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for Egress Analysis  
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By

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# **A Computational Framework for Egress Analysis with Realistic Human Behaviors**

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**Abstract:** Studies of past emergency events indicate that evacuating occupants often exhibit social behaviors that affect the evacuation process. This paper describes a multi-agent based simulation tool which enables the modeling of social behaviors during evacuation. In this modeling framework, each agent has a three-level representation that allows users to incorporate individual, group, and crowd behavioral rules in simulation. This paper describes the basic framework and the implementation of several social behaviors, which are based on recent social science studies about human response in emergency situations. Simulation results from the prototype reveals that social behaviors exhibited by the evacuating crowd can lead to changes in the overall egress time and pattern. By representing the virtual agents and the environment specific to evacuation situation, the research addresses the issues in incorporating human and social behaviors in egress simulation.

**Keywords:** Agent-based simulation; Emergency evacuation; Human factors; Decision-making; Design; Human and social behaviors

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## **1. Introduction**

Emergency evacuation (egress) is an important aspect in building and facility design. Safe egress design is particularly crucial in today's facilities, such as office towers and shopping malls, with high occupant capacity and complex floor layouts. Besides design standards and codes of practice (ICBO, 2009), computer simulation programs are often used to assess the building's egress performance. Although many simulation tools are now available, there is still a dire need to "*improve the realism and accuracy of crowd behaviors and movement, in addition to improving visual aesthetics [in existing simulation tools]*" (Challenger et al., 2009). The lack of realistic social behavior in current simulation tools has also been echoed by authorities in fire engineering and social science (Aguirre et al., 2011b, Gwynne et al., 2005, Santos and Aguirre, 2004). Our research aims to develop an egress simulation framework that can incorporate social behavioral theories related to crowd dynamics and emergency evacuations. The framework is designed to facilitate the generation of different agent profiles and behavioral rules for diverse populations. This paper describes the system framework and the features currently incorporated in the prototype. Through implementing several well-studied social behaviors in the prototype model, we study the effects of such social behaviors on an evacuation scenario based on the historical fire accident at the Station Nightclub in Warwick, Rhode Island (Grosshandler et al., 2005).

## **2. Literature Review**

### **2.1. Social behaviors in emergency situations**

Social scientists and disaster management researchers have been studying human behaviors in emergency situations and have developed a variety of theories about crowd behaviors in emergency situations. A comprehensive review of various social theories about crowd behaviors has recently been reported by Challenger et al. (2009). Examples of prevalent theories on crowd behaviors include the panic theory (Le Bon, 1960), the decision-making theory (Mintz, 1951),

the normative theory (Aguirre et al., 2011; McPhail, 1991; Turner and Killian, 1987), the affiliative theory (Mawson, 2005; Sime, 1983), and the place script theory (Donald and Canter, 1990). Earlier theories in crowd behavior suggest that people tend to behave individually and show non-adaptive behaviors in dangerous situations. For example, the panic theory suggests that people become panicked in an emergency situation and act irrationally. In contrast, the decision-making theory argues that people act rationally to achieve a better outcome in the situation. Recent theories, on the other hand, emphasize the sociality of the crowd (such as pre-existing social relationships or emerging identity during an emergency situation) in explaining the occupants' reactions in past accidents. For example, the normative theory stresses that the same social rules and roles that govern human behavior in everyday life are also applicable in emergency situations. The affiliative theory and place script theory further emphasize the importance of past experience, social relationships, and roles on people's reactions in emergencies. Although there is no unified theory which fully explains human behavior in different emergency situations, recent theories stress that evacuating crowds retain their sociality and behave in a socially structured manner.

Different social theories explain human behaviors in emergencies using different mechanisms and variables. In order to systematically study different social theories and incorporate them into a computational framework, we classify the theories into three behavior categories; namely, individual, group, and crowd.

- *Individual:* Individual behaviors are often the results of *personal knowledge and experience*. In an emergency situation, individuals refer to their past experience and knowledge to decide on their actions. For examples, the affiliative theory and place script theory examine individuals' behaviors in emergencies based on their knowledge and familiarity with the place. According to the affiliative theory, people's emergency response depends on their familiarity of the surroundings and the knowledge about the severity of the situation (Mawson, 2005; Sime, 1983). When individuals are close to their familiar figures or located in familiar place with the perception of low physical danger, people tend to downplay the seriousness of the situation and delay evacuation. Otherwise, even mild environmental threats could initiate people's flight action to seek familiar objects. The place script theory

highlights the importance of a normative “script” that guides people’s reaction in emergency events (Donald and Canter, 1990). The ‘script’ may include one’s knowledge of his/her role, the daily norms of the place and the environment. Generally speaking, these social theories suggest that individuals derive their actions based on personal knowledge, experience, perceptions, and routines.

- *Group*: Group behaviors depend on *group structure* and *group norms*. People often participate in mass gatherings with their social group. The social group has its own pre-existing social structure (relations between group members) and group norms (expectations of each other's behavior) that may affect the behavior of an individual. There are several recent social theories that examine the effect of groups on individuals during emergency situations, examples of social theories on group effects are the emergent norm theory (Aguirre et al., 1998; McPhail, 1991) and the pro social theory (Aguirre et al., 2011a). The emergent norm theory suggests that people interact with their social group to assess the evolving situation and derive solutions collectively (McPhail, 1991). Group characteristics, such as group size and the kind of relationship, are significant factors that affect the interaction and the emergence of collective definition of the situation (Johnson et al., 1994; Kuligowski, 2011). For example, enduring social relationships can facilitate the process of recognizing the threats and initiate early evacuation (Aguirre et al., 1998). Furthermore, the pro social theory emphasizes the group process and the solidarity of social group in an emergency situation (Aguirre et al., 2011a). Based on their empirical study of the Station Nightclub Fire incident, Aguirre et. al. (2011a) found that people put themselves at risk in search for others dearing to them even in a rapidly developing emergency situation. In other words, people continue to maintain the group structure and behave in a pro social manner during emergencies.
- *Crowd*: Crowd behaviors are *emergent* phenomena and often follow *social norms*. Mass gathering events (such as concerts, demonstrations, theme parks, etc.) typically compose of small groups and non-socially bonded individuals. The interactions among the individuals and groups can greatly affect the collective actions during emergencies. For example, the social identity theory suggests that people have a tendency to categorize themselves into one or more "in-groups," building their identity in part on their membership in the groups and enforcing boundaries with other groups (Drury et al., 2009). Increasing threats would

intensify the sense of “we-ness” within the crowd, and the emerging collective identity motivates people’s social behavior, such as mutual assistance among strangers in dangerous situations. Moreover, past accidents studies have shown that people exhibit altruistic behaviors among people who are not socially bonded as they continue to respect the social norms that operate in daily situation (Averill et al., 2005; Drury et al., 2009; Johnson et al., 1994). In general, people in emergencies continue to maintain their social awareness and follow social norms.

As is evidenced from the selected prevailing social theories on human behaviors, social characteristics of individuals play an important role in determining their behaviors during emergencies. We conjecture that human behaviors in egress are influenced at three levels: individual experience, social group, and crowd interactions. The staged representation of social effects forms the basis in the design of our egress simulation framework.

## **2.2. Egress simulation models and human behaviors modeling**

There exists an extensive literature on modeling crowd movement in virtual environment. We classify different modeling approaches based on the system’s virtual representation of the building environment and the occupants. The three most common approaches are the particle systems, cellular automata and agent-based systems.

- Particle systems consider each individual in the crowd as self-driven particle subject to social and physical forces. One well-known example of this approach is the social force model (Helbing et al., 2000), which represents evacuees’ movement based on repulsive and attractive forces due to external factors and internal motivations. Moussaïd et al. (2011) extends the formulation of the social force model by adding forces reflecting heuristics based on visual information.
- In a cellular automata system, the environment is divided into a uniform grid of discrete cells, representing floor areas, obstacles, areas occupied by people, or other relevant

attributes, such as exits and doors. Individual moves to unoccupied neighboring cells based on defined rules. Being computationally efficient, many simulation systems such as buildingEXODUS (Gwynne et al., 2005), AEA EGRESS (Ketchell et al., 1996), and Simulex (Thompson and Marchant, 1995) are implemented using this approach.

- Agent-based systems model the crowd as a collection of autonomous entities known as “agents”, representing the occupants in the environment. It allows emergent phenomena as a result of interactions of virtual agents. In the recent years, many egress models have adopted this approach and have different representations of the agents and the virtual environment. One example is the HiDAC model (Durupinar et al., 2011) which parameterizes virtual agent based on individual personality in order to mimic human behaviors in normal and panic situations. ViCrowd (Musse and Thalmann, 2001) is another agent-based model built to simulate virtual crowds with user-specified or default behavioral rules.

As noted in the detailed review by Kuligowski and Peacock (2005), there have been a wide variety of computational tools available for egress simulation. However, human and crowd behaviors are often ignored and group effects on evacuation pattern are seldom explored in current tools (Challenger et al., 2009; Aguirre et al., 2001b). Only recently have efforts been attempted to incorporate social behaviors into egress simulations. For example, Gwynne et al. (2005) developed the social adaptation mechanism in an egress simulation program. The mechanism considers the social effect at three stages: formulation (the generation of the collective), communication (the provision of relevant data), and adaptation (the selection of an appropriate response of individuals). In their study, Gwynne et al. (2005) conclude that the effect of social behaviors cannot be underestimated in egress simulations. Aguirre et al. (2011b) describe the use of an agent-based simulation model which attempts to implement the pro social model in simulating emergency evacuations. Features such as roles of leader and followers among a group of agents are implemented to provide a means to simulate population at a group level and observe emergent pattern as a result of social relationships.

Due to the high variability of human behaviors in different situations, a single behavioral theory may not be sufficient to explain the response of people in different emergency scenarios. A



flexible simulation platform, which can account for various social theories in different emergency scenarios, is therefore desirable. The ability to model social behavioral theories in a computational program not only provides more realistic simulation results, but also provides a means to test and validate the corresponding behavioral theories.

### 3. A computational simulation framework for modeling social behaviors

This work extends a multi-agent based simulation framework, MASSEgress (Pan, 2006), which is designed to model human and social behaviors in emergency evacuations. MASSEgress has demonstrated the ability of a multi-agent based approach for simulating some common emergent social behaviors such as competitive, herding and queuing behavior. In the following sections, we first provide an overview of the simulation framework and describe each major component of the system. We then discuss the parameters used to model human behaviors in egress, followed by the methodology used to model occupants' behaviors in an emergency situation.

#### 3.1. System architecture

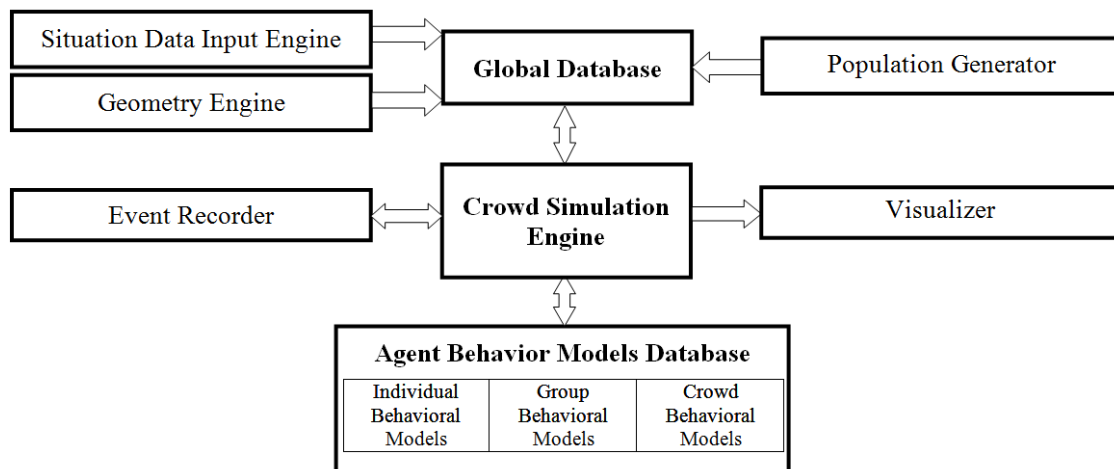


Figure 1. Overall architecture of the framework

Figure 1 schematically depicts the system architecture of the multi-agent based simulation framework. The Global Database, Crowd Simulation Engine, and Agent Behavior Models Database constitute the key modules of the framework and are supported by a set of sub-modules, namely, Population Generator, Geometric Engine, Situation Data Input Engine, Event Recorder, and Visualizer.

- The Population Generator receives input assumptions of the agent population and generates the agents using a distribution of age, mobility, physical size, and other human and social factors. According to the agent's definition, each agent is assigned with its physical and behavioral profile. This module can also generate both pre-defined and random social groups to study different human and social behaviors.
- The Geometric Engine maintains the spatial information, such as the physical geometry, exit signs, and openings about a facility. A virtual 3D model is built based on the spatial information and is used for collision avoidance and agents' perception, as well as for simulation visualization.
- The Situation Data Input Engine contains the properties of emergency cues and threats, such as fire alarms, smoke, and fire, which the virtual agents perceive during the simulation.
- The Global Database stores all the information about the agent population, the physical geometries, and the status of emergency situations. It maintains the state information (such as mental tension, behavioral decisions, locations, etc.) of the agents. The database is also used to support interactions and reactions among the individuals and groups.
- The Event Recorder stores the simulation results at each time step for playback. The results can be retrieved for further analysis, such as identifying congestion areas and exit usages. The events captured can also be used to compare with known and archived scenarios.
- The Visualizer, currently implemented using OpenGL, receives the positions of agents and then dynamically generates and displays simulation results as 2D/3D visual images.
- The Agent Behavior Models Database contains the individual, group, and crowd behavioral models. In our prototype, we have defined a set of default models that an agent can choose for decision making. New behavioral models can be created and included in addition to the default models to investigate a wider range of behaviors under different scenarios.

- The Crowd Simulation Engine is the key module of the system. The crowd simulation engine interacts closely with the Global Database and the Agent Behavior Models Database. It keeps track of the simulation and records and retrieves information from the Global Database. The simulation follows a perception-interpretation-action paradigm. At each time step, an agent perceives the information about the situation, interprets the information, chooses behavioral models, and executes the decision through its movement. The generated results are sent to the Event Recorder and Visualizer.

The modular simulation framework allows investigation of crowd dynamics and incorporation of different behavioral models. Diverse populations of individuals and groups can be modeled and emergent collective behaviors can be simulated.

### **3.2. Agent representation**

In the simulation system, each individual is modeled as an autonomous agent who interacts with the dynamic environment and other agents. Agents are defined by their population type, experience profile, group affiliation, and social traits, and is equipped with sensors for perception and actuators for executing the decisions.

- Population type: Human individuals differ from each other by their physical traits and demographics. Instead of modeling each individual, an agent is assigned to one of the five categories: median, adult male, adult female, child, and elderly (Thompson and Marchant, 1995). Each of the five categories represents one typical human population and has distinct physical characteristics. In each population type, the parameters used to define the agent are *age*, *gender*, *body size*, and *travelling speeds*.
- Individual experience profile: Past experience has a profound effect on people's evacuation actions in threatening situations (Mawson, 2005; Donald and Canter, 1990; Kuligowski, 2011; Sime, 1983). It is important to define a virtual agent with relevant "history" to model the reasoning and decision-making process of humans more realistically. In the current prototype, each agent is defined with an experience profile

which describes its level of *familiarity with the building* prior to the event and the exits that the agent has knowledge of (*known exits*), such as the entrance used. The parameters that instantiate the experience profile are *familiarity with the building* and *known exits*.

- Group membership: Individuals interact with their social groups to make decisions in emergencies (Aguirre et al., 1998; 2011a; Johnson et al., 1994; McPhail, 1991). We model the group effect by assigning agents to affiliate with one or more social groups. Within the same group, the member agents share the same group profile which describes the existence of a *group leader*, the kind of group relationship and the *group intimacy level* (for example, family group will have a high *group intimacy level*), the *group seeking* property that describes the willingness for the group to search for missing members, and the *group influence* between a group member and the others in the same group. The parameter used to link an agent to a group is *group affiliation*, and a social group is characterized by its *group leader*, *group intimacy level*, *group seeking*, and *group influence* between members.
- Social traits: Even in situation which individuals are not socially bonded to others in an emergency, they will still be influenced by their surrounding crowd and act in a social-orderly manner (Averill et al., 2005; Drury et al., 2009; Johnson et al., 1994). We define the social position of an agent with the parameter *social order*, which measures how other agents would respect the individual agent. For example, other agents would give access priority to the agent with higher *social order* by allowing the individual agent to pass through, and therefore, the agent with higher *social order* can navigate a congested area more easily.
- Sensors: An agent can detect the physical environment, other agents, cues, and threats with sensors. The information perceived includes: (1) floor objects such as windows, door exit signs, and assembly locations; (2) nearby agents within a certain radius; (3) visible agents in the same social group; and (4) locations and properties of cues and threats, such as alarms and fire. As the agent perceives the environment, it updates internally the parameters *visible objects*, *visible group members*, and *threat objects*. Moreover, when executing the decision, an agent can detect physical collisions and recognizes the location and the type of object it collides with. The information received from sensors is utilized by an agent to make navigation decisions.

- **Actuators.** Actuators of an agent refer to its faculties of being able to walk, run, stop, and change navigation direction. These faculties are the basic locomotions of an agent to maneuver in a virtual environment.

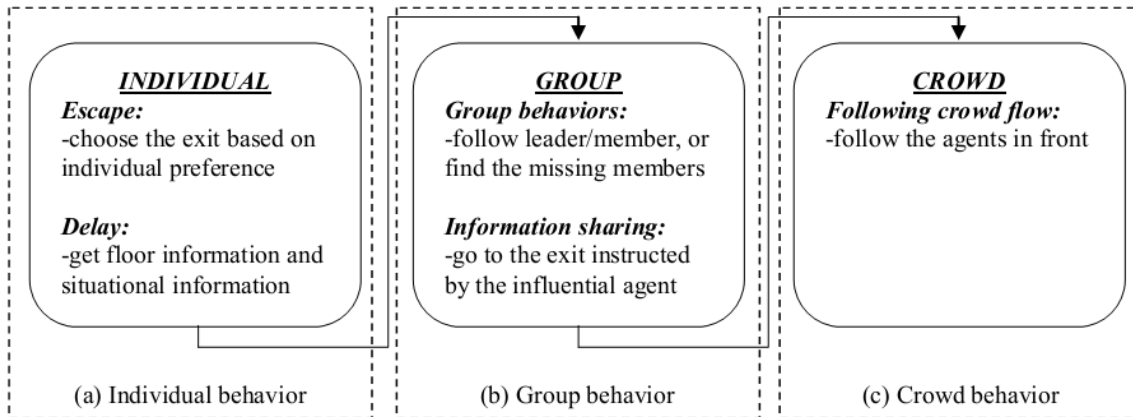


Figure 2. The decision-making process at the individual, group, and crowd level

An agent behavioral model consists of three basic components; namely, perception, decision-making and execution. At each step, an agent updates its perceived environmental information and the social information about its group(s) and the surrounding crowd. Based on the perceived information and its behavioral profiles, an agent chooses a behavior among the different behaviors at individual, group and crowd level. As shown in Figure 2, the agent's decision-making process is staged, moving from individual level, then to the group, and finally to the crowd level. At the beginning of the decision making process, agent's individual behavior is used as the base decision. For example, an individual agent can choose to escape through the preferred exit or to delay the evacuation. If the agent is affiliated to at least one of the social groups, the agent proceeds to consider group level behaviors, such as following or seeking other group member(s). Furthermore, if the agent detects any neighboring agents, the agent proceeds to consider crowd level behaviors, such as following the crowd. After reasoning through the individual, group and crowd level behaviors, the agent selects a final behavior and defines a specific target. At the execution level, the agent navigates towards the goal with low-level locomotion. Each potential move is assigned with a value based on the heuristics about the

target distance, interpersonal distances, and obstacle avoidance. The agent then executes the optimal move associated with the largest value.

#### **4. Implementing social behaviors in simulation framework**

Behavioral models that consider social relationships and hierarchy among people during emergencies, as identified in crowd disasters literature and social science studies, are selected to illustrate the current prototype implementation.

##### **4.1. Group behaviors**

Studies have shown that people belonging to the same group tend to evacuate as a group and escape through the same exit, even during emergency situations (Aguirre et al., 2001b; Donald and Canter 1990; Mawson, 2005; Sime, 1983). There are several typical group behaviors that can be observed. For example, in a highly hierarchical group, people follow their group leader when making decision and navigating the floor (Averill et al., 2005; Kuligowski, 2011). Moreover, members tend to stay close to each other and navigate as a group (Aguirre et al., 2001a; Sime, 1983; Mawson, 2005). When there are group members missing, other members in the group also attempt to search for the missing members. In the current prototype, we implement three typical group behaviors, namely, leader following, group member following, and group member seeking. Each of these behaviors is defined by a set of decision rules, as shown in Table 1. We organize the behavioral rules into three levels, namely, individual, group, and crowd. Parameters that define the group membership of the agent and perceived information from sensors are used in testing the conditions of the decision rules:

- Group membership: *group affiliation, group leader, group intimacy level, group seeking, group influence*

- Perceived information: *neighboring agents, visible group members*

Table 1. Process of group behaviors

<b>PERCEPTION</b>			
1. Detect <i>visible group members</i>			
2. Detect <i>neighboring agents</i>			
<b>DECISION- MAKING</b>			
Individual level →	Group level →	Crowd level →	Target
<b>Leader following</b>			
<ul style="list-style-type: none"> <li>• The agent is not a <i>group leader</i> of its <i>affiliated group</i></li> <li>• <i>Group leader</i> of its <i>affiliated group</i> is visible</li> </ul>	<ul style="list-style-type: none"> <li>• The <i>group influence</i> of <i>group leader</i> is &lt;HIGH&gt;</li> <li>• Separation distance between the <i>group leader</i> and the agent is larger than &lt;NEAR&gt;</li> </ul>	<ul style="list-style-type: none"> <li>• Crowd density of <i>neighboring agents</i> is &lt;LOW&gt;</li> </ul>	<i>Group leader</i>
<b>Group member following</b>			
<ul style="list-style-type: none"> <li>• The agent is not a <i>group leader</i> of its <i>affiliated group</i></li> <li>• There exist(s) <i>visible group member(s)</i></li> </ul>	<ul style="list-style-type: none"> <li>• The <i>group influence</i> of all <i>visible group members</i> are the same</li> <li>• Average separation distance among <i>visible group member</i> and the agent is larger than &lt;NEAR&gt;</li> </ul>	<ul style="list-style-type: none"> <li>• Crowd density of <i>neighboring agents</i> is &lt;LOW&gt;</li> </ul>	<i>Visible group member</i> nearest to the agent
<b>Group member seeking</b>			
<ul style="list-style-type: none"> <li>• The agent is a <i>group leader</i> of its <i>affiliated group</i></li> </ul>	<ul style="list-style-type: none"> <li>• Percentage of <i>visible members</i> is less than &lt;<i>group seeking</i>&gt; of the <i>affiliated group</i></li> </ul>	<ul style="list-style-type: none"> <li>• Crowd density of <i>neighboring agents</i> is &lt;LOW&gt;</li> </ul>	Exploring floor

(< > denotes parameter values defined by users)

At the perception stage, an agent detects any *visible group members* and the *neighboring agents*. Next, at the decision-making stage, an agent reasons through the rules at the individual, group and crowd level successively for each behavioral model and consider the model with all the conditional rules satisfied. Finally, if the agent is closely affiliated with a social group (its *affiliated group* has a high *group intimacy level*) such that the group behavior has a high priority, the agent will make decision to set its navigation targets as following group leaders, following other group members, or explore randomly, according to the specification in the selected behavioral model.

Figure 3 illustrates a simple simulation scenario for the group member seeking behavior. The figure shows the trajectories of a group of six agents with high *group seeking* value (i.e., the group has to find all the members before searching for exit signs). Initially, the group members

are separated with the circled member missing (Figure 3a). To seek the missing member, the group explores the floor instead of proceeding to the exit (Figure 3b). Only when all members are visible, the group then starts to leave and go towards the same exit (Figure 3c). By adjusting the *group intimacy level* and *group seeking* of the social group, we can simulate different types of groups with different levels of group following intention and their desires to look for other members. In other words, implementing group behaviors in egress simulation would affect the evacuation time and the escape route of the entire group, depending on the initial distribution of the group members and their relationship.

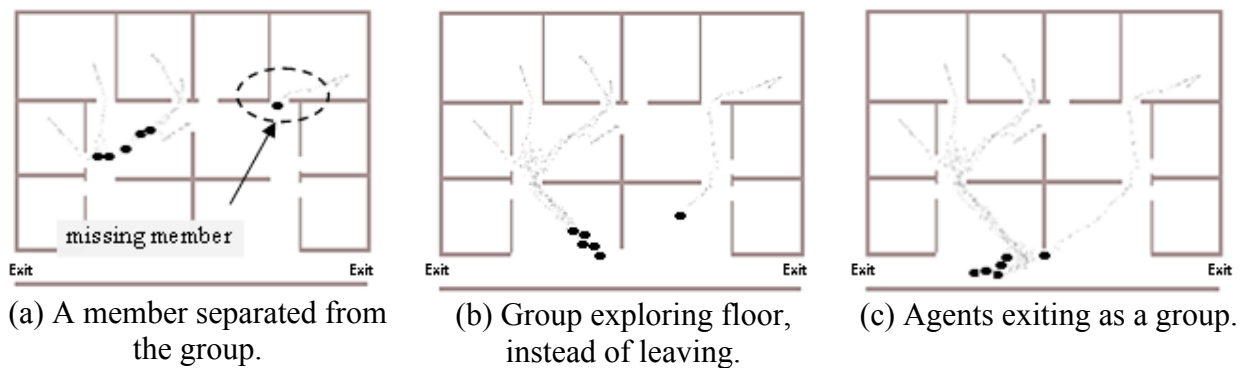


Figure 3. Screenshots showing group member seeking behavior

Another commonly observed group behavior is the interaction and the sharing of information among group members during emergency situations (Donald and Canter, 1990; Kuligowski, 2011; Turner and Killian, 1987). While individuals in the same group may have different interpretations of a situation, their roles in the group can influence others' evacuation decisions. Our model implements the group members' influence on an agent's exit route choice as a three-step process: (1) upon deciding an exit according to individual preference, the agent shares the information about the exit (*known exits*) with other group members; (2) the agent weights the different pieces of exit information shared by other members on the basis of each member's influence defined using the parameter *group influence*; (3) the agent may or may not follow the direction to the most-weighted exit, depending on the influence of the information-sharing agent.



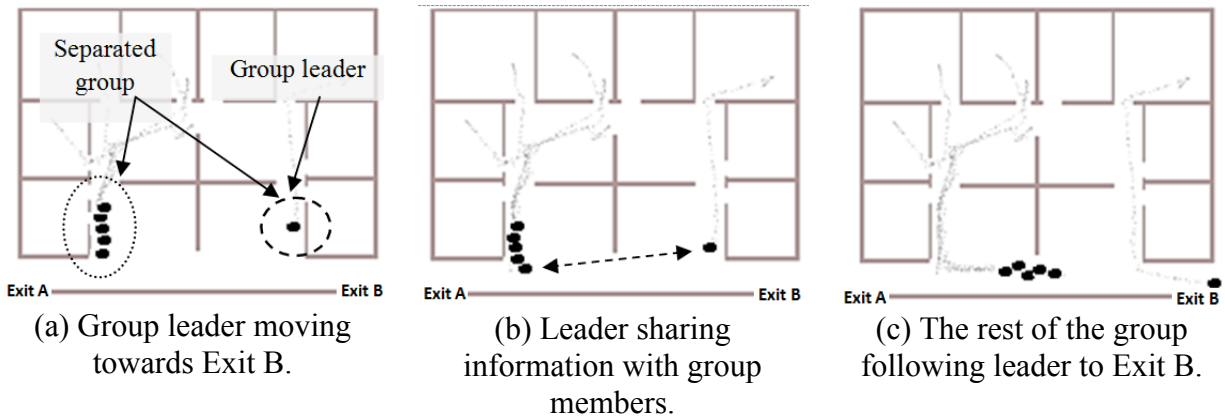


Figure 4. Screenshots showing group influence process

Figure 4 shows an example of information sharing and group influence behavior. In this example, the group is initially separated from their leader and the members intend to go to the nearest exit (Figure 4a). When the members see the leader, they receive the shared information from the leader about escaping through Exit B. The high influence of group leader causes the members to change their exit route (Figure 4b). As the leader exits from Exit B, the rest of the group would follow the leader’s instruction to escape through the same exit even though they are closer to Exit A (Figure 4c). This scenario is consistent with real-life observations of group navigation in that members in a group would choose their preferred exit considering information from the leader and other group members, rather than simply selecting the “nearest exit”. That is, group affiliation can influence an agent’s exit route choice and hence affect the evacuation pattern and time.

## 4.2. Crowd following

People tend to walk by following people ahead of them, which lend themselves to form “lanes”, and, in turn, lead to bidirectional flow. It is also known that in high density crowd, an individual may not have choice in navigating but follows the general direction of the crowd (Aguirre et al, 2011a; Still 2000). Norm following behavior and lane forming patterns are commonly observed in such situation. In our simulation, the agent detects neighboring agents’ locations and updates

the list of *neighboring agents*. When the crowd density (as calculated using the number of *neighboring agents*) is high, instead of navigating to its own target, the agent follows an agent ahead and sets it as the temporary target. Figure 5 shows the simulation result of lanes formation when two groups cross over. Simulating the crowd following behavior is particularly important in areas where crowd density is very high, such as areas along the critical exit route.

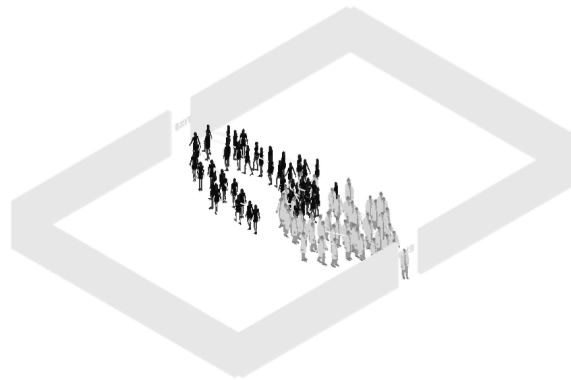


Figure 5. Lanes formation

### 4.3. Respecting social hierarchy

Studies have identified that the social hierarchy can have significant effect on human behavior. It has been observed that people exhibit different forms of altruistic behavior during emergency evacuation, for example, giving access priority to people who are more senior or in need (Averill et al., 2005; Drury et al., 2009). The social effect can be translated into locomotion rules by assigning higher value of *social order* to a specific type of agents representing the population at higher position within the social hierarchy (such as elderly or needy). The locomotion module iterates through each agent and determines their best position in the crowd using heuristic search. The agents with higher *social order* will search for their optimal move first in the module. A high value of *social order* also leads to a reduced interpersonal distance tolerance, which results in a larger potential movement zone for the agent during its search for the next move. Figure 6 illustrates one example of respecting social hierarchy in a crowd. In Figure 6a, at the narrow opening where the evacuees meet (indicated by the arrow), the agents with higher *social order* (as shown in darker color) have a reduced tolerance of interpersonal distances, so they have a larger zone for deciding the next movement. Agents with lower *social order* (as shown in lighter

color) will have significant reduction in potential movement zone as a result of maintaining interpersonal distances. Figure 6b shows the agents with lower *social order* waiting at the narrow opening. Simulating social hierarchy in agent's navigation helps understanding the crowd flow and detecting changes in congestion patterns of different occupant populations.

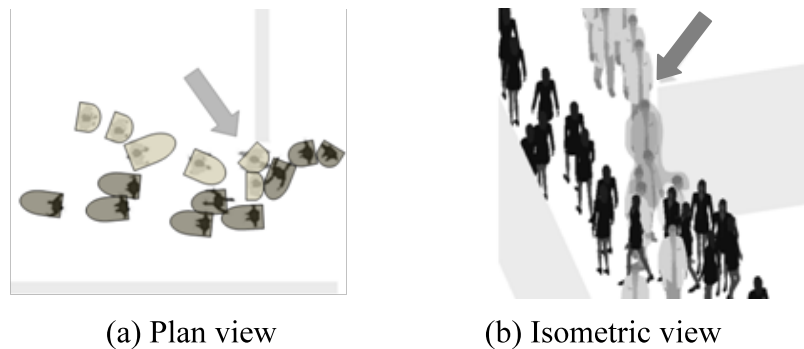


Figure 6. Example of deferring to agents with high value of *social order*

## 5. A benchmark simulation scenario

In this section, we study the effects of different behavioral assumptions on the evacuation time and pattern using a historical event. The scenario is based on the 2003 Station Nightclub fire incident in Warwick, Rhode Island. The Station Nightclub Fire was one of the most lethal and well-studied fire accidents involving 452 people and causing 100 deaths (Aguirre et. al., 2011a; 2011b; Grosshandler et al., 2005). A band accidentally ignited the polyurethane foam installed at the platform during the performance. The fire initiated at 11:08 pm, and evacuation was delayed as patrons were engaged in different activities and were making sense of the situation. The band stopped performing 30 seconds later and started evacuating. One minute 40 seconds later, the main entrance was clogged and some began to escape from the windows at the bar area and sunroom. The latest time recorded for an individual escaping window was 4 minutes 8 seconds after initiation of the fire.

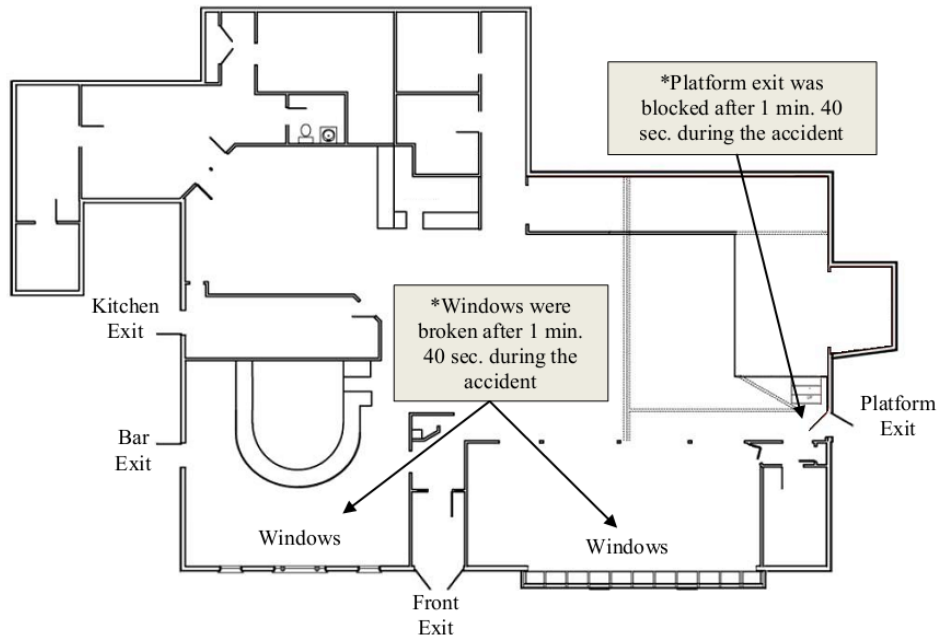


Figure 7. Floor plan of the Station Nightclub

The floor plan of the nightclub building is shown in Figure 7. In the following, we first provide a comparison study between our simulation model and the research results reported by the National Institute of Standards and Technology (NIST) (Grosshandler et al., 2005) and other researchers (Aguirre et. al., 2011a; 2011b). The baseline comparison, however, do not take into consideration the possible effects of group and social behaviors during the evacuation. We then report the results from our prototype tool when group and social behaviors are included in the simulations.

### 5.1. Baseline comparison results

The purpose of establishing the base models is to test that simulation results generated by our prototype are reasonable, when comparing our results to the analyses conducted by authorities in fire engineering and disasters management. Two sets of comparison tests are conducted with reference to the NIST report (Grosshandler et al., 2005) and the actual evacuation pattern

reported by Aguirre et. al. (2011a; 2011b). The first test compares the total evacuation time and exit usages of our model to the NIST simulation results. The second test compares the simulated evacuation pattern (exit usages) to the actual evacuation pattern (Aguirre et. al., 2011a; 2011b), taking into consideration the changes in the physical geometry of the building and delayed response during the evacuation.

### **5.1.1 NIST simulation results comparison**

NIST conducted simulations of the 2003 Station Nightclub building with two commercial egress analysis programs, Simulex and buildingEXODUS. The simulation test is based on the test scenario #1 as described in the NIST report (Grosshandler et al., 2005). The test scenario involves all 420 occupants who are assumed to be evacuated under normal circumstances (i.e., all occupants evacuate). The purpose is to compare the evacuation time and exit usages obtained from the simulations. We follow closely the model assumptions as described in the NIST report (Grosshandler et al., 2005):

*a. Agent population and characteristics:*

- There are 420 agents, which correspond to the maximum occupant capacity allowed for the facility.
- The population consists of 60% male and 40% female.
- Occupants' spatial distribution follows the patterns as described in Appendix L of the NIST report (Grosshandler et al., 2005).

*b. Evacuation delay*

- There is no pre-evacuation delay time, i.e., all occupants evacuate instantaneously.

*c. Evacuation behavior*

- All agents exhibit individual behaviors only and escape through the nearest exit.

*d. Physical geometry change during simulations:*

- No change of the building geometry is considered.

*e. Condition for terminating the simulation:*

- All agents evacuate.

As shown in Table 2, the evacuation pattern and time from our simulations match closely the simulation results in the NIST report (Grosshandler et al., 2005).

Table 2. Comparison of exit usages and egress time

Exit Location	Front	Platform	Bar	Kitchen	Total Time
MASSEgress	50.0%	41.7%	7.1%	1.2%	183s
NIST 1*	50.7%	43.8%	4.8%	0.7%	188s
NIST 2^	51.0%	42.9%	5.2%	1.0%	202s

\* Simulations by Simulex (Grosshandler et al., 2005)

^ Simulations by buildingEXODUS (Grosshandler et al., 2005)

### 5.1.2 Actual evacuation pattern comparison

In the second comparison test, we take into account the occupants' statistics in the fire, the changes in the physical geometry of the building during the emergency evacuation, and the initial delay of escape behaviors. Several important assumptions, as derived from the post-fire studies (Aguirre et al., 2011a; 2011b), have been made in our simulation:

*a. Agent population and characteristics:*

- There are 452 agents, which correspond to the number of occupants who were present at the nightclub at the time of fire.
- The population consists of 70% male and 30% female.
- Occupants' spatial distribution follows the empirical study reported by Aguirre et al. (2011a).

*b. Physical geometry change during simulations:*

- At 1 minute 40 seconds into the simulation, the building model is being updated (using the Situation Data Input Engine) to allow agents passing through windows and to disable the platform exit which was impassable due to fire.

*c. Condition for terminating the simulation:*

- 352 agents, the number of survivors of the fire, evacuate.

In addition, we make two other assumptions on the evacuation behaviors of the agents in our simulation. First, since in the best of our knowledge, there are no data on the pre-evacuation delay time, we assume agent’s pre-evacuation delay time using a truncated normal distribution with a mean of 15 seconds and standard deviation of 10 seconds within the interval [0, 41] seconds (as the alarm rang at 41 seconds after the start of the fire). Second, we consider only individual behaviors and all agents escape through the nearest exit.

To evaluate the overall evacuation pattern, we compare the simulation results with the exit usages reported by Aguirre et al. (2011a; 2011b). As shown in Table 3, which tabulates the usage of different exits, the result of exit usages from our simulation compared favorably to the actual data reported by Aguirre et al. (2011a; 2011b). Capturing the exit usages is an indication that our egress simulation reflects the flow patterns and the potential congestion areas. From the simulations, the average evacuation time is 184 seconds (number of simulation runs = 10, standard deviation = 14.4 seconds). The shorter evacuation time in our simulation (as comparing to the actual evacuation time, 248 second) can be attributed to many factors, such as the omission of other dimensions of the incident (e.g., effect of smoke and fire on people’s movement). Nevertheless, the results from the evacuation patterns provide a good base to study the group and social effects on emergency evacuation.

Table 3. Comparison of exit usages

Exit Location	Front	Platform	Bar	Windows	Kitchen
MASSEgress	37.9%	9.5%	22.8%	29.3%	0.5%
Actual data*	36.4%	6.8%	22.2%	29.9%	4.7%

\* Data as reported by Aguirre et al. (2011a)

## **5.2. Simulation results incorporating group and social behaviors**

This section describes the simulation results considering group and social behaviors and their effects on the evacuation time. In order to test the group effect, agents are assigned to affiliate with different groups. In the Station Nightclub fire, most of the occupants in this accident were in a group of two people or more (group sizes ranged from 2 to 9). Following the post-fire study by Aguirre et al. (2011b), we assume that there are 43 individual agents. The remaining 409 agents are associated to social groups, where 118 agents are assigned to groups of two, 54 agents to groups of three and 72 agents to groups of four, and the rest to larger groups ranging from 5 to 9 people. Furthermore, we consider in over-congested situation, i.e., when the average occupant area was less than 2-3 ft<sup>2</sup> /person (level of service E for queuing) (Fruin 1971), the crowd following model (as describe in Section 4.2) overrides other social behavioral models.

### **5.2.1 The effect of group behavior**

As opposed to modeling the occupants with individualistic behaviors, group behaviors can have a significant effect on the total evacuation time. Evacuees reported behaviors such as searching for and staying with group members even under extreme danger (Aguirre et al. 2011a). The group effect is captured in the simulation by modeling group behaviors (as described in Section 4.1) for agents that belong to a social group. We test the effect of the group behaviors on evacuation time by varying the percentage (from 0% to 100%) for the total number of groups that exhibits the group behaviors. In Figure 8, 0% group with group behaviors would mean that all agents behaved individually while 25% would refer to 45 out of 179 groups consisted of agents with group behaviors, etc. As shown in Figure 8, the evacuation time increases as the percentage of groups with group behaviors increases. The result also shows that the lengthening in evacuation time varies nonlinearly and the effect levels off as the percentage of groups with group behaviors increases.



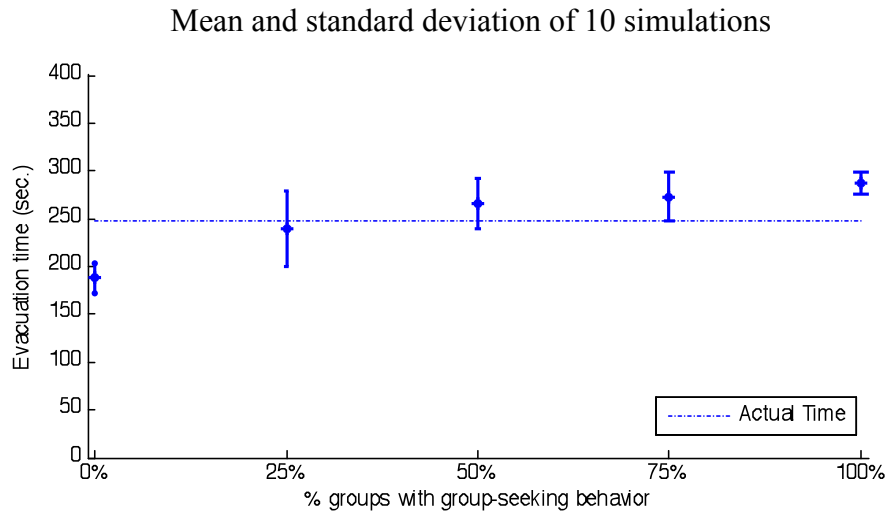


Figure 8. Effect of group behaviors on egress time

### 5.2.2 The effect of respecting social hierarchy

The effect of social order in the crowd can also affect the overall evacuation time. The survey conducted with the survivors of the accident reveals that about one-third of the evacuees had received help during the evacuation process (Aguirre et al. 2011a). Even in emergencies, people maintain social order by allowing needy to pass through (Donald and Canter, 1990, Johnson et al., 1994). To illustrate the social behavior, we create a special type of needy agent with reduced travelling speed and assign one-third of the population as this needy agent type. For example, 0% reduction means that all agents maintain the travelling speed as assigned by the Population Engine. For 10% reduction, the needy agent would reduce their travelling speed by 10% while other agents maintain their regular speeds. To assess the effect of social hierarchy in evacuation, we have conducted two sets of simulations. The first set assumes equal *social order* among all agents and the second set assigns a higher *social order*, i.e., higher moving priority, to the special type of agents. As shown in Figure 9, the evacuation time increases as special (needy) agents are assigned with higher speed reduction. Furthermore, the lengthening in evacuation time is more significant when the special (needy) agents have a higher moving priority over the other agents.

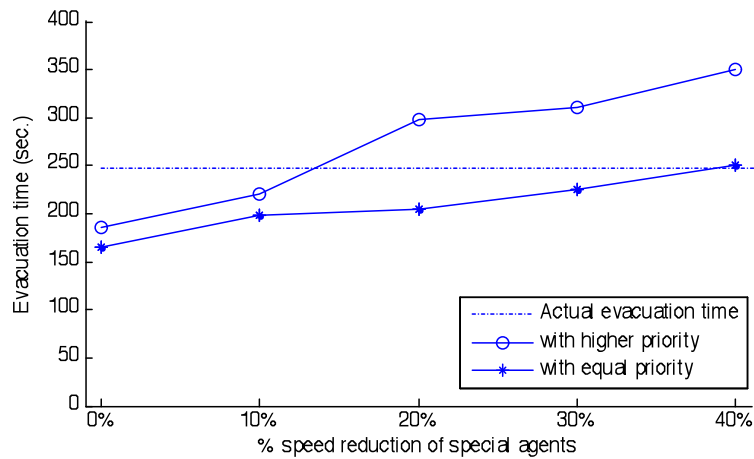


Figure 9. Effect of respecting social hierarchy on egress time

## 6. Discussions

In this paper, we have described an ongoing research effort in developing a modular and flexible computational framework to incorporate human and social behavioral models for egress simulations. In the following, we first discuss the results for possible effects of social behaviors on evacuation. We then discuss our overall framework for the multi-agent based simulation system. Finally, we conclude this section and the paper with a brief discussion on future work.

### 6.1. Effects of social behaviors in egress simulation

In our prototype, we have implemented several behaviors, namely the group behaviors, group information sharing, crowd following, and respecting social hierarchy to illustrate the ability of our framework for simulating social behaviors in emergencies. Although the implemented social behaviors do not represent an exhaustive list of all possible behaviors occurred during emergencies, these are commonly observed behaviors reported in many post-fire studies (Aguirre et al. 2011a; 2011b; Donald and Canter, 1990; Drury et al., 2009; Johnson et al., 1994;

Kuligowski, 2011; Mawson, 2005; Sime, 1983). Using the case of the Station Nightclub fire, we have compared the overall evacuation patterns to the actual data and studied the effects of the implemented behaviors to the evacuation time. Our simulation results show that the group behaviors demonstrated by the agents of a social group would lengthen the overall evacuation time. Similarly, the total evacuation time is longer when social hierarchies among agents and altruistic behavior are considered in the simulations.

The simulation assuming purely individualistic behavior in an emergency evacuation shows an underestimation in the total evacuation time, as compared to the actual data. It is clear that other factors should be taken into account in order to provide a more realistic prediction. In our prototype, we have implemented four behavioral models based on past events studies and real-life observations. In a complex emergency situation, like the fire accident in the Station Nightclub, other operational and environmental factors, such as the presence of people with special roles and low visibility due to the spread of smoke, could also affect the evacuation speed and pattern. Our simulation framework could provide flexibility in egress modeling by including default behaviors and also allowing new behavioral rules to be incorporated into the simulation framework.

## **6.2. Representation of agents and the egress environment**

In order to incorporate social and group behaviors into egress simulation, we have developed an agent representation rested on three levels, namely individual, group, and crowd. In our prototype, we have implemented a set of social variables that describe the agents not only in individual context, but also from the social group and the crowd perspectives. With this representation, a virtual agent's decision is not only determined by its own behavioral profile, but is also influenced by its group profile and the neighboring crowd. By adopting this staged decision-making process, we are able to model some commonly observed social behaviors during emergencies in the simulations.

To represent the dynamic environment of an emergency situation, we establish a generic data structure of environmental objects which can represent exits, alarms, and other evacuation related information. Users can define the characteristics of the objects created and assume relationships and rules among these objects and the virtual agents for simulation purpose. It is important to represent the emergency situation in the context of threats (such as fire and smoke) and floor geometric components (such as the signage and openings) that can significantly change the occupants' perception during egress. For example, in the Station Nightclub fire, the alarm rang at 41 seconds after the start of the fire. This emergency signal, together with the fire and smoke, presented a cue to all the patrons and initiated their escape behaviors, particularly to those who were previously unsure about the emergency situation.

### **6.3. Future works**

Although the importance of modeling realistic human and social behaviors in egress simulations has been recognized by social scientists and disaster management researchers, such factors are still seldomly considered in current egress simulation tools. This paper describes our current research in bridging this gap by modeling human behaviors with group and crowd considerations in egress simulations. Based on a systematic study on egress related social theories, we have designed a computational framework which includes a three-stage decision-making process to simulate the effect of group and crowd on individual decision during emergencies. Our prototype has demonstrated the potential of including social behaviors in a multi-agent based simulation platform. The simulation framework can be used to model different social behaviors that are deemed appropriate in a specific emergency situation, obtain valuable information to evaluate egress design, and to derive insight on emergency planning and management.

We continue to incorporate additional social behaviors, particularly those identified in disaster management research and empirical studies of past events, and to enrich the simulation platform

at the individual, group, and crowd level. Along with the further development of the simulation framework, model validation presents the next challenge. We plan to develop methodologies to analyze real-life data, establish benchmark models for validation, and design interactive tools to facilitate the use of the simulation tool for egress design. Last but not least, we plan to integrate the simulation framework with other engineering analyses, such as performance-based assessments of facilities and spaces, sprinkler layout designs, and smoke and fire simulations.

## 7. References

Aguirre, B., Wenger, D., and Vigo, G. (1998). 'A test of the emergent norm theory of collective behavior.' *Sociological Forum*, Volume 13, 301–320.

Aguirre, B. E., Torres, M. R., Gill, K. B., and Hotchkiss, H. L. (2011). "Normative collective behavior in the station building fire." *Social Science Quarterly*, 92(1), 100–118.

Aguirre, B. E., El-Tawil, S., Best, E., Gill, K. B., and Fedorov, V. (2011). "Contributions of social science to agent-based models of building evacuation." *Contemporary Social Science*, 6(3), 415–432.

Averill, J. D., Mileti, D. S., Peacock, R. D., Kuligowski, E. D., Groner, N., Proulx, G., Reneke, P. A., and Nelson, H. E. (2005). *Occupant Behavior, Egress, and Emergency Communications*, Technical Report, NCSTAR, 1–7, NIST.

Challenger, W., Clegg W. C., and Robinson A.M. (2009). *Understanding Crowd Behaviours: Guidance and Lessons Identified*, Technical Report prepared for UK Cabinet Office, Emergency Planning College, University of Leeds.

Donald I., and Canter D. (1990). "Behavioural aspects of the king's cross disaster." *Fires and Human Behaviour*, 2<sup>nd</sup> Ed, David Fulton Publishers, London, 15- 30.

Drury, J., Cocking, C., and Reicher, S. (2009). "Everyone for themselves? A comparative study of crowd solidarity among emergency survivors." *British Journal of Social Psychology*, 48, 487–506.

Durupinar, F., Pelechano, N., Allbeck, J., Gudukbay, U., and Badler, N. I. (2011). "How the ocean personality model affects the perception of crowds." *IEEE Computer Graphics and Applications*, 31(3), 22-31, IEEE Computer Society.

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

Grosshandler, W., Bryner, N., Madrzykowski, D., and Kuntz, K. (2005). *Report of the Technical Investigation of the Station Nightclub Fire*, Technical Report, NCSTAR 2: Volume I and II, NIST.

Gwynne, S., Galea, E. R., Owen, M., and Lawrence, P. J. (2005). "The introduction of social adaptation within evacuation modeling." *Fire and Materials*, 2006(30), 285–309.

Helbing, D., Farkas, I., and Vicsek, T. (2000). "Simulating dynamical features of escape panic." *Nature*, 407:487–490.

ICBO. (2009). "Means of Egress." *2009 International Building Code*, Chapter 10.

Johnson, N.R., Feinberg W.E., and Johnson D.M. (1994). "Microstructure and panic: the impact of social bonds on individual action in collective flight from the Beverly Hills Supper Club fire." In Dynes R.R. & Tierney K.J. (ed.), *Collective Behavior and Social Organization*, Delaware University Press, Newark.

Ketchell, N., Webber, D.M., and Cole, S.K. (1996). "Assessment and simulation of crowd evacuation issues." *Fire Engineering and Emergency Planning*, Edited by R.Barham, 162–167.

Kuligowski, E. D., and R. D. Peacock. (2005). "A review of building evacuation models." *Technical Note 1471*, Fire Research Division, Building and Fire Research Laboratory, U.S. Department of Commerce, Technology Administration, NIST.

Kuligowski E.D. (2011). "Terror Defeated: Occupant Sensemaking, Decision-Making and Protective Action in the 2001 World Trade Center Disaster." Ph.D. Thesis, University of Colorado, U.S.A.

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

Mawson, A. R. (2005). "Understanding mass panic and other collective responses to threat and disaster." *Psychiatry*, 68, 95–113.

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

Mintz, A. (1951). "Non-adaptive group behavior." *Journal of Abnormal and Social Psychology*, 46, 150–159.

Moussaïd, M., Helbing, D., and Theraulaz, G. (2011). "How simple rules determine pedestrian behavior and crowd disasters." *Proceedings of the National Academy of Sciences of the United States of America*, Apr. 2011.

Musse, S. R., and Thalmann, D. (2001). "Hierarchical model for real time simulation of virtual human crowds." *IEEE Transactions on Visualization and Computer Graphics*, 7, 152–164.

Pan, X. (2006). "Computational modeling of human and social behavior for emergency egress analysis." Ph.D. Thesis, Stanford University.

Santos, G., and Aguirre, B. E. (2004). "A critical review of emergency evacuation simulations models." in Peacock, R. D., and Kuligowski, E. D., (ed.). *Workshop on Building Occupant Movement during Fire Emergencies*, June 10–11, 2004, Special Publication 1032, NIST.

Sime, J. D. (1983). "Affiliative behaviour during escape to building exits." *Journal of Environmental Psychology*, 3(1), 21–41.

Still, G. K. (2000). "Crowd dynamics." Ph.D. Thesis, University of Warwick, UK.

Thompson, P.A., and Marchant, E.W. (1995). "Testing and application of the computer model 'SIMULEX'." *Fire Safety Journal*, 24:149–166.

Turner, R. and Killian, L. (1987). *Collective Behavior*, Englewood Cliffs, NJ: Prentice-Hall.