changes (e.g., change from random walk to seek), or (2) blending different behaviors together (e.g., blending seek and collision avoidance). For instance, the implementation of "GO_TO_GOAL_PT()" blends together two behaviors, Seek and Collision Avoidance (see Figure 5-8), so that an agent steers toward a chosen assembly point without colliding into obstacles. "QUEUE_AT_EXIT()" is another example, which requires an agent to both blend and switch between different steering behaviors (see Figure 5-9). When a complex logic is required to blend and/or switch among different steering behaviors, such logic can be represented and implemented in the form of decision trees. For example, the logic related to the behavior routine "QUEUE_AT_EXIT()" can be represented as a decision tree shown in Figure 5-10.

PROCEDURE (GO_TO_GOAL_PT()):
IF the chosen goal point is still in sight
THEN compute a steering angle toward the goal point;
IF a potential collision is detected
THEN evoke *Collision avoidance* to avoid the collision;
ELSE evoke *Seek* to move toward the goal point;
ELSE evoke *Random walk*;

Figure 5-8: The implementation of GO_TO_GOAL_PT()

PROCEDURE (QUEUE_AT_EXIT()):
IF the chosen exit is still in sight
THEN compute a steering angle toward the exit;
evoke *Negotiation* to sort the queue;
IF no other agent in front
THEN evoke *Seek* to move toward the exit;
ELSE evoke *Target following* to follow the agent in front;
ELSE evoke *Random walk*;

Figure 5-9: The implementation of QUEUE_AT_EXIT()

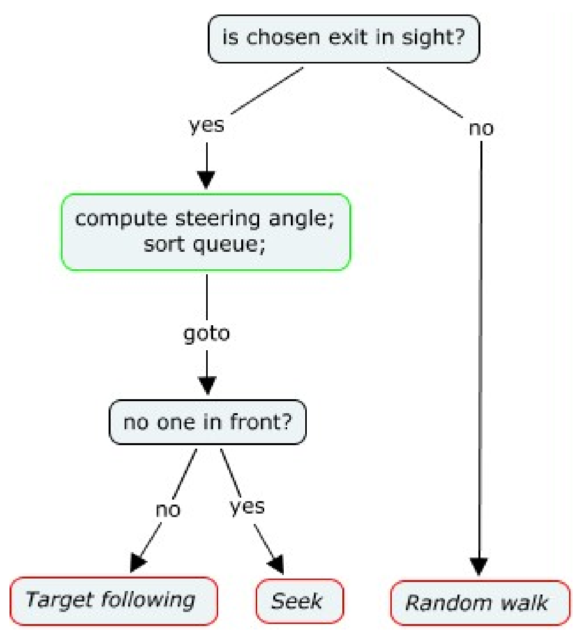


Figure 5-10: The decision tree to blend different steering behaviors

5.4 Social Behavior Simulation

Social behaviors are complex phenomena emerged from interactions among individuals. A single agent's behavior is essentially nondeterministic at a microscopic level; if the system is executed multiple times with the same initial setting, the agents would not behave exactly the same way each time due to the randomness (i.e., for each time step, agents are selected in an random order for executing their move) embedded in the system. However, at a macroscopic level, certain behavioral patterns could be observed across the multiple runs. These social behavioral patterns are called emergent phenomena. The emergence of a social behavior is sensitive to a number of factors:

- The individual behavior. Social behaviors are collective efforts of individuals. The behavior of each agent directly impacts the behavior of the group. For example, initial reactors in an emergency have significant influences within a crowd; if the initial reactors begin to push, then others may react similarly.

- Group size. Social behavior may not emerge if the size of the group is too small. For example, group competitive behavior will probably not occur among only a few individuals.

- Individual behavior distribution within a crowd. Agents may demonstrate multiple behaviors based on population type and perceived situation. When and where a behavior occurs and how different behaviors are distributed within a group have significant influences to the emergence of a particular social behavior.

- Geometric constraints. Certain social behaviors are the direct results of geometric constraints. For example, if a large number of stressful evacuees encounter a narrow exit, then competitive behavior at a group level would likely occur.

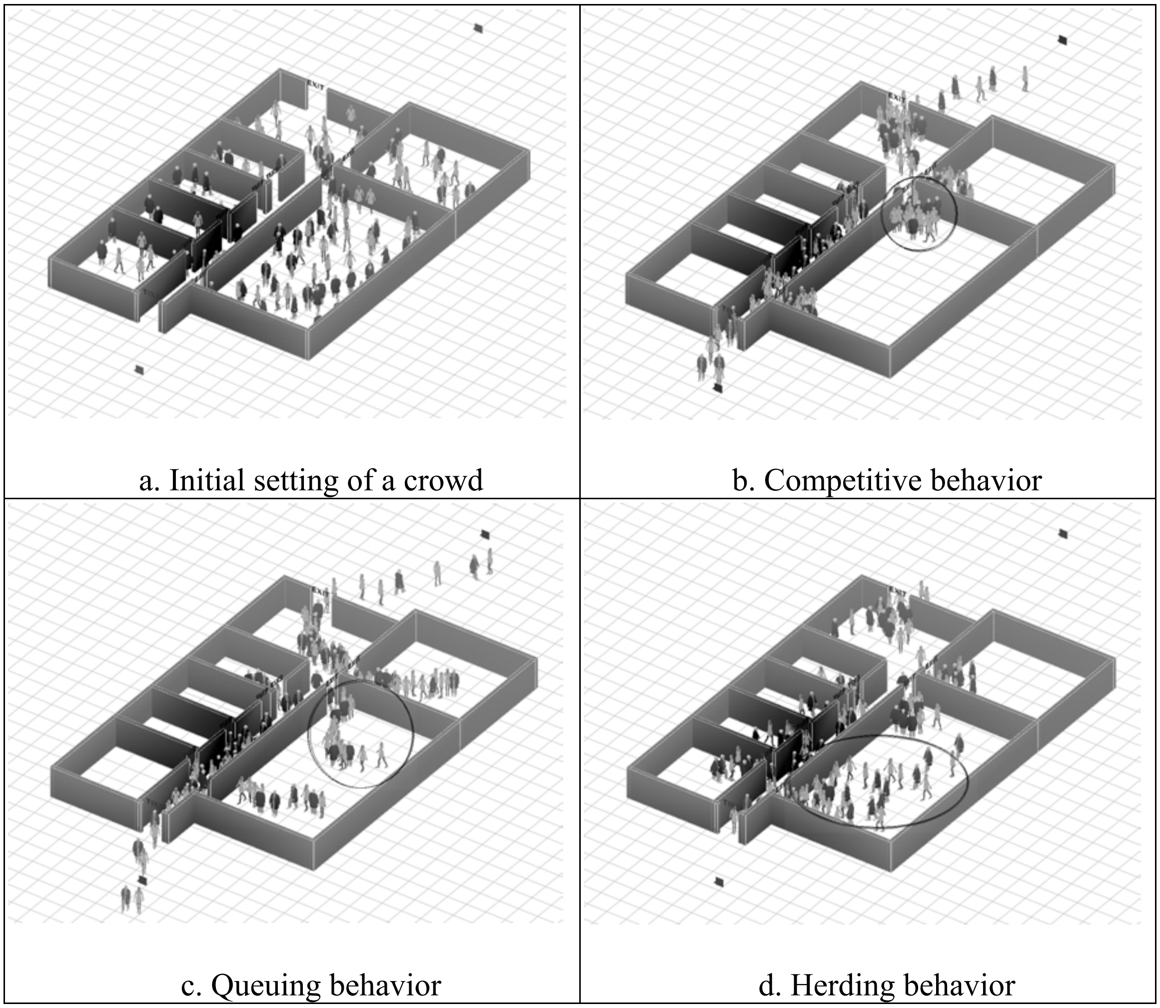
Therefore, in order to simulate a specific type of social behavior, it is necessary to configure the above factors properly. The following discussion demonstrates how

MASSEgress simulates some commonly observed social behaviors during emergency evacuations, such as competitive behavior, queuing behavior, herding behaviors, and bi-directional crowd flow.

Figure 5-11a illustrates an initial setting of a crowd consisting of one hundred agents in a particular geometric configuration. During the simulation, when different individual behaviors are activated at a microscopic level (i.e., individual level), the crowd demonstrates very different social behaviors, such as competitive behavior (Figure 5-11b), queuing behavior (Figure 5-11c), and herding behavior (Figure 5-11d).

Competitive behavior is often observed in emergency situations, when human individuals compete to exit. Competitive behavior usually leads to inefficient evacuations and/or nonadaptive crowd behaviors. In MASSEgress, competitive behavior occurs when all agents execute the "COMPETE_AT_EXIT()", which contains the following decision rules: (1) walk randomly until a goal is determined, (2) seek the goal with maximum velocity if possible and do not negotiate with other agents, and (3) do not preemptively avoid collision.

Sometimes, queuing behavior emerges spontaneously when a crowd gathers at an exit, permitting the crowd to stream out of the exit in an orderly manner. The formation of a queue is largely the manifestation of self-organization. Unlike competitive behavior, queuing behavior does not lead to clogs at exits but often leads to more effective evacuations. MASSEgress illustrates that, queuing behavior could take place when sufficient number of agents execute the "QUEUE_AT_EXIT()" routine, which contains the following decision rules: (1) walk randomly until a goal is determined, (2) seek the goal, (3) if obstructed by other agents, negotiate to initiate a queue, (4) join an existing queue if encounter one, and (5) execute target following to move forward in a queue.



a. Initial setting of a crowd

b. Competitive behavior

c. Queuing behavior

d. Herding behavior

Figure 5-11: Simulation of human social behaviors

Herding behavior is often observed during the evacuation of a crowd in a room with two exits — one exit is clogged while the other is not fully utilized . Sometimes herding behavior helps people to exit safely, and at other times, it may cause blockages at an exit even though other exits are available. Building designers often assume that a crowd would exit evenly among multiple exits of a room in case of an emergency; herding behavior contradicts such an assumption. MASSEgress illustrates that, herding behavior could occur when agents exercise the “HERDING()” routine, which contains the following decision rules: (1) random walk until a goal is detected, (2) if multiple goals are detected, compute the ‘popularity’ of each goal by observing other agents, and then choose the most crowded goal, and (3) seek the goal.

Bi-directional crowd flow typically occurs in places where individuals or groups must pass one another to reach different goals (e.g., a subway station), which can be difficult to model with fluid or particle systems. MASSEgress demonstrates that bi-directional crowd flow can be realistically simulated if (1) a crowd is composed of individuals with different goals, (2) individuals executes "GO_TO_GOAL_PT()" routine, which enables them to constantly steer toward their goals and take actions to avoid collision with one another (see Figure 5-12).

The social behaviors described above are not necessarily independent from one another. Various social behaviors can be combined to construct more complex behaviors. For example, the simulation shown in Figure 5-11d demonstrates herding behavior as well as competitive behavior.

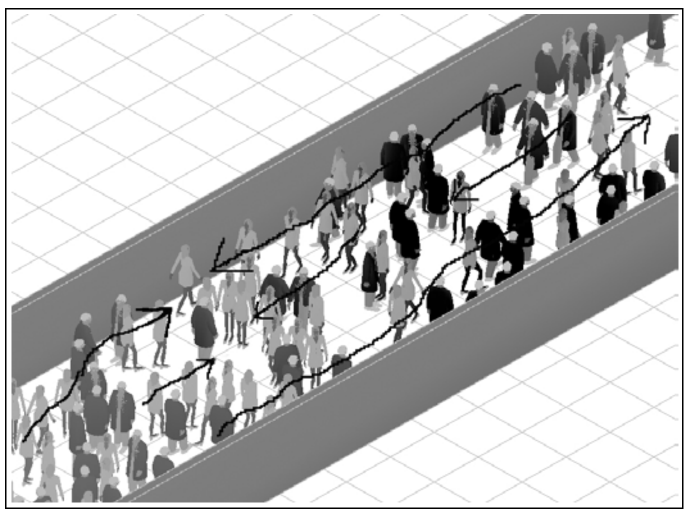


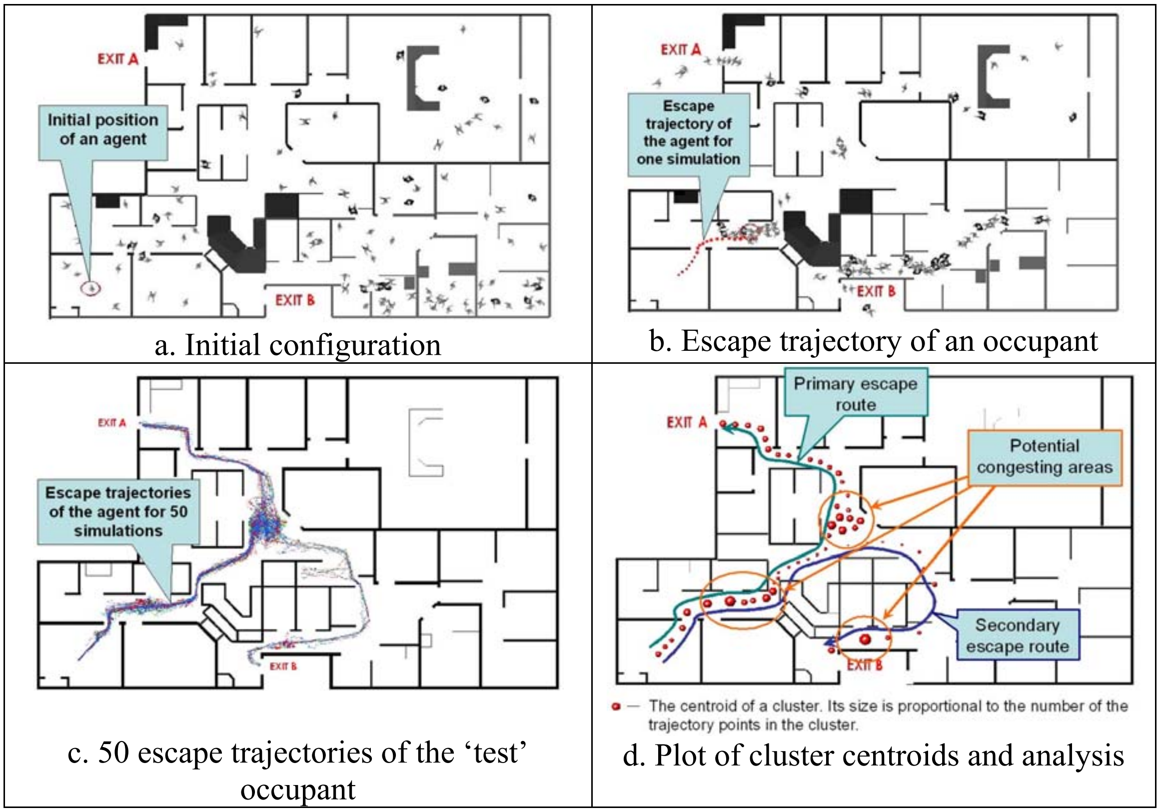
Figure 5-12: Bi-directional crowd flow

5.5 Emergent Evacuation Patterns with Statistical Analysis

MASSEgress, as a simulation tool, can potentially be used for many practical applications. One example is to facilitate egress analysis for building designs. When designing a floor plan for a building, although the intended usage of the space is usually known, it is difficult to account for every possible scenario for safe evacuation, because of the uncertainties such as spatial distributions of the occupants and their behaviors. However, with the layout of a floor plan, some typical evacuation patterns can be drawn statistically by conducting multiple evacuation simulations with different occupant configurations. These evacuation patterns can provide insights to help improve the design. The following scenario represents an instance of how to capture some evacuation patterns for a specific floor plan design.

Figure 5-13a depicts a hypothetical floor plan of an office building. The floor plan contains a number of office spaces organized along hallways and corridors. There are two egress exits, exit A on the west and exit B on the south. We intend to find out what are the evacuation patterns of the design from the perspective of egress.

At first, we place a 'test' occupant in a specific room with the presence of other occupants distributed randomly in other spaces. Evacuation simulations are then performed many times (say 50 times in this example), with different spatial distribution of the occupant. That is, for each simulation, while fixing the location of the 'test' occupant, we randomize the locations and behavioral types of other occupants, so that the 'test' occupant would exhibit different evacuation behaviors for a range of different situations. Figure 5-13b shows an example escape trajectory of the 'test' occupant in one of the simulations.



a. Initial configuration

b. Escape trajectory of an occupant

c. 50 escape trajectories of the 'test' occupant

d. Plot of cluster centroids and analysis

Figure 5-13: Using simulations for safe egress analysis

Figure 5-13c shows all fifty trajectories of the 'test' occupant from the simulations. Using a K-Means clustering algorithm (MacQueen, 1967), the trajectory points are categorized into clusters represented by a set of centroids. The resultant centroids are plotted as shown in Figure 5-13d, and the size of each centroid reflects the number of trajectory points that the centroid contains. By analyzing the distribution of the centroids, we can identify the primary and the secondary escape routes from the perspective of the 'test' agent, the relative frequency for the usage of the routes, and the potential congested areas during evacuations. The same process can be repeated by placing the 'test' occupant in different locations, thus showing different emergent evacuation patterns. By exploring different geometric configurations and re-arranging exit signs, a designer can modify the floor plan to alleviate congested areas and to provide more efficient egress routes.

5.6 Summary

Simulation of agent behavior in MASSEgress involves three basic steps: (1) receiving sensory data relevant to behavior through the use of the Perception System, (2) modeling of the process of behavior selection and decision making through the use of the Behavior System, and (3) implementing the behavior through the use of the Motor System. Sensory information is perceived by agent's sensors. Based on the sensory input, behavior types are selected according to the decision trees representing the agent's decision-making process. Dynamic integration of many decision trees allows MASSEgress to simulate a broad range of scenarios and to incorporate a variety of psychological and sociological characteristics of human behavior.

In a given situation, an agent selects and executes a decision tree based on the factors of decision-making type and urge to exit. Executing a decision tree will lead to the triggering of one or more agent behavior types and the corresponding routines. Behavior routines are composed of one or more steering behaviors, each of which in turn is composed of sequences of basic locomotion.

Social behaviors are complex phenomena which emerge from interactions among individuals, which are sensitive to individual behavior, group size, heterogeneity of individual distribution within groups and crowds, and geometric constraints. By combining individual agent behaviors, MASSEgress is able to simulate many typical social behaviors such as competitive, queuing, herding, and bi-directional crowd flow behaviors. Furthermore, by using statistical analysis with multiple simulations, MASSEgress can reveal emergent evacuation patterns and has the potential to facilitate egress analysis for building design.

Chapter 6

Validation and Application

This chapter describes the validation and application of MASSEgress, including (1) comparison of simulation results with results obtained by other evacuation models (namely, Simulex (Thompson et al., 2003) and buildingEXODUS (Fire Safety Engineering Group 2003)) which have been validated extensively and are commonly used in egress analyses; (2) use of MASSEgress to simulate and to replicate a historical case of crowd evacuation—(Rhode Island Nightclub Fire); and (3) application of MASSEgress to facilitate egress design analysis for a multi-story university building.

6.1 Crowd Flow Rate versus Passageway Width

Crowd flow rate test has been used to validate other evacuation models (Thompson and Marchant, 1995). In a typical test, evacuation of one hundred individuals is simulated with exits of varying widths. Crowd flow rates obtained from the simulations are then compared with other data sources, such as design regulations and field experiments. If simulation results are consistent with the other data sources, then the evacuation model is considered valid. Simulex model (Thompson et al., 2003) was tested in this manner, and simulation results were reported consistent with several other reliable data sources

(Thompson and Marchant, 1995). Here, the simulation results of the crowd flow rate test are compared with the prior reported results from the Simulex model. For comparison, similar settings, such as configuration and number of occupants, are used for MASSEgress and Simulex. Two specific differences between Simulex and MASSEgress should be noted. First, while MASSEgress allow different behavior models (and their combinations) to be specified either randomly or explicitly (e.g., 60% of agents are competitive and 40% of agents are collaborative, or the behaviors of agents vary as a function of different stress levels), the behavior model cannot be changed in Simulex. Second, given a particular setting, simulation results from Simulex will remain the same while, because of the randomness in its execution, the results from MASSEgress will be different for each run. The first crowd rate test simulation using MASSEgress, to be discussed in Section 6.1.1, is conducted by assigning all agents with competitive behavior in order to produce crowd movement that is similar to what occurs in Simulex. For the second simulation, to be discussed in Section 6.1.2, MASSEgress simulation is executed with agent behavior set to queuing. Section 6.1.3 briefly summarizes the crowd flow rate test results and their implications.

6.1.1 Crowd Flow Rate Test with Competitive Behavior

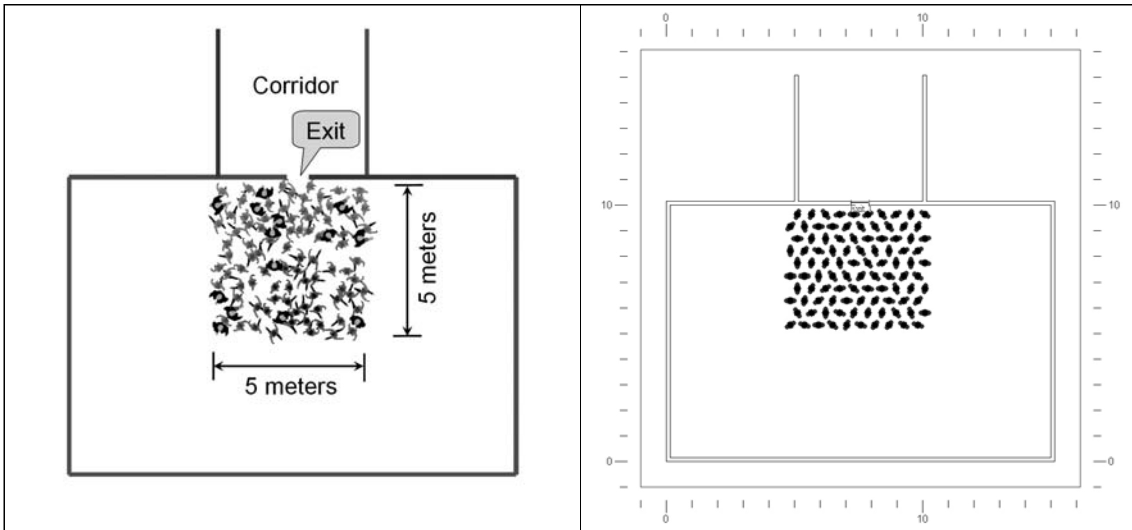
In the crowd flow rate test, the exit widths range from 0.7 to 3.0 meters with increments of 0.1 meter. For the simulation with competitive behavior, a group of one hundred individuals are randomly distributed within a 5 meter by 5 meter space next to an exit (Figure 6-1). A corridor is placed on the other side of the exit. The crowd is expected to go through the exit and then continue walking in the corridor. For the simulation tests, the position, orientation, and movement velocity of each individual remain constant. For each simulation, the flow rate Q (persons/m/s) is calculated as follows (Thompson and Marchant, 1995):

$$Q = \frac{80}{w(T_{90} - T_{10})} \quad (w >= 1.1 \text{ m}) \qquad (1)$$

$$Q = \frac{65}{w(T_{70} - T_{5})} \quad (w < 1.1 \text{ m}) \qquad (2)$$

where w = exit width (m). The parameters $\mathbf{T_5}$, $\mathbf{T_{10}}$, $\mathbf{T_{70}}$ and $\mathbf{T_{90}}$ represent, respectively, the times that take 5, 10, 70 and 90 people to pass through the exit.

One simulation by Simulex was conducted for each exit width (because Simulex is a deterministic model). For MASSEgress five simulations were conducted for each exit width and the results over the five simulations are averaged. The results for Simulex and MASSEgress are shown in Tables 6-1 and 6-2, respectively. Figure 6-2 presents comparison of the results, which indicate that, while the modeling principles of MASSEgress and Simulex are different, the simulation results of this particular test are quite similar.



a. MASSEgress screenshot

b. Simulex screenshot (Simulex, 1998)

Figure 6-1: Initial crowd distribution for crowd flow rate test

Table 6-1: Simulex crowd flow against different exit width simulation results

Exit Width (meter)	T5 (second)	T10 (second)	T70 (second)	T90 (second)	Total time (second)	Flow Rate (persons/m/s)
0.70	6.00	12.00	72.00	92.00	100.80	1.41
0.80	5.00	9.00	55.00	72.00	77.90	1.63
0.90	4.00	6.00	45.00	57.00	62.60	1.76
1.00	3.00	7.00	39.00	50.00	55.50	1.81
1.10	3.00	6.00	35.00	45.00	49.60	1.86
1.20	5.00	8.00	32.00	40.00	45.10	2.08
1.30	4.50	8.00	30.00	38.00	42.30	2.05
1.40	4.00	7.00	27.00	35.00	38.40	2.04
1.50	3.00	5.00	24.00	31.00	34.90	2.05
1.60	3.00	6.00	24.50	30.30	33.90	2.06
1.70	3.00	6.00	25.00	30.00	35.20	1.96
1.80	3.00	5.50	23.00	29.00	32.20	1.89
1.90	2.50	5.00	23.00	27.00	31.10	1.91
2.00	2.50	4.80	21.00	26.50	29.80	1.84
2.10	2.50	4.80	19.50	24.50	26.80	1.93
2.20	1.50	3.20	17.50	23.00	26.30	1.84
2.30	2.00	3.50	18.00	22.50	26.50	1.83
2.40	2.00	4.80	17.50	22.00	24.70	1.94
2.50	1.50	3.20	17.00	20.10	23.40	1.89
2.60	1.20	4.50	16.00	21.00	24.40	1.86
2.70	1.50	4.00	17.00	20.10	23.10	1.84
2.80	1.50	3.00	15.10	18.20	23.60	1.88
2.90	1.50	3.50	15.20	17.00	21.80	2.04
3.00	13.00	3.40	14.00	16.50	19.80	2.04

Table 6-2: MASSEgress crowd flow against different exit width simulation results (competitive behavior for all agents)

Exit Width (meter)	T_5 (second)	T_{10} (second)	T_{70} (second)	T_{90} (second)	Total Time (second)	Flow Rate (persons/m/s)
0.70	3.87	13.08	106.88	146.35	160.36	0.90
0.80	6.67	12.69	78.05	108.55	117.91	1.14
0.90	2.48	7.56	60.02	80.09	90.54	1.26
1.00	2.58	7.13	54.15	70.93	76.55	1.26
1.10	1.82	3.99	43.30	53.12	59.98	1.48
1.20	1.46	3.34	32.59	43.38	48.54	1.67
1.30	1.60	2.80	26.54	34.38	39.50	1.95
1.40	1.77	3.50	22.31	29.79	34.84	2.17
1.50	1.55	3.35	24.41	28.64	36.92	2.11
1.60	1.34	2.40	19.78	25.91	32.41	2.13
1.70	1.20	2.31	18.34	23.39	28.41	2.23
1.80	1.10	1.58	17.18	21.83	27.24	2.19
1.90	1.17	2.04	18.03	23.03	27.94	2.01
2.00	1.30	1.72	17.38	22.47	27.07	1.93
2.10	1.05	1.61	13.76	19.50	24.97	2.13
2.20	0.79	1.40	13.55	18.87	23.34	2.08
2.30	0.90	1.59	14.02	17.35	23.28	2.21
2.40	0.78	1.35	11.04	15.65	20.60	2.33
2.50	0.92	1.45	10.00	15.48	19.43	2.28
2.60	0.56	1.27	10.30	14.66	19.99	2.30
2.70	0.65	1.19	8.96	13.85	16.52	2.34
2.80	0.67	1.20	9.27	13.03	17.20	2.42
2.90	0.78	1.25	8.96	13.00	17.17	2.35
3.00	0.54	1.19	8.62	12.55	17.17	2.35

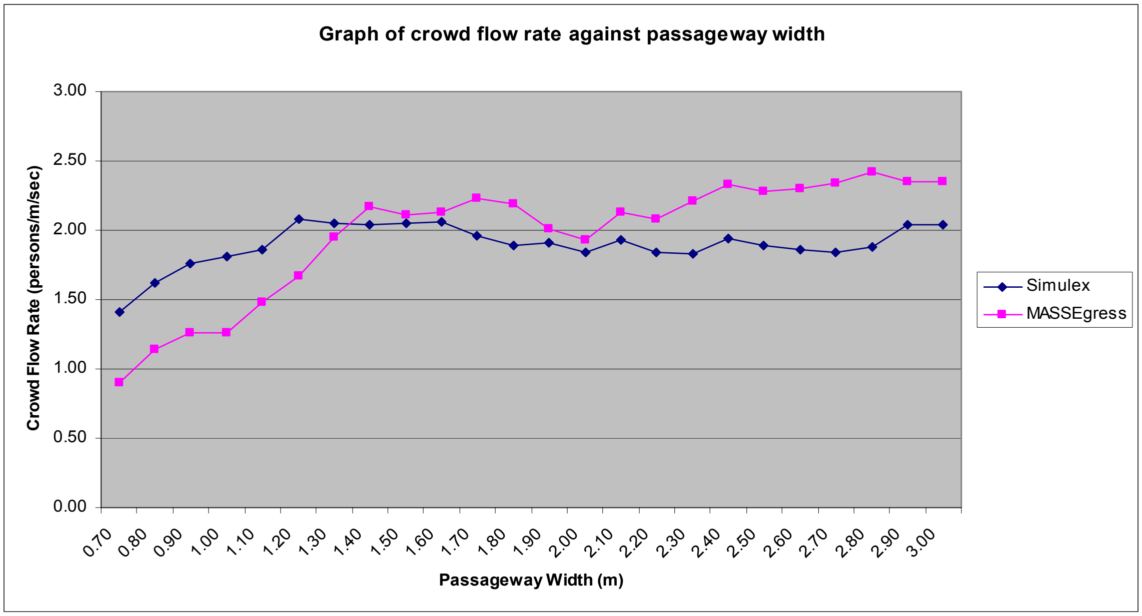
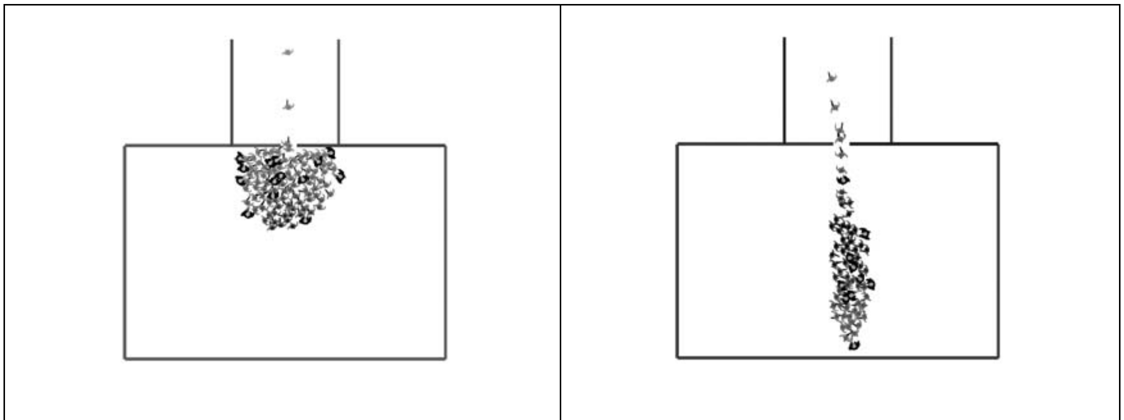


Figure 6-2: Comparison of Simulex and MASSEgress crowd flow rates against different exit width simulation results

6.1.2 Crowd Flow Rate Test with Queuing Behavior

For the crowd flow rate test scenario with queuing behavior[1], MASSEgress is utilized with the same configuration as the previous simulations described in Section 6.1.1 except that the agents are distributed throughout the room rather than confined to a 5 meter by 5 meter square to decrease crowd density. Agents behave differently, as expected (Figure 6-3). Five runs were conducted against each exit width. Recorded results represent the average of five results for each exit width (see Table 6-3). The comparison regarding the crowd flow rate between Table 6-2 and Table 6-3 is shown in Figure 6-4. Figure 6-5 compares total egress times between competitive and queuing behavior.

[1] In MASSEgress, only single-line queue is implemented. In reality, multiple-line queue is also commonly observed.



a. competitive behavior   b. queuing behavior

Figure 6-3: MASSEgress crowd flow rate test with competitive and queuing behaviors

Table 6-3: The results of using MASSEgress to simulate crowd flow against different exit width (queuing behavior)

Exit Width (meter)	T_5 (second)	T_{10} (second)	T_{70} (second)	T_{90} (second)	Total Time (second)	Flow Rate (persons/m/s)
0.70	7.34	14.22	62.24	76.36	85.12	1.69
0.80	6.04	9.42	54.26	68.42	77.28	1.68
0.90	6.06	9.18	52.48	60.16	77.24	1.56
1.00	4.52	8.06	51.16	58.06	75.08	1.39
1.10	5.08	8.26	52.06	67.32	75.46	1.23
1.20	4.52	9.12	56.36	69.44	77.56	1.11
1.30	5.14	8.42	49.16	64.34	74.26	1.10
1.40	5.14	8.26	56.32	71.26	79.22	0.91
1.50	5.32	9.36	49.34	65.34	75.54	0.95
1.60	5.34	8.08	55.44	71.14	79.52	0.79
1.70	5.22	8.12	52.34	69.02	77.18	0.77
1.80	5.26	6.48	53.22	67.26	77.02	0.73
1.90	5.18	8.32	55.08	68.26	76.22	0.70
2.00	5.12	10.02	54.36	71.12	77.54	0.65
2.10	5.18	9.42	57.36	73.02	80.12	0.60
2.20	5.02	8.16	59.22	74.34	86.28	0.55
2.30	4.58	7.42	52.08	68.26	74.56	0.57
2.40	4.48	7.48	53.18	70.56	76.22	0.53
2.50	5.08	7.04	52.32	69.42	76.04	0.51
2.60	4.52	6.46	52.08	66.22	79.04	0.51
2.70	6.02	7.58	51.12	65.22	74.36	0.51
2.80	4.44	7.36	50.16	68.08	74.52	0.47
2.90	5.14	8.06	51.48	67.04	75.38	0.47
3.00	5.18	8.36	53.12	69.08	77.32	0.44

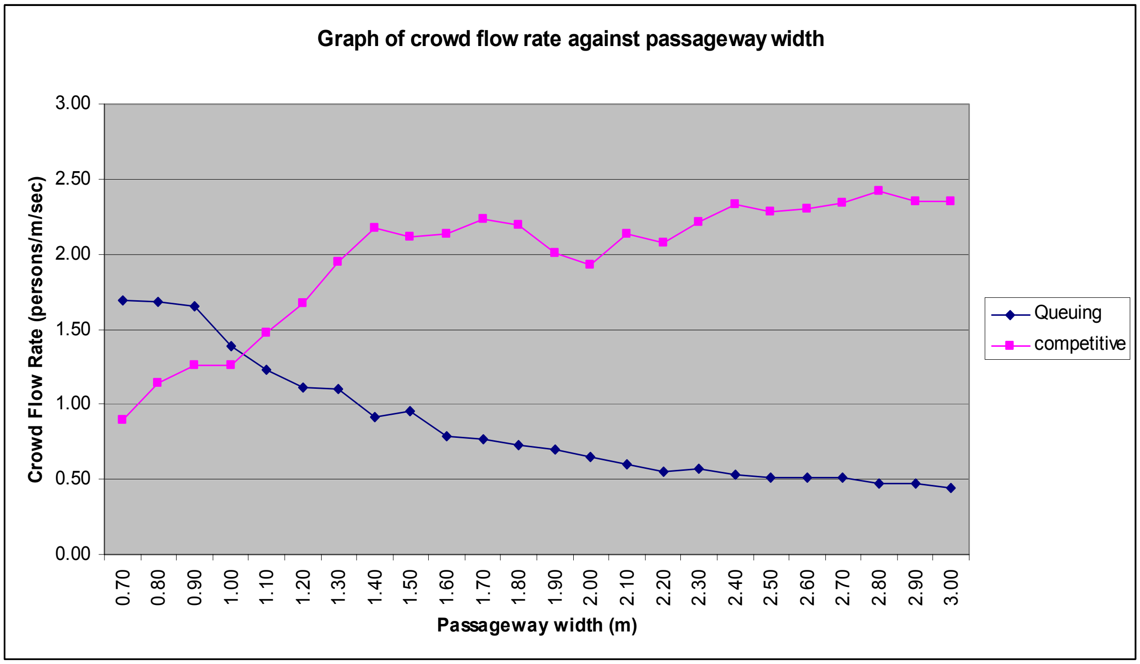


Figure 6-4: MASSEgress to calculate crowd flow rate against different passageway width with different agent behaviors

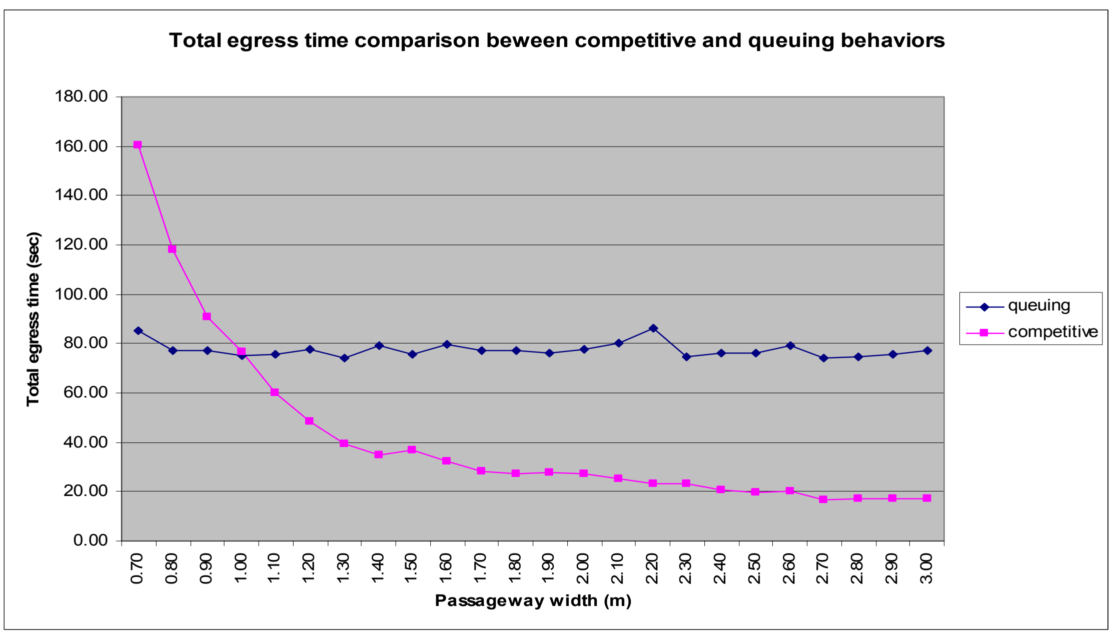


Figure 6-5: Competitive and queuing behavior total egress time comparison

6.1.3 MASSEgress / Simulex Comparison Implications

Implications that can be drawn from the above comparisons include:

- Competitive behavior at exits may imply that wider exit increases crowd flow rate. Exit size 0.7 m, for example, exhibits a crowd flow rate of 0.9 persons/m/s, and exit size 3.0 m exhibits a crowd flow rate of 2.35 persons/m/s (see Figure 6-4). On the other hand, as shown in Figure 6-4 and Figure 6-5, the crowd flow rate as well as the total egress time level off at about 2.2 m (which is approximately the size of double doors typically employed at most public exits!). Competitive behavior at exits may imply that narrower exit increases total egress time. For example, the case of exit size 3.0 m exhibits a total egress time of 17.17 seconds, and the case of exit size 0.7 m exhibits a total egress time of 160.36 seconds (see Figure 6-5).

- Increased exit width seems to imply that effectiveness of a single queue decreases. For example, exit size 0.7 m exhibits a crowd flow rate of 1.69 persons/m/s, and exit size 3.0 m exhibits a crowd flow rate of 0.44 persons/m/s (see Figure 6-4). This is because the current simulation assumes a single queue; as a result, queuing behavior (i.e., single-line queuing) at exits result on wider exits not significantly affecting total egress time. For example, the total egress time is approximately 78 seconds regardless of exit width under the influence of single queuing behavior (Figure 6-5). Both the crowd flow rate and the total egress time remain approximately the same beyond 1.3 m. For wider exits, this example clearly shows that multiple queues should be modeled.

Based on the results and the discussions above, crowd behavior influences on egress processes seem evident. The ability for an evacuation model to simulate various human behaviors would therefore appear efficacious.

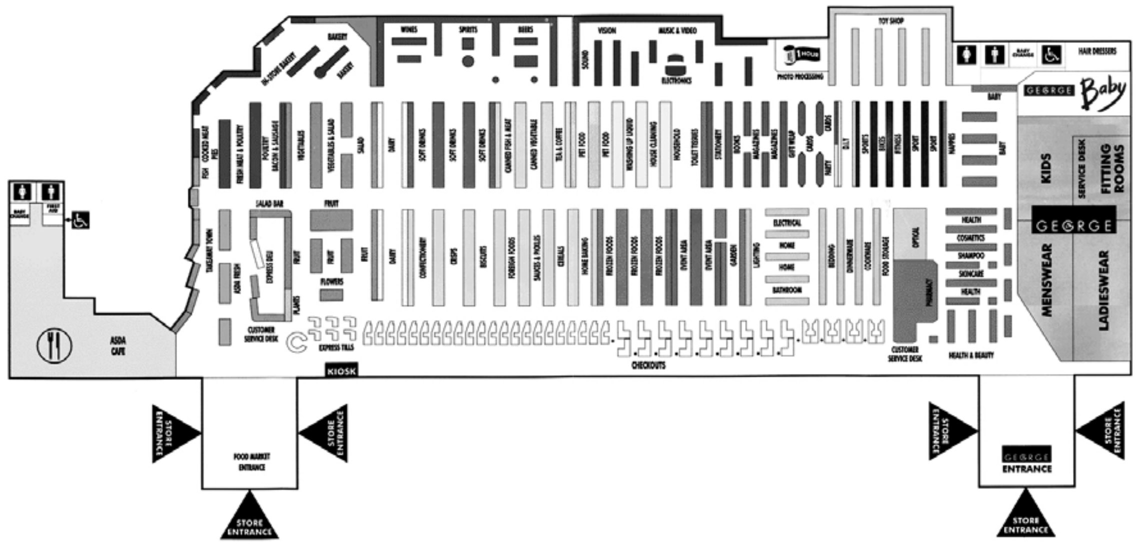


Figure 6-6: The floor plan of a department store

6.2 Evacuation Simulation of a Department Store

While the flow rate comparisons show that the evacuation at exits are similar between MASSEgress (with competitive behavior) and Simulex, the evacuation patterns and, therefore, the total egress time for an entire building plan could still be significantly different. In this example, the floor plan of a department store as shown in Figure 6-6 is used for simulation. The gross floor area of the store is approximately 98,000 sq. ft.. The calculated maximum occupant load is 980 persons assuming that the net floor area is 50% of gross floor area, and based on 50 net sq. ft. per occupant allowance (ICBO, 2000, Section 1003.2.2.2). MASSEgress and Simulex are utilized to simulate minimum evacuation time and results compared. For MASSEgress, the population is a mix of five different population types (i.e., Median, Adult Male, Adult Female, Child, and Elderly) (20% for each population type) and is randomly distributed throughout the store. For Simulex, the population is set to "Shoppers"[2]. The pre-movement time is set to zero. All

[2] The description of "Shoppers" is not given in Simulex software.

evacuees will seek for the nearest exit. In addition, for MASSEgress, agents are assigned with either competitive or queuing behavior (i.e., one half of the agents behave competitively, and the other half behave cooperatively), and some exit signs are placed in the store space to guide agents. Selected simulation screenshots from Simulex and MASSEgress are shown in Figure 6-7 and Figure 6-8, respectively. One Simulex simulation is executed. Five MASSEgress simulations are performed, and the results are averaged. Comparison of results is shown in Figure 6-9. Minimum evacuation time predicted by Simulex is 2 minutes 19 seconds. Minimum evacuation time predicted by MASSEgress is 3 minutes 9 seconds.

The difference in evacuation time may result from varying behavior types. Simulex assumes all agents have perfect knowledge and all evacuate via shortest routes to the nearest exits. MASSEgress agents must search for nearest exits, and dependent upon their initial locations may require more time to find them. Minimum evacuation time predicted by MASSEgress may more accurately reflect human reality, in that the patrons of the department store may not be familiar with the exits.

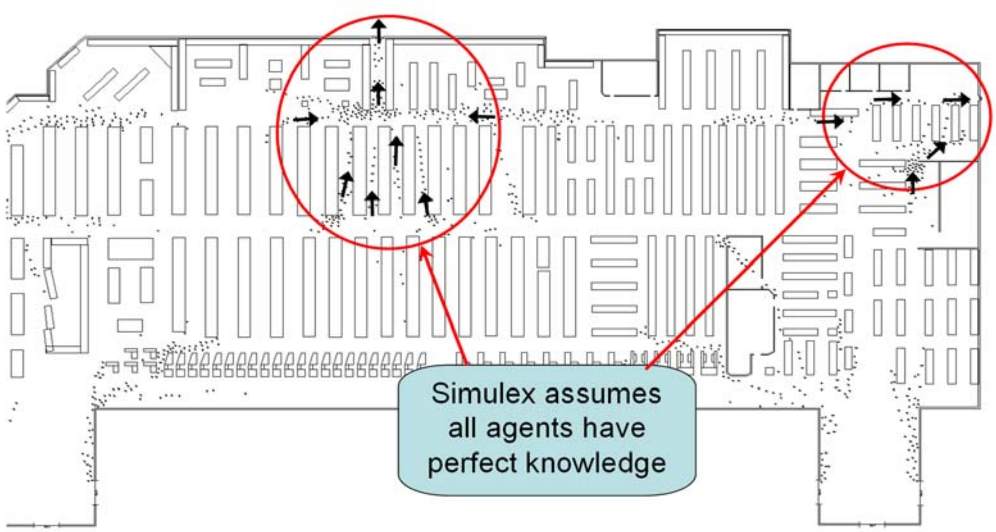


Figure 6-7: A simulation screenshot from Simulex

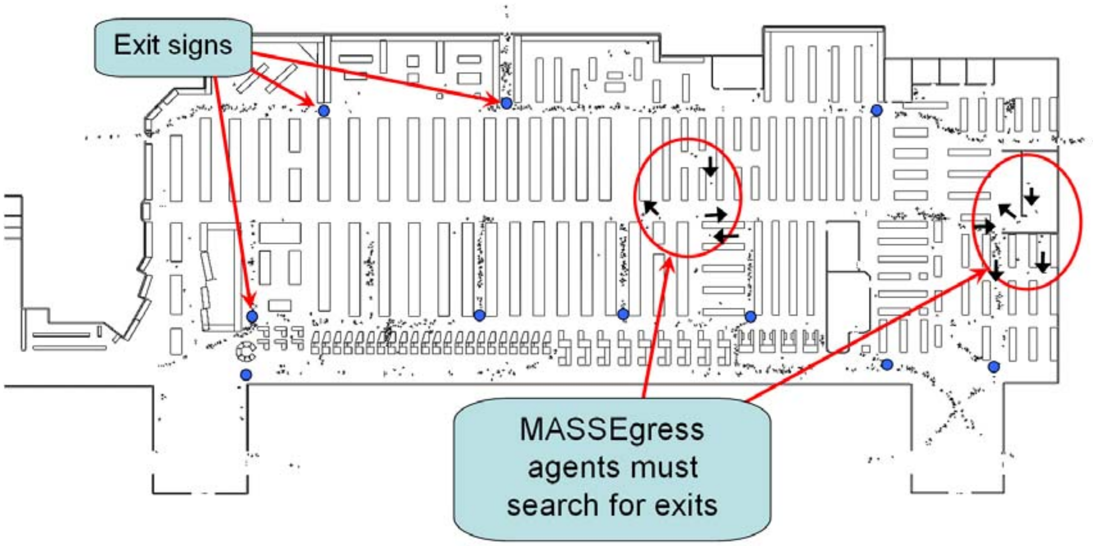


Figure 6-8: A simulation screenshot from MASSEgress

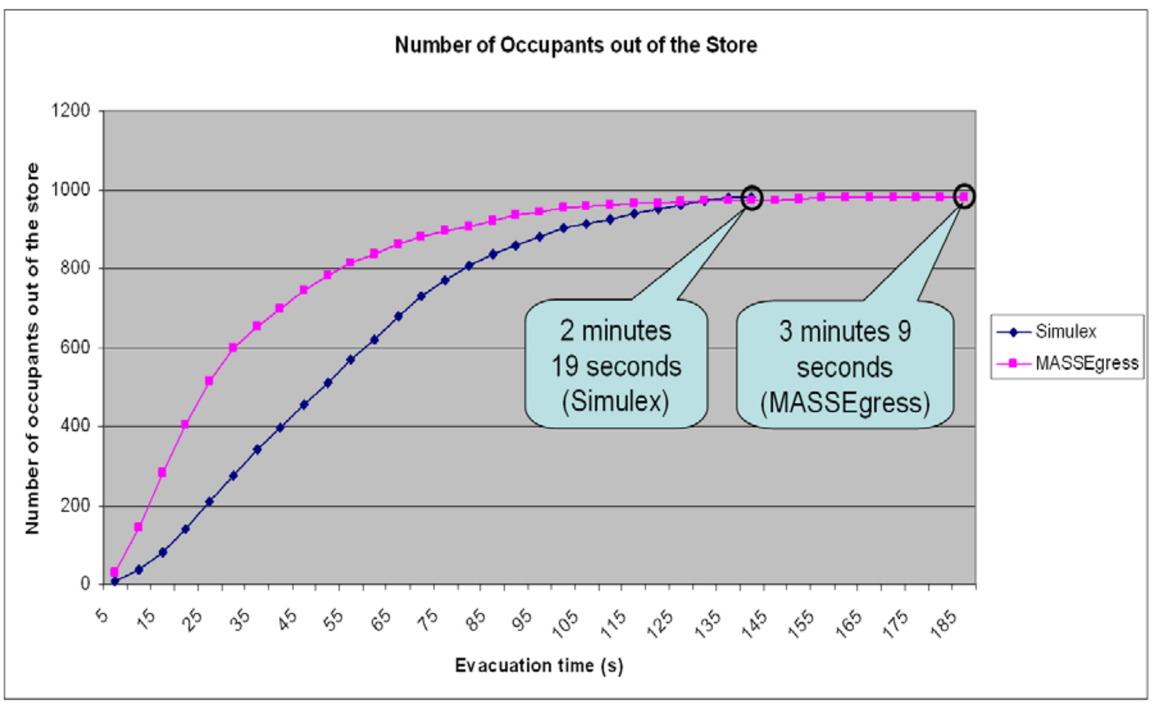


Figure 6-9: Comparison between Simulex and MASSEgress for evacuation simulation of a department store

The difference in evacuation time may also result from varying agent populations. In MASSEgress, 60% of the agents are adults, and the rest are either children or elderly. Since most of the agents (i.e. adults) evacuate quickly while the children and elderly take a longer time to evacuate, it explains the results presented in Figure 6-9 — the MASSEgress curve climbs faster at the beginning but then flattens out in the end when elderly and slow moving people are exiting.

The arrangement of exit signs can have significant influence on evacuation time. As shown in Figure 6-10, additional exit signs are added into the department store. MASSEgress is then employed to simulate the evacuation again using the same input as described in Figure 6-8. As shown in Figure 6-11, the total evacuation time is improved from previous 3 minutes 9 seconds to 2 minutes 14 seconds which is comparable with the simulated results by Simulex. Such improvement is mainly because the additional exit signs provide guidance to the agents who might have been lost in searching for escape routes as in the previous case.

Figure 6-10: A simulation screenshot from MASSEgress with additional exit signs

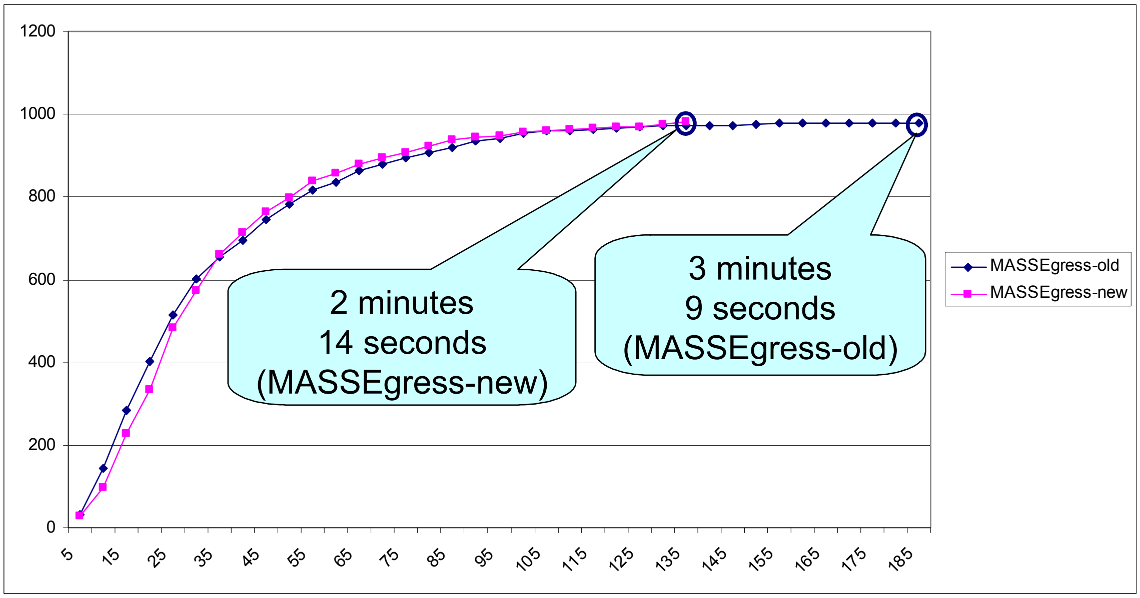


Figure 6-11: Egress time is improved with additional exit signs

6.3 Evacuation Simulation of a Historical Event—the Rhode Island Nightclub Fire Case

This section describes the application of MASSEgress for the evacuation simulation of a historical event when a fatal fire occurred at a nightclub in Rhode Island. The purpose of the simulation is to replicate the evacuation patterns, calculate the total evacuation time and compare the results produced by Simulex and buildingEXODUS (as described in the Investigation Report by the National Institute of Standards and Technology, NIST (Grosshandler et al., 2005)).

6.3.1 Description of Historical Case and Building

A fire erupted in the Station nightclub, 211 Cowesett Avenue, West Warwick, Rhode Island on the night of February 20, 2003. The fire spread and became fatal within tens of seconds. As reported, evacuation was hampered by crowding at the main entrance to the building. Approximately one hundred people died, most during evacuation.

The Station nightclub was a single-story wood frame building with a footprint of approximately 4484 square ft. As shown in Figure 6-12, there are four exit locations—the main entrance facing north, an exit door adjacent to the main bar, an exit door by the kitchen and an exit door near the platform. A band, during its performance on the night of February 20, 2003, used pyrotechnics which ignited polyurethane foam insulation lining the walls and ceiling of the raised platform on which they performed. Initiation of the fire occurred at 11:08 pm, and evacuation began a few seconds later. The platform door became impassable due to fire approximately 30 seconds later. The main entrance became clogged with people attempting to exit approximately 1 minute 40 seconds later; some individuals began to break windows to escape from the poolroom and sunroom. The latest time recorded for an individual escaping from the main bar through a window was 4 minutes 8 seconds after initiation of the fire. Flames were observed extending out of windows and the front doorway at five minutes after initiation of the fire. Some individuals knew of the existence of the side exit door near the main bar; approximately 46 individuals used this exit. Approximately 20 individuals, primarily those associated with the band or the club, used the exit near the platform early in the fire. Many survivors indicated that they were not aware of any exit doors other than the main floor entrance.

Of approximately 350 occupants, 248 successfully evacuated. Of the 169 who evacuated through doors, 91 evacuated through the main front door, 46 through the side door next to the bar, and 32 through the door near the platform. Seventy nine individuals evacuated through windows; 25 through the sunroom windows, and 54 through the main bar windows. Of 96 who died, 58 were found in the main entry way. Two thirds of total occupants attempted to evacuate through the main entrance, and only about 40% of those were successful.

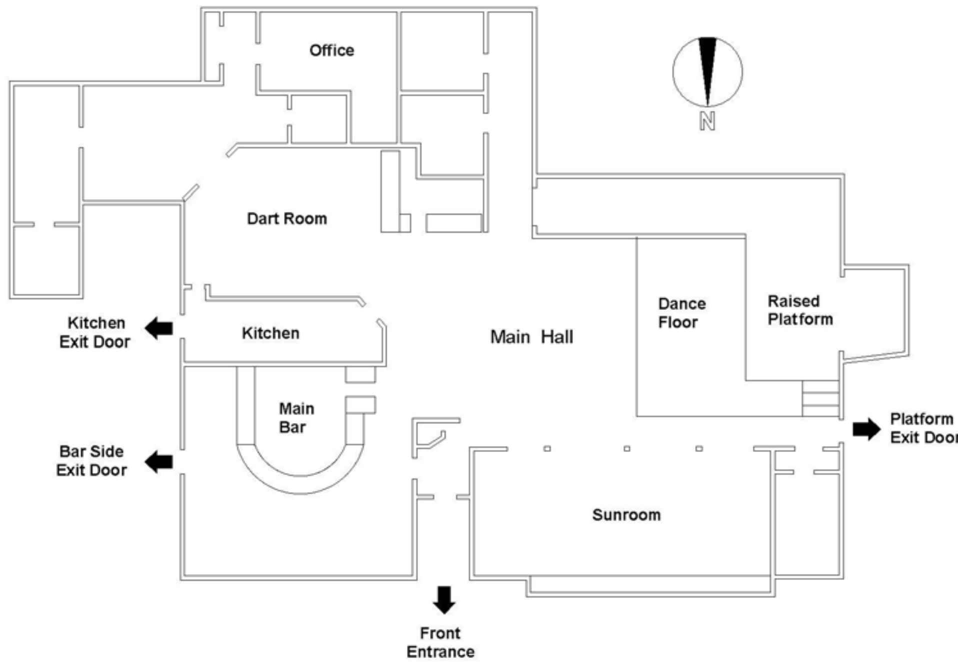


Figure 6-12: The nightclub floor plan

6.3.2 Scenario One: Replicating the Incident

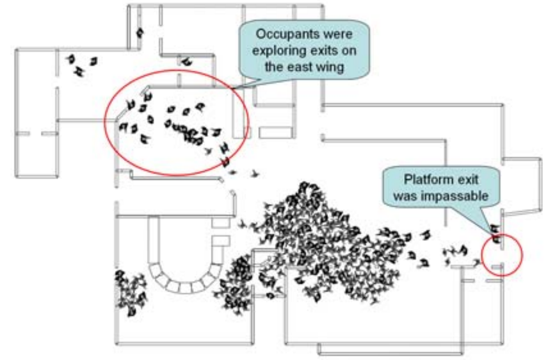
The first scenario that MASSEgress simulates is crowd evacuation pattern based on empirical data provided by the NIST Investigation Report (Grosshandler et al., 2005). The simulation is based on the following assumptions provided in the NIST report:

- A total of 350 occupants, most of them are on the dance floor and in the main bar. The population comprises a random mix of adult males and females (approximately 50% for each gender).

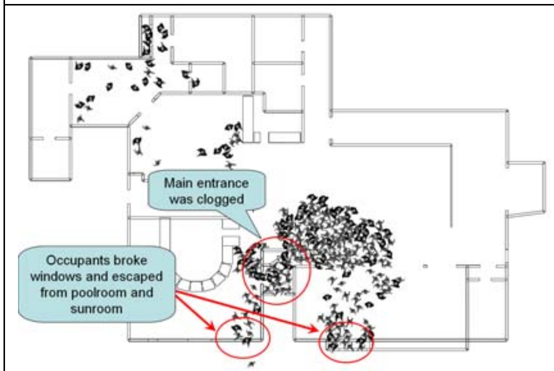
- 20 occupants aware of the platform door, and 2/3 of the occupants believe the main entrance is the only exit.

- All agents are of high stress level and will therefore behave competitively.

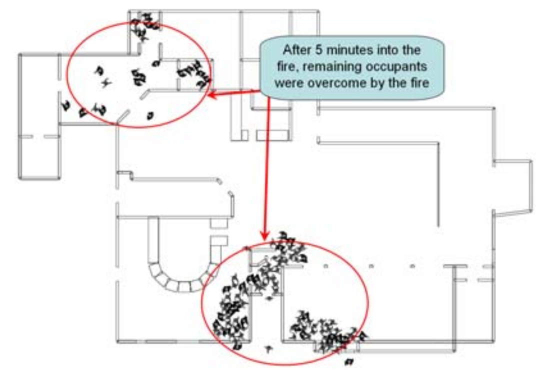
a. initial crowd distribution at time 0



b. platform exit was impassable at 30 seconds



c. occupants broke windows and escaped from the poolroom and sunroom



d. after 5 minutes into the fire, occupants remained in the nightclub were overcome by the fire

Figure 6-13: A typical simulation of the scenario one in MASSEgress

Excluded from the simulation due to MASSEgress limitation include (1) the progress of fire and smoke, and the fact that they caused fatalities during evacuation; and (2) crowd crushing occurred at the main entrance.

MASSEgress simulated the scenario 15 times. The input remained the same for all the simulations with the exception that the spatial distribution of the crowd is randomized for each simulation. The simulation results demonstrate that MASSEgress is able to replicate the overall crowd evacuation patterns as described in the NIST report. A typical simulation is shown in Figure 6-13 and can be described as follows:

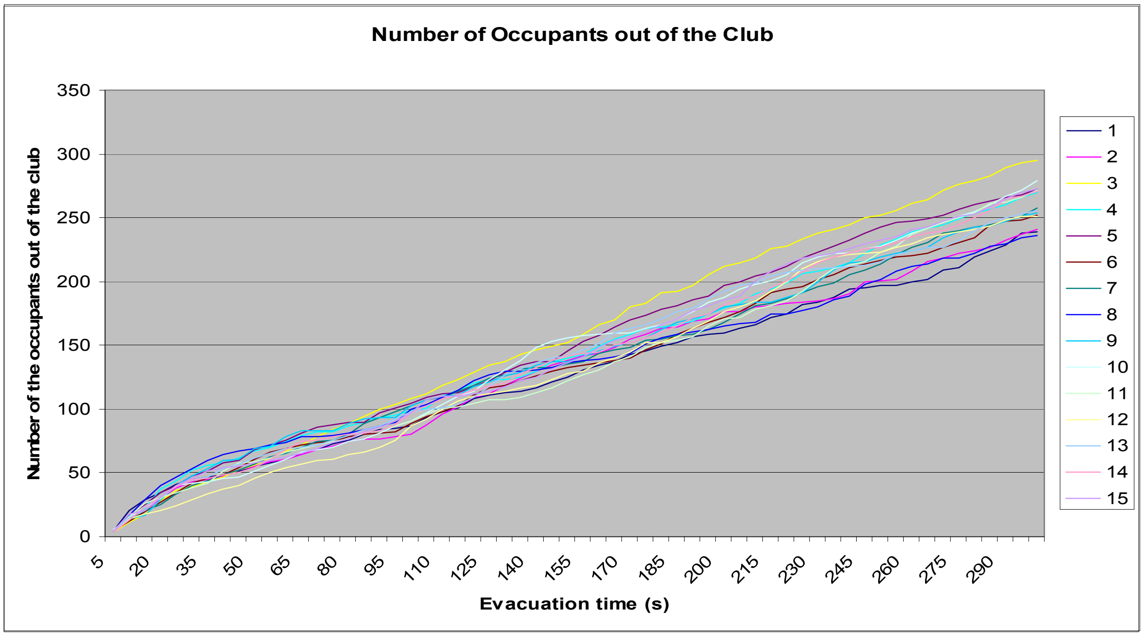


Figure 6-14: Cumulative plot of 15 simulation runs for scenario one

1. At time 0 the initial crowd distribution in the nightclub is shown in Figure 6-13a; most agents are in the main hall and the main bar. Fire was assumed to initiate in the walls and ceiling of the raised platform.

2. At 30 seconds the platform exit door was impassable. Agents began to explore other spaces for exit, further from the fire including the east side of the building (Figure 6-13b).

3. At 1 minute 40 seconds the main entrance was congested by the crowd, and some agents evacuated through the poolroom and the sunroom windows (Figure 6-13c).

4. Simulation stopped at 5 minutes into the fire. Agents remaining in the building are assumed unable to escape (Figure 6-13d).

The number of agents evacuated over the duration time is shown in Figure 6-14, in which the 15 curves represent the results of the 15 simulation runs. Figure 6-15 shows the average number of occupants escaped from the club over time. At five minutes into the fire, simulation results indicate that on the average, 261 of 350 agents evacuated (184 through doors, and 77 through windows), and the remaining 89 are assumed dead.

Notice that the general trend of evacuation is more linear in this case than the department store example. This is primarily caused by the difference in population characteristics. While the department store includes a population with very different travel speed, here all the population are young adults with approximately uniform traveling speed.

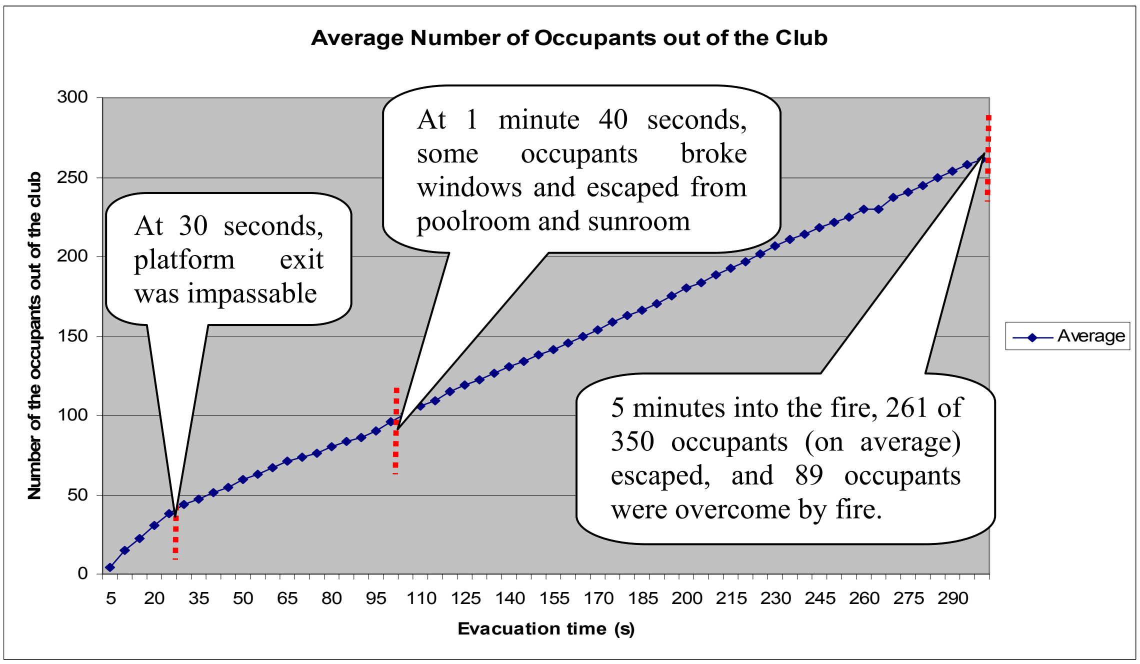


Figure 6-15: Cumulative plot of the average number of occupants out of the club based on 15 simulation runs

Table 6-4: Comparing MASSEgress simulation results to NIST data

	Total Occupants	Escaped from doors	Escaped from windows	Total escaped	Total fatalities (approximate)
NIST Data	350	169	79	248	100 fatalities
MASSEgress Results (average)	350	184	77	261	89 assumed dead

Table 6-4 shows the comparison of the results from the MASSEgress simulations and the data provided in the NIST report. It can be seen that the simulated results closely replicate the reported results of this historical event.

6.3.3 Scenario Two: Simulation of Minimum Evacuation Time

NIST utilized Simulex (Thompson et al., 2003) and buildingEXODUS (Fire Safety Engineering Group, 2003) evacuation models to determine the minimum time to evacuate the nightclub assuming the absence of fire at the platform area. Results are presented in the NIST Investigation Report (Grosshandler et al., 2005). In this study, MASSEgress is utilized to determine the minimum time to evacuate the nightclub. The results are compared to those of Simulex and buildingEXODUS. MASSEgress simulation uses the assumptions on the input identical to those used in the simulations by both Simulex and buildingEXODUS:

- A total occupant load of 420 individuals, of which 384 are located in the main hall, sunroom and main bar, and 36 are located in the kitchen, restroom, offices, and corridor.

- All agents are assumed to always select the nearest exits and to behave competitively.

While MASSEgress can assign different behaviors to agents as they exit, neither Simulex nor buildingEXODUS can. In the MASSEgress simulation, all agents are assigned with medium stress levels and competitive exit behavior. Ten MASSEgress simulation runs are conducted. Table 6-5 shows the results by buildingEXODUS and Simulex and the average evacuation time computed by MASSEgress. The estimated numbers of agents who evacuated through each exit are tabulated in the table.

Simulation results indicate that MASSEgress differs in the number of agents who exit through the platform door, in comparison to Simulex and buildingEXODUS: 184 for Simulex, 180 for buildingEXODUS, and 87 for MASSEgress. A greater number of agents exit through the front entrance during MASSEgress simulation, in comparison: 213 for Simulex, 214 for buildingEXODUS, and 293 for MASSEgress. The front entrance may function as a critical point for the evacuation; the number of agents who evacuated through the front entrance may thus determine total evacuation time, and suggest why MASSEgress minimum evacuation time is greater than that indicated by the other two systems.

Although all three systems assume agents choose the nearest exits, this rule is carried out differently in MASSEgress. In MASSEgress, agents use their visual sensors to look for exit locations. If MASSEgress agents cannot see the exits, they will not move towards them even though they may be nearer. The nearest exit for agents in area A (Figure 6-16), for example, is the platform door, but because these agents could not see the platform door from their locations they would choose to exit through the front entrance.

Table 6-5: Comparison of MASSEgress, Simulex and buildingEXODUS results

	Total evacuation time	occupants to front door	Occupants to platform door	Occupants to kitchen door	Occupants to main bar door	Total remaining at 90 s
Simulex	188 s	213	184	3	20	166
EXODUS	202 s	214	180	4	22	208
MASSEgress	217 s	293	87	4	36	173

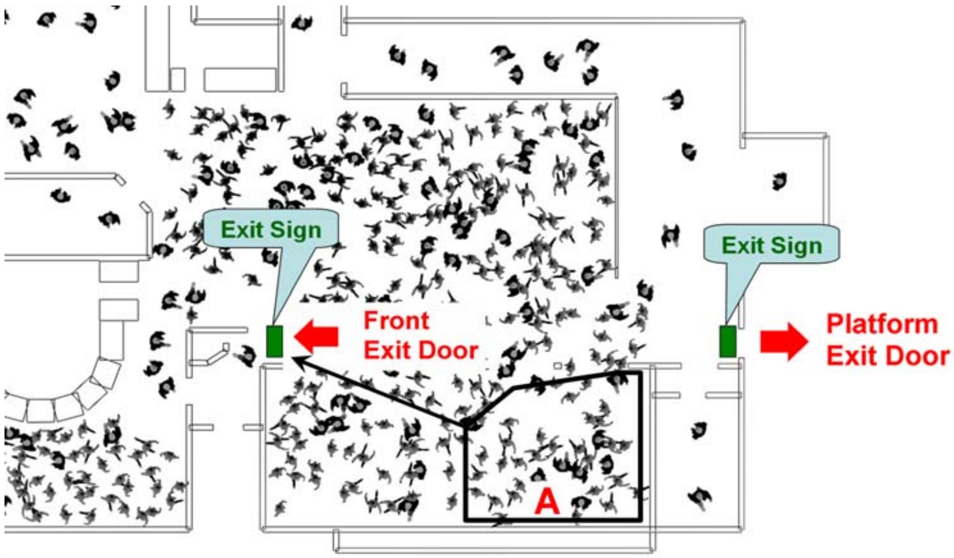


Figure 6-16: MASSEgress agents, unable to see nearby platform door, choose front entrance for exit

6.3.4 Scenario Three: Simulation of Minimum Evacuation Time with Different Agent Stress Level

In this scenario, MASSEgress is employed to conduct additional tests in order to demonstrate that different stress levels can have significant impact on agents' behavior and evacuation time. For each of the tests, same input from the scenario two (Section 6.3.3) is used except that the stress level of agents is set differently for each test. Specifically:

- for test #1, all agents are set to low stress level (i.e., 0.2), and therefore they would search for the nearest exit and execute queuing behavior;
- for test #2, all agents are set to high stress level (i.e., 0.9), and therefore they would search for the most popular exit (i.e., herding) and execute competitive behavior;
- for test #3, the stress level of all agents are set as a function of time, which linearly increases from 0.2 to 0.9 as time progresses (within a time range of 200

seconds); as the result of that, all agents would behave collaboratively in the beginning but competitively towards the end.

Ten MASSEgress simulation runs are conducted for each test and results are averaged. Comparison of simulation results is shown in Figure 6-17. The shortest egress time (i.e., 190 seconds) is produced when all agents are set to low stress level, and the longest egress time (i.e., 278 seconds) is produced when all agents are set to high stress level. When the stress levels of all agents increase linearly as a function of time, although the total egress time (i.e., 247 seconds) that it produces is not the longest, it is still significantly longer than the case with low stress level (57 seconds longer). These test results indicate clearly that, higher stress levels can lead agents to behave competitively, and competitive behaviors in turn create congestions at exit areas which hinder the evacuation flows. Such results are consistent with observations in real situations.

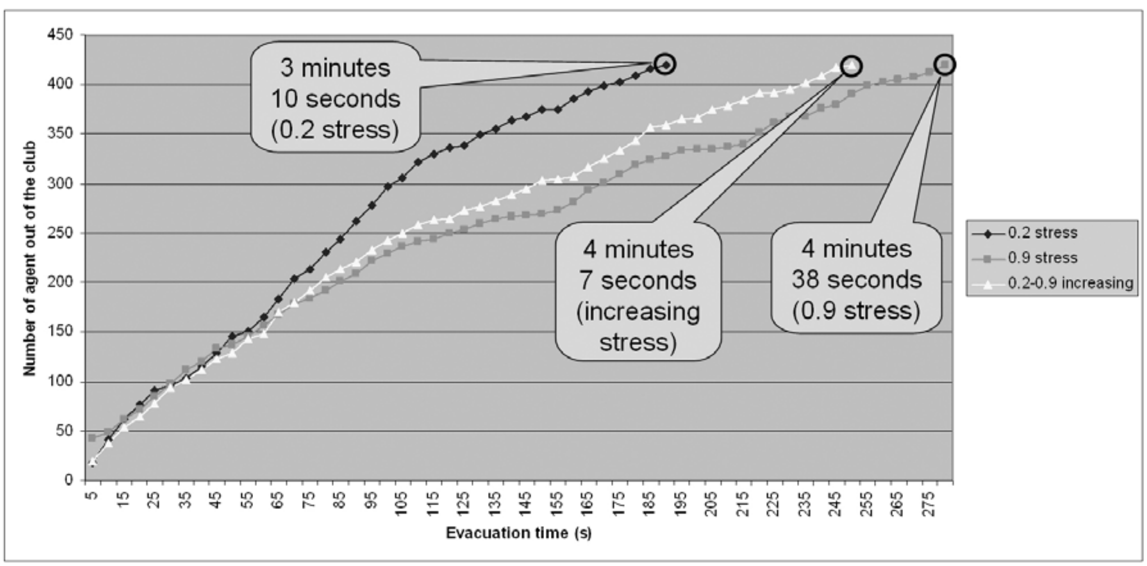


Figure 6-17: Agent stress levels have significant impact on evacuation time

6.4 Egress Design Analysis of a Large Multi-Story University Building

A university building (Figure 6-18) currently under design development is selected for MASSEgress application to performance-based egress design analysis. The building is selected because: (1) the building is in a design stage which may enable MASSEgress predictions to serve as examples of how performance-based analysis can illustrate critical egress issues which may have been overlooked by prescriptive building codes; and (2) the building has multiple floors and has up to 2500 person capacity which may offer a test of MASSEgress scalability and stability.

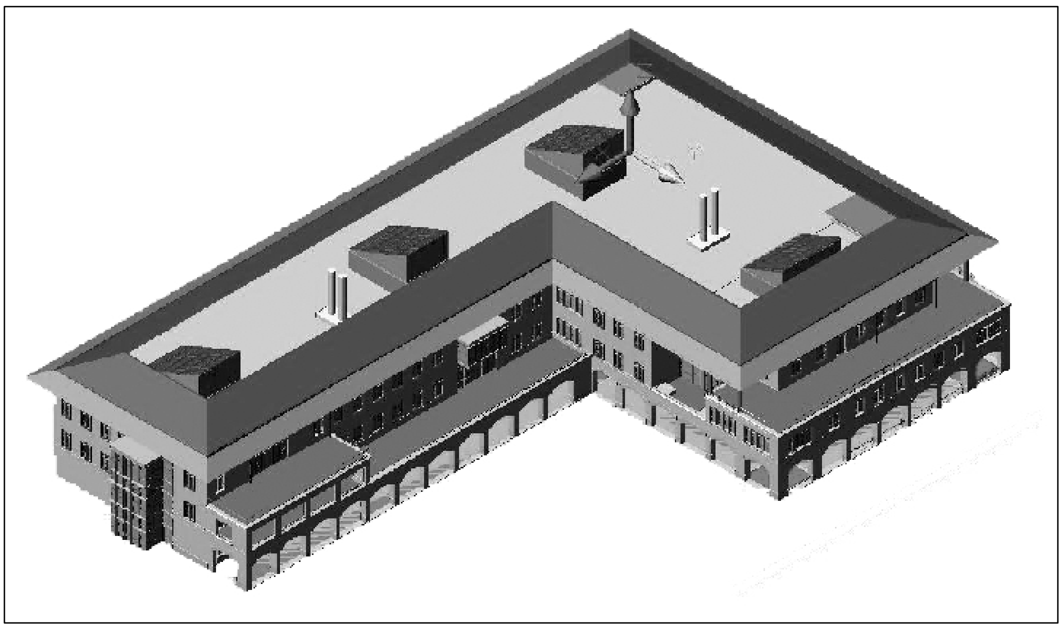


Figure 6-18: A university building

Figure 6-19: The typical floor plan of the building

6.4.1 Description of the Building and Occupant Load Calculation

The design of the building provides a central gathering place where faculty, students and visitors from various disciplines can interact and brainstorm. The building has four stories. It contains office spaces for over 40 faculty and 200 graduate students, as well as classrooms, seminar rooms, and labs. A typical floor plan is shown in Figure 6-19. Vertical circulation is achieved via three staircases distributed in the floor plan. The longest distance between two staircases is 238 ft. (Figure 6-19). Horizontal circulation is achieved via corridors, and user spaces are organized along corridors.

The calculated occupant load and the gross area for each floor are shown in Table 6-6. Occupant load calculation follows the International Building Code (ICBO, 2000), Section

1003.2.2, where floor area in sq. ft. per occupant is net 20 for classrooms and labs, and for areas having fixed seats installed, the occupant load is determined by the number of seats.

Table 6-6: The gross area and maximum occupant load for each floor.

	Gross Area (square ft)	Occupant load (persons)
Floor 0 (basement)	54,418	889
Floor 1	32,868	564
Floor 2	43,526	563
Floor 3	37,279	508
Total	168,091	2524

6.4.2 Scenario One: Minimum Evacuate Time

MASSEgress is applied to determine the minimum time required to evacuate the building assuming it is at full occupancy. Four behaviors types are predefined and randomly assigned to the agents: (1) choose the nearest exit and then pursue it using competitive behavior; (2) choose the nearest exit and then pursue it using queuing behavior; (3) choose the exit that is most crowded (herding), and then pursue it using competitive behavior; and (4) choose the exit that is most crowded, and then pursue it using queuing behavior. As for the input for the simulation, it is assumed that floor one is the only floor where agents can exit the building; occupants on other floors must move to floor one through staircases in order to exit.

Figure 6-20 shows a screenshot of the simulation with the building fully occupied. A total of 15 simulation runs are conducted, and the average numbers of agents exiting in relation to time are recorded as shown in Figure 6-21.

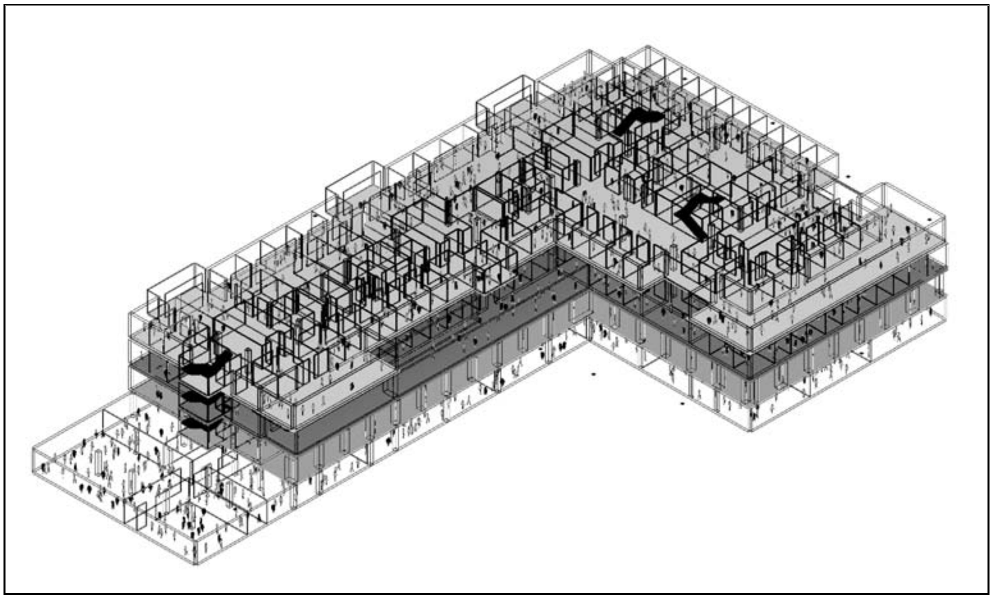


Figure 6-20: Simulation screenshot—building occupied to capacity

Simulation results indicate that with 2524 agents, the minimum time required to evacuate the entire building is 17 minutes and 5 seconds. At 3 minutes 38 seconds, all occupants originally located on floor one have exited. However, it takes another 13 minutes 27 seconds elapse before all agents on other floors are evacuated through staircases!

Because such a building would rarely be occupied fully in reality, additional simulations with 600 occupants are conducted (all inputs are remained the same as the previous case except that occupant load is reduced proportionally). The final simulation results show that the minimum evacuation time is 4 minutes 58 seconds (see Figure 6-22).

Figure 6-21 and Figure 6-22 initially exhibit a nonlinear trend which is produced by different population exiting the ground floor where egress does not involve the use of staircases. However, after approximately 160 seconds, all remaining occupants need to use the staircases. The average flow rate of evacuation is controlled by the flow rate in the staircases which produces a linear trend for the remaining of the evacuation.

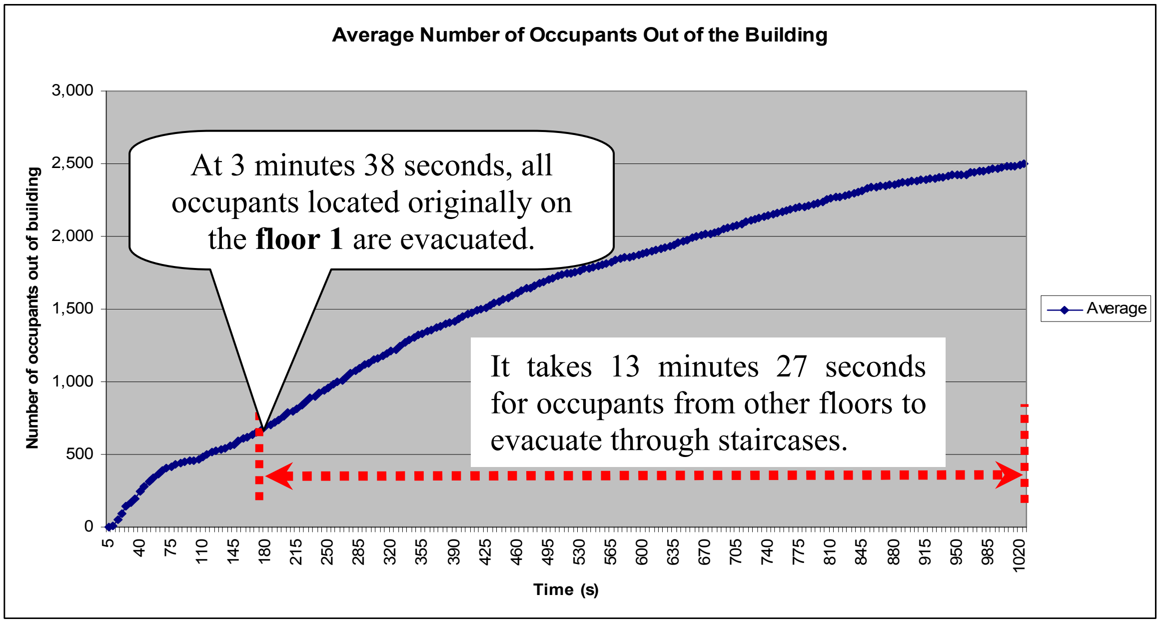


Figure 6-21: Cumulative plot of average quantity of agent which exit based on 15 simulation runs

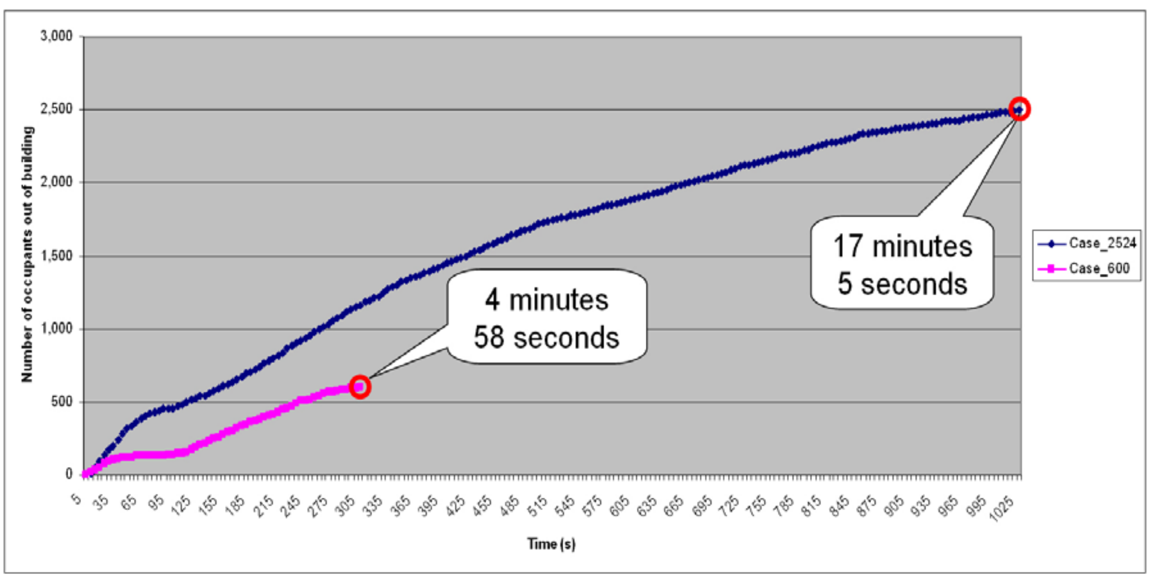


Figure 6-22: Comparison of egress time between 2524 and 600 occupants

6.4.3 Scenario Two: Evacuation Pattern Analysis

K-Means clustering algorithm is employed to draw evacuation patterns statistically for individual floors to assess current floor plan design capability to provide efficacious egress. The testing procedures are similar to those described in Chapter 5 (see Section 5.5). Six test locations are randomly selected for each floor, and a test agent is assigned to each location. Ten simulations are conducted for each location with fully occupied floor plans, and the escape trajectories of the 'test' agents are recorded during the simulations. K-Means clustering algorithm is executed to classify recorded trajectory points into clusters represented by a set of centroids. The size of each centroid reflects the number of trajectory points that the centroid contains.

Simulation results can demonstrate the areas that may potentially become congested during evacuation. Figure 6-23 shows the plot of resultant centroids based on multiple simulations conducted for the second floor of the building, where the potential congested areas have been identified. A general observation based on Figure 6-23 suggests: (1) crowd flow can be hindered in the middle of the corridor between the east and west staircases, and (2) it would be desirable for the corridor at area A be widen to allow efficacious crowd flow. The plots of resultant centroids for other floors are shown in Figure 6-13, Figure 6-14, and Figure 6-15. A general observation based on these plots is that the corners of long corridors and staircase entry areas may potentially become congested during a building evacuation.

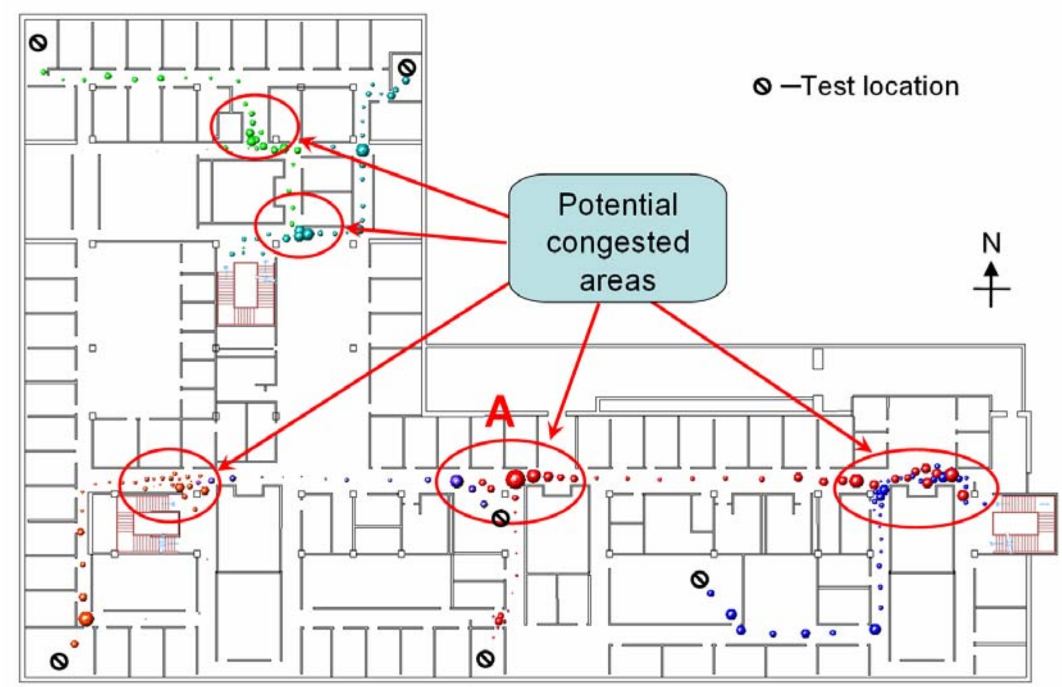


Figure 6-23: Evacuation patterns drawn from multiple simulations for the second floor

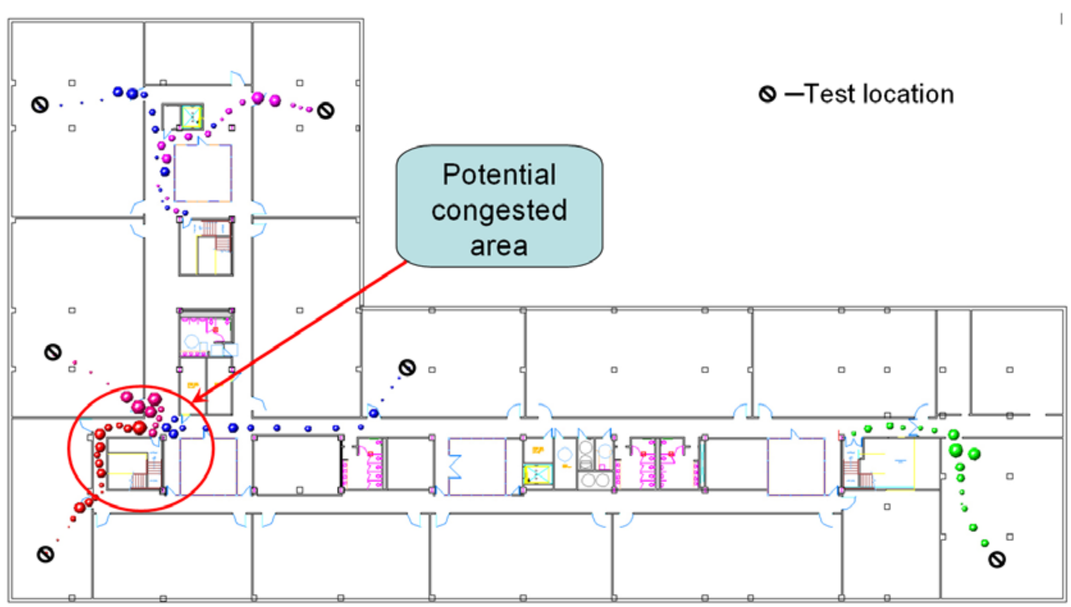


Figure 6-24: Evacuation patterns drawn for the basement

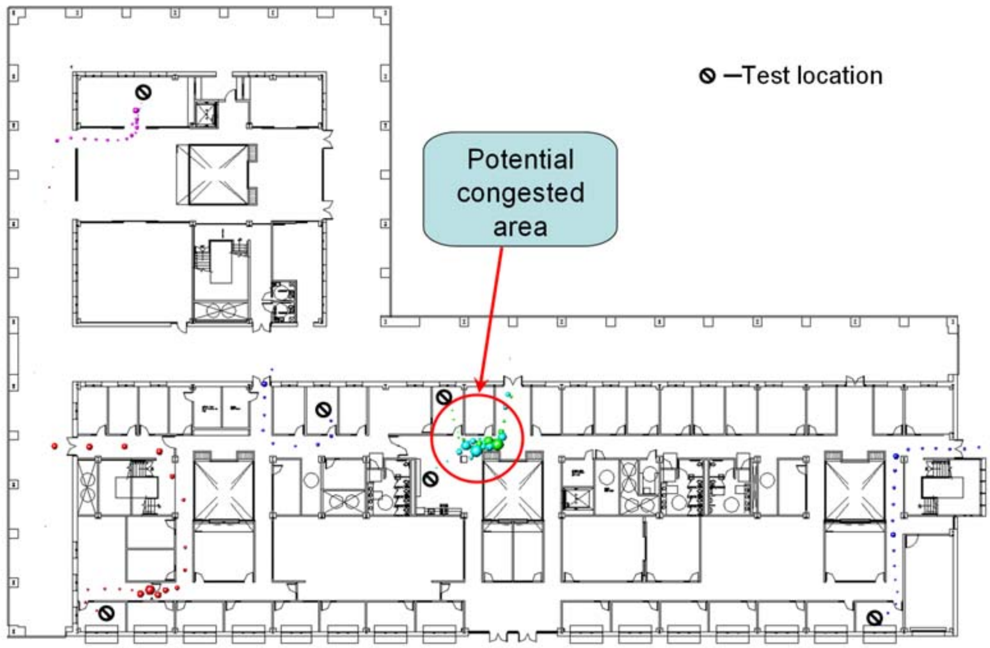


Figure 6-25: Evacuation patterns drawn for the first floor

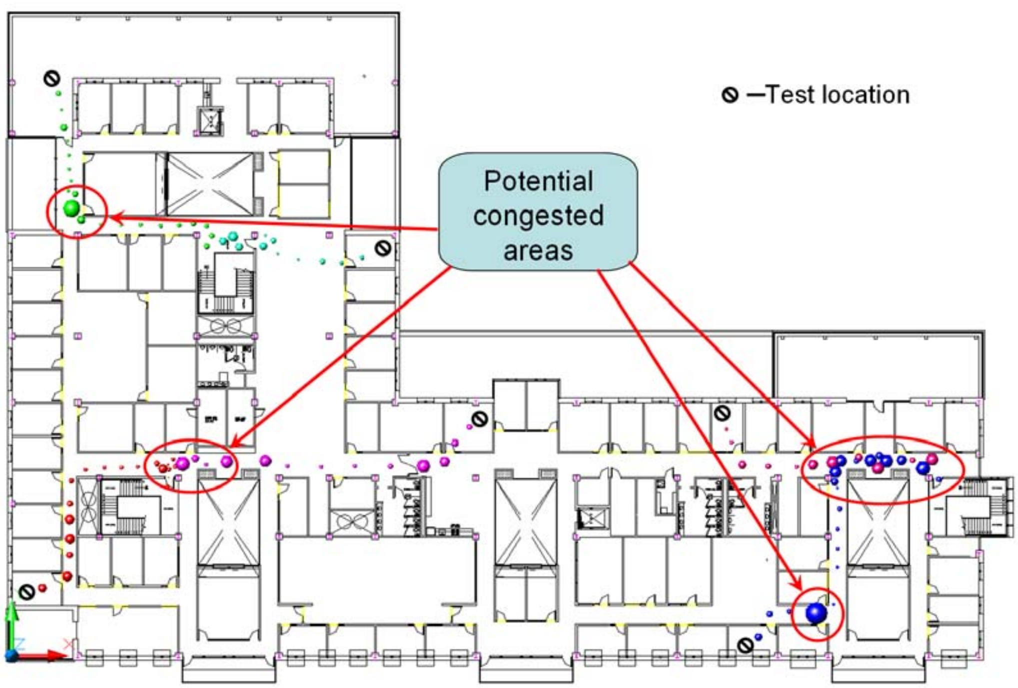


Figure 6-26: Evacuation patterns drawn for the third floor

6.5 Summary

In this Chapter, a set of experimental tests has been selected, conducted, and presented to validate MASSEgress.

Crowd Flow Rate tests against various exits were conducted to compare MASSEgress results with those of Simulex, an extensively validated evacuation model. While modeling principles of MASSEgress and Simulex differ significantly, simulation results of this particular test are similar. Additional tests were conducted with MASSEgress which appear to support increased value in evacuation model ability to simulate varying human behaviors.

MASSEgress was used to simulate a historical event of the fatal fire at the Rhode Island Nightclub. The simulation results are consistent with the observations reported by NIST. MASSEgress was also utilized to conduct simulations to determine the minimum time required to evacuate the Nightclub; the results are compared with those using Simulex and buildingEXODUS.

MASSEgress was applied to design analysis for a four-story university building. It is demonstrated that the simulations can potentially identify the possible congested areas and such performance-based analysis may be beneficial to test a design plan even though the plan is in compliance with the prescriptive building code.

Chapter 7

Conclusions

7.1 Summary

The goals of this dissertation are to investigate human and social behavior in emergency situations and to integrate them into a dynamic computational model suitable for building egress analysis. The objectives include:

1. To research and document human individual and social behaviors in emergency situations;

2. To develop a computational framework that can model some aspects of human individual and social behaviors for egress analysis.

Results of the first objective have led to the development of a theoretical framework that examines human and social behaviors at three interdependent levels: individual, interaction among individuals, and group. At an individual level, the framework illustrates how evacuees make decisions during emergencies. Individual behavior at this level can be viewed as the outcome of individual's decision-making processes. Evacuee decision-making generally follows three conventions: instinct, experience, and bounded rationality. Individuals may shift decision-making conventions during emergencies depending on the level of stress being experienced. High stress levels may drive individuals to act on instinct, which can result in nonadaptive behavior.

At the level of interaction among individuals, social identity, personal space and social proof influence evacuation behavior. Perceived emergencies can drive evacuee to not comply with the social identities that normally regulate his/her usual behavior and to act non-socially. This includes intrusion upon the personal space of others, which can result in competitive behaviors. Individuals in highly uncertain and stressful situations tend to follow others blindly to seek social proof (i.e., to follow what the most people do), which can result in herding behaviors during egress.

At a group level, nonadaptive crowd behavior can occur when a crowd holds the characteristics of high crowd density, severe environmental constraint, and high emotional arousal. The emotional arousal may or may not be related to an actual emergency.

Results of the second objective include design and implementation of MASSEgress, a computational framework capable of modeling human behavior for emergency egress analysis. MASSEgress consists of six basic modules: a Geometric Engine, a Population Generator, a Global Database, a Crowd Simulation Engine, an Events Recorder, and a Visualizer. Such modular design provides flexibilities to the actual implementation of each module. For example, Geometric Engine is currently implemented in LISP language running in an ADT (Architectural Desktop) environment, while Crowd Simulation Engine is written in C++.

MASSEgress adopts a multi-agent based simulation paradigm in which individuals are represented as virtual agents. Agents sense their environments and situations, make decisions, and act according to their pre-programmed behavior models. Social behavior is simulated through modeling individual agent behavior and social interactions among agents. Such a framework allows integration of psychological and sociological characteristics into agent decision-making processes. MASSEgress is able to simulate a set of commonly observed human social behaviors during evacuation, such as herding, queuing, and competitive behaviors, and to simulate evacuation of multi-story buildings which in some cases contain thousands of individuals. MASSEgress also is able to simulate how diverse human behaviors and stress levels can affect an evacuation, and the results are consistent with observations in real situations. In addition, by design, the framework facilitates incorporation of additional behaviors into the system. MASSEgress is also able to track individual and overall egress time and generate crowd density maps. A statistical method has been developed to draw evacuation patterns from multiple simulation runs.

Initial validation of MASSEgress includes: (1) comparison of simulation results with results obtained by other evacuation models which have been extensively validated (Simulex and buildingEXODUS); (2) use of MASSEgress to simulate replication of an historical case evacuation (Rhode Island Nightclub Fire); and (3) application to facilitate egress design analysis for a relatively large multi-story building. Validation results indicate promising potential of MASSEgress, with applications to a broad range of engineering analysis scenarios.

7.2 Future Directions

Incorporation of physics-based human modeling into MASSEgress constitutes a potential additional research focus. The dissertation emphasizes incorporation of psychological and sociological characteristics into human egress modeling rather than physics based modeling. Specifically, agent mass and agent movement moment of inertia are not yet incorporated into MASSEgress. Incorporation of physics based modeling might allow more accurate simulation of behavior during a more extensive range of scenarios. Extremely overcrowded situations and behavior such as pushing, falling, and trampling are examples.

Exploration and development of additional types of evacuation behavior models which incorporate characteristics of social and organizational interaction might enrich and extend the ability of MASSEgress to accurately simulate human behavior. Extension of MASSEgress behavior models may be of significant value not only to safety engineering, but also to the study of human behavior in general in such scientific fields as psychology and sociology.

Extension of agent sensing capability may represent another valuable direction for future research. MASSEgress agents are currently equipped with visual sensors to detect where exits are, but their capabilities can be expanded to detect other visual stimuli such as seeing people running can cause the increase of stress level. Human perception is based on receipt of information through other senses as well. Extended sensory capability which might be of value to MASSEgress could include, for example, ability to hear sirens, hear people screaming, smell and see smoke, smell burning objects, and detect temperature change. Extending the sensing ability of an agent can greatly enhance its potential to simulate more sophisticated human behaviors.

Integration of fire and smoke simulation into MASSEgress, and specifically integration of its perception on agent behavior may represent a useful future research focus. Many buildings are evacuated due to fire. Incorporation of fire and smoke could allow simulation of impact of their progression on individual and social behavior, and overall evacuation patterns, which could be of significant value, for example, to the field of fire safety.

Last but not least, further psychological and social studies are needed to better understand and to improve human and social behavior models for emergency evacuation. Equally important is to organize and structure these models suitable for implementation in a behavior-based computational framework such as MASSEgress.

Bibliography

AEA Technology, *A Technical Summary of the AEA EGRESS Code*, Technical Report, AEAT/NOIL/27812001/002(R), Issue 1, 2002. (Available at http://www.aeat-safety-and-risk.com/Downloads/Egress%20Technical%20Summary.pdf)

Ashcraft, N. and Scheflen, A., *People Space: the Making and Breaking of Human Boundaries,* Anchor Press, New York, 1976.

Aveni, A., "The Not-So-Lonely Crowd: Friendship Groups in Collective Behavior," *Sociometry*, 48:96-99, 1975.

Averill, J., Mileti, D., Peacock, R., Kuligowski, E., Groner, N., Proulx, G., Reneke, P., and Nelson, H., *Occupant Behavior, Egress, and Emergency Communications,* National Institute of Standards and Technology, Technical Report, NCSTAR 1-7, September, 2005.

Batson, C., "Self-other Merging and the Empathy-Altruism Hypothesis: Reply to Neuberg et al.," *Journal of Personality and Social Psychology*, 73:517-522, 1997.

Batson, D., "Altruism and Prosocial Behavior," in *The Handbook of Social Psychology*, Fourth Edition, Gilbert, D., Fiske, S., and Lindzey, G., (Eds), Mcgraw-hill Companies, pp. 282-316, 1998.

Berlin, G., "Modeling Emergency Evacuation from Group Homes," *Fire Technology*, 18(1):38-48, Feb. 1982.

Billings, R., Milburn, T., and Schaalman, M., "A Model of Crisis Perception: A Theoretical and Empirical Analysis," *Administrative Science Quarterly*, 25(2):300-316, 1980.

Braun, A., Musse, S., de Oliveira, L., and Bodmann, B., "Modeling Individual Behaviors in Crowd Simulation," *Proceedings of CASA: Computer Animation & Social Agents*, New Jersey, pp.143-148, May 2003.

Brogan, D. and Johnson, N., "Realistic Human Walking Paths," *Proceedings of Computer Animation and Social Agents (CASA)*, pp. 94–101, 2003

Brown, R., *Social Psychology*, Free Press, New York, 1965.

Bryan, J., "Human Behavior and Fire," In *Fire Protection Handbook*, 19th Edition, Vol.1, Cote, A. (Ed.), National Fire Protection Association, pp.4.3-4.32, 2003.

Chertkoff, J. and Kushigian, R., *Don't Panic: The Psychology of Emergency Egress and Ingress*, Praeger, London, 1999.

Cialdini, R., *Influence: The Psychology of Persuasion*, William Morrow, New York, 1993.

City of Cincinnati, *Crowd Management: Report of the Task Force on Crowd Control and Safety*, Technical Report, 1980. (Available at http://www.crowdsafe.com/taskrpt/whocrowdmanagementstaffandcontentspages.pdf)

Durkheim, E., *Elementary Forms of the Religious Life*, Free Press, New York, 1995. (Original publication, 1912)

Epstein, J., and Axtell, R., *Growing Artificial Societies: Social Science from the Bottom Up*, MIT Press, Cambridge, MA, 1996.

Eubanks, J. and P. Hill, P., *Pedestrian Accident Reconstruction and Litigation*, 2nd edition, Lawyers Judges Publishing Co, 1998.

Fahy, R., "EXIT89: An Evacuation Model for High-Rise Buildings," *Proceedings of the Third International Symposium in Fire Safety Science*, Elsevier Applied Science, New York, pp. 815-823, 1991.

Fire Safety Engineering Group, *BuildingEXODUS: the Evacuation Model for the Building Environment,* Sept. 2003. (Available at http://fseg.gre.ac.uk/exodus/air.html#build)

Fruin, J., *Pedestrian and Planning Design*, Metropolitan Association of Urban Designers and Environmental Planners, 1971.

Fruin, J., "Crowd Dynamics and Auditorium Management," *Auditorium News*, May 1984. (Available at http://www.iaam.org/CVMS/IAAMCrowdDyn.doc)

Galea, E., (Ed.), *Pedestrian and Evacuation Dynamics*, London, CMC Press, 2003.

Goldenstein, S., Karavelas, M., Metaxas, D., Guibas, L., Aaron, E., and Goswami, A., "Scalable Non-Linear Dynamical Systems for Agent Steering and Crowd Simulation," *Computers and Graphics*, 25(6):983–998, 2001.

Gottschalk, S., Lin, M., and Manocha, D., "OBB-Tree: A Hierarchical Structure for Rapid Interference Detection," *Computer Graphics*, Vol. 30, pp. 171-180, 1996.

Greenwood, T., *Guide to Fire Precautions in Existing Places of Entertainment and Like Premises*, Her Majesty's Stationary Office, London, 1990.

Grosshandler, W., Bryner, N., Madrzykowski, D., and Kuntz, K., *Report of the Technical Investigation of the Station Nightclub Fire*, National Institute of Standards and Technology, Technical Report, NCSTAR 2: Vol. I, 2005. (Available at http://www.nist.gov/public_affairs/releases/Vol_I_NCSTAR2.pdf)

Halcrow Group Limited, *Pedroute*, Sept. 2003. (Available at http://www.halcrow.com/pdf/ urban_reg/pedrt_broch.pdf)

Halperin, D. and Overmars, M.H., "Spheres, Molecules, and Hidden Surface Removal," *Computational Geometry: Theory and Applications*, 11(2): 83-102, 1998.

Helbing, D., Farkas, I., and Vicsek, T., "Simulating Dynamical Features of Escape Panic," *Nature*, 407:487-490, 2000.

Horiuchi, S., Murozaki, Y., and Hokugo, A., "A Case Study of Fire and Evacuation in a Multi-Purpose Office Building," *Proceedings of the First International Symposium on Fire Safety Science*, Hemisphere Publishing Corp., Washington, DC, pp. 523-532, 1986,

ICBO, "Means of Egress", *International Building Code*, Chapter 10, pp. 211-247, 2000.

Johnson, S., *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*, Simon & Schuster, New York, 2001.

Juillet, E., “Evacuating People with Disabilities,” *Fire Engineering*, Vol. 126, No. 12, pp. 100-103, Nov. 1993.

Kelley, H., Condry, J., Dahlke, A, and Hill, A., “Collective Behavior in a Simulated Panic Situation,” *Journal of Experimental Social Psychology*, 1:20-54, 1965.

Klote, J., *Feasibility and Design Considerations of Emergency Evacuation by Elevators*, National Institute of Standards and Technology, Technical Report, NISTIR 4870, 1992.

La Piere, R., *Collective Behavior*, McGraw-Hill, New York, 1938.

Latane, B., and Darley, J., “Group Inhibition of Bystander Intervention in Emergencies,” *Journal of Personality and Social Psychology*, 10(3):215-221, 1968.

Latombe, J., *Robot Motion Planning*, Kluwer Academic Publishers, Boston, 1991.

Lystad, M., *Mental Health Response to Mass Emergencies: Theory and Practice*, Brunner/Mazel, New York, 1988.

Le Bon, G., *The Crowd*, Viking, New York, 1960. (Original publication, 1895)

Legion International Ltd., *Legion*, Nov. 2004. (Available at http://www.legion.biz)

Low, D., “Following the Crowd,” *Nature*, 407:465-466, September 2000.

March, J., *A Primer on Decision Making: How Decisions Happen*, Free Press, New York, 1994.

McDougall, W., *The Group Mind*, Cambridge University Press, Cambridge, UK, 1920.

McPhail, C., *The Myth of the Madding Crowd*, Aldine de Gruyter, New York, 1991.

McPhail, C. and Wohlstein, R., "Collective Locomotion as Collective Behavior," *American Sociological Review*, 51: 447-463, 1986.

MacQueen, J., "Some Methods for Classification and Analysis of Multivariate Observations," *Proceedings of 5th Berkeley Symposium on Mathematical Statistics and Probability*, Berkeley, University of California Press, 1:281-297, 1967.

Mintz, A., "No-Adaptive Group Behavior," *Journal of Abnormal and Social Psychology*, 46: 150-159, 1951.

Musse, S., Babski, C., Capin, T., and Thalmann, D., "Crowd Modeling in Collaborative Virtual Environments," *Proceedings of ACM Virtual Reality Software Technology,* Taiwan, pp. 115-123, Nov. 1998.

Palmer, I. and Grimsdale, R., "Collision Detection for Animation using Sphere-Trees," *Computer Graphics Forum*, 14(2):105-116, 1995.

Pauls, J., "Movement of People in Building Evacuations," in *Human Response to Tall Buildings*, Conway, D., ed., Dowden, Hutchinson and Ross, Stroudsburg, PA, pp. 281-292, 1977.

Pelechano, N., O'Brien, K., Silverman, B., and Badler, N., "Crowd Simulation Incorporating Agent Psychological Models, Roles and Communication," *Proceedings of First International Workshop on V-Crowds*, Geneva, Switzerland, 2005.

Penn, A., "Vision, Configuration and Simulation of Static Interaction for Design," *Proceedings of 2nd International Conference: Pedestrian and Evacuation Dynamics*, pp. 1-16, 2003.

Proulx, G., "As of Year 2000, What Do We Know about Occupant Behavior in Fire?" *The Technical Basis for Performance Based Fire Regulations*, United Engineering Foundation Conference, San Diego, January 7-11, pp. 127-129, 2001.

Proulx, G., "Understanding Human Behaviour in Stressful Situations," *Workshop to Identify Innovative Research Needs to Foster Improved Fire Safety in the United States*, National Academy of Sciences, Delegate Binder Section 7, Washington, D. C., April 15-16, pp. 1-5, 2002.

Proulx, G. and Richardson, J., "The Human Factor: Building Designers Often Forget How Important the Reactions of Human Occupants Are When they Specify Fire and Life Safety Systems," *Canadian Consulting Engineer*, 43(3): 35-36, May 2002.

Proulx, G. and Sime, J., "To Prevent Panic in an Underground Emergency: Why Not Tell People the Truth? Fire Safety Science," *Proceedings of the 3rd International Symposium one Fire Safety Science*, Elesevier Applied Science, Newe York, pp 843-852, 1991.

Quarantelli, E., "The Nature and Conditions of Panic," *The American Journal of Sociology*, 60(3): 267-275, 1954.

Reynolds, C., "Steering Behaviors for Autonomous Characters," *Proceedings of Game Developers*, San Jose CA, March 15-19, pp. 763-782, 1999.

Santos G. and Aguirre, B., "A Critical Review of Emergency Evacuation Simulation Models," *Proceedings of Building Occupant Movement during Fire Emergencies*, Gaithersburg, Maryland, June 10-11, pp. 27-52, 2004.

Shields, T. and Proulx, G., "The Science of Human Behavior: Past Research Endeavors, Current Developments and Fashioning a Research Agenda," *Proceedings of the Sixth International Symposium on Fire Safety Science*, IAFSS, pp. 95-114, 2000.

Sime, J., "Perceived Time Available: The Margin of Safety in Fires," *Proceedings of the First International Symposium on Fire Safety Science*, Hemisphere Publishing Corp., Washington, DC, pp.561-570, 1986.

Sime, J., *Escape Behaviour in Fires: Panic or Affiliation?* PhD Thesis, Department of Psychology, University of Surrey, England 1984.

Sime, J., "Crowd Psychology and Engineering: Designing for People or Ballbearings?" *Proceeding of International Conference on Engineering for Crowd Safety*, London, March 17-18, pp. 119-132, 1993.

Sime, W., *Stress Management: A Review of Principles*, 1997. (Available at http://www.unl.edu/stress/mgmt/)

Simon, H., *Models of Bounded Rationality*, MIT Press, Cambridge, MA, 1982

Simulex (software), Version 11.1.3, Integrated Environmental Solutions Ltd., 1998.

Smelser, N., *Theory of Collective Behavior*, Free Press, New York, 1963.

Society of Fire Protection Engineers, *Engineering Guide to Human Behavior in Fire*, Technical Report, August 2002.

Sommer, R., *Personal Space: The Behavioral Basis of Design*, Englewood Cliffs, New Jersey, Prentice-Hall International, 1969.

Stahl, F., *Simulating Human Behavior in High-Rise Building Fires: Modeling Occupant Movement Through a Fire Floor from Initial Alert to Safety Egress,* Center for Fire Research, National Bureau of Standards, Technical Report, NBS-GCR-77-92, Washington, DC., 1975.

Still, G., *Crowd Dynamics*, Ph.D. thesis, University of Warwick, UK, 2000.

Thompson, P., Lindstrom, H., Ohlsson, P., and Thompson, S., "Simulex: Analysis and Changes for IMO Compliance," *Proceedings of 2nd International Conference: Pedestrian and Evacuation Dynamics*, pp. 173-184, 2003.

Thompson, P. and Marchant, E., "Testing and Application of the Computer Model 'Simulex'," *Fire Safety Journal*, 24:149-166, 1995.

Tu, X., *Artificial Animals for Computer Animation: Biomechanics, Locomotion, Perception, and Behavior,* Ph.D Dissertation , Department of Computer Science, University of Toronto, 1996.

Tucker, C., Schweingruber, D. and McPhail, C., "Simulating arcs and rings in gatherings," *International Journal of Human Computer Studies*, 50(6): 581-588, 1999.

Welford, A., “Stress and Performance,” in Man under Stress, Welford, A. (Ed.), *Proceedings of the 9th Annual Conference of the Ergonomics*, Society of Australia and New Zealand, August 24-25, pp.1- 41, 1972.

Wills, R., *Human Instincts, Everyday Life, and the Brain*, (Volume One), the Book Emporium, Canada, 1998.