Simulating Effects of Signage, Groups and Crowds on Emergent Evacuation Patterns

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Abstract

Studies of past emergency events have revealed that occupants' behaviors, egress signage system, local geometry, and environmental constraints affect crowd movement and govern the building evacuation. In addition to complying with code and standards, building designers need to consider the occupants' social characteristics and the unique layout of the buildings to design occupant-centric egress systems. This paper describes an agent-based egress simulation tool, SAFEgress, which incorporates important human and social behaviors observed by researchers in safety and disaster management. Agents in SAFEgress are capable of perceiving building emergency features in the virtual environment and deciding their behaviors and navigation. In particular, we describe four agent behavioral models, namely, following familiar exits, following cues from building features, navigating with social groups, and following crowds. We use SAFEgress to study how agents (mimicking building occupants) react to different signage arrangements in a modeled environment. We explore agents' reactions to cues as an emergent phenomenon, shaped by the interactions among groups and crowds. Simulation results from the prototype reveal that different designs of building emergency features and levels of group interactions can trigger different crowd flow patterns and affect overall egress performance. By considering the occupants' perception about the emergency features using the SAFEgress prototype, engineers, designers, and facility managers can study the human

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factors that may influence an egress situation and, thereby, improve the design of safe egress systems and procedures.

Keywords: crowd simulation, egress simulation, building egress, social agents, social behavior, collective behavior, simulated perception

1. Introduction

We designed a computer model (Social Agent for Egress or SAFEgress) for studying how agents react to cues in emergency situations. Instead of treating agents as isolated atoms reacting to emergency scenarios, we embedded them into social groups, each defined by a unique social structure and group norm. The agents make decisions considering group members and neighbors, in addition to individual preferences. Moreover, each agent is equipped with the capabilities of sensing, reasoning, memorizing, and locomotion to decide and execute its actions. This setting allows us to explore reactions to cues as an emergent phenomenon, shaped by the interactions between individual preferences, group characteristics and crowd behaviors.

Specifically, we use SAFEgress to study the impacts of different exit signage systems within the constraints of a given building layout. Simulation results from our demonstration indicate that occupants' exit preferences, visual perception of the signage system, herding behavior, and social behavior among groups can lead to very different reactions to cues. The results can be used to suggest potential improvements in the placement of exit signs in order to trigger more efficient evacuations from buildings during emergencies. Furthermore, our model also has applications outside the field of induced behavioral change. For instance, SAFEgress can be used to study the effects of human and social behaviors on collective crowd movement patterns. Most egress simulation tools assume simplistic behavioral rules and mostly ignore social behaviors of the agents (Aguirre et al., 2011; Kuligowski 2011). By modeling agents with social behaviors, SAFEgress addresses these deficiencies.

This paper is organized as follows: Section 2 describes the related work in modeling human and social behaviors in egress. Section 3 explains the SAFEgress simulation platform and the key components of the platform. Section 4 describes some examples of plausible egress behaviors in the current prototype. Section 5 concludes the paper with discussion.

2. Related work

2.1. Social behaviors during emergencies

A *shikake* is a mechanism or a device that triggers a behavioral change. Matsumura (2013) defines a shikake more precisely using three interrelated factors: (1) a shikake is an embodied trigger for behavioral change; (2) the trigger is designed to induce a specific behavior; and (3) the behavior solves a personal or social issue. These factors highlight that a shikake is a practical and simple mechanism that offers a solution to a (social or personal) problem (Matsamura 2013). For example, the placing of fly targets in urinals in airports reduced spillage by 80% due to the propensity of men to aim at the fly. In turn, reduced spillage contributed toward reducing cleaning time and water consumption (Matsamura and Fruchter 2013). The simplicity of a shikake rests on the complexity of the psychological or social mechanism it triggers (Rosenberg et al. 2013; Salganick et. al., 2006). In this paper we focus more on the latter, keeping psychological processes in the background. Before describing how we model the social behavior of agents, we review the previous literature on how people react to emergency scenarios.

Post-fire studies have shown that occupants in emergencies do not act randomly, as if in a panic, nor act in an identical manner without individual cognitive ability as if they are physical molecules (Aguirre, 1998; Drury et al., 2009; Sime, 1983; McPhail, 1991). Rather, occupants in emergencies often base their actions on their past experience, social structures, and perceptions and interactions with others to define an emergent understanding of the situation. For example, the affiliative theory (Mawson, 2005; Sime, 1983) and place script theory (Tong and Canter, 1985) examine individuals' behaviors based on their personal knowledge, risk perceptions, experience, and routines. The emergent norm theory (ENT) specifies that disasters may lead to collective behavior through the process of milling and keynoting (Turner and Killian 1987). Milling is a communication process whereby individuals in a collective attempt to define the situation, while during keynoting, leaders emerge, interpret the situation and make suggestions on what to do next (McPhail, 1991). Aguirre (1998) further applied ENT to explain occupants' reactions in the World Trade Center Explosion in 1993, and showed that social groups and enduring social relationships could lengthen the time of evacuation.

ENT and the pro social theory suggest that people continue to maintain group structure and behave in a pro social manner during emergencies (Aguirre et al., 2011). The social identity theory infers 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). Moreover, studies in sociology and psychology suggest that people influence each other's behaviors through the spreading of information and emotions (Rydgren, 2009; Hoogendoorn et al., 2010).

Researchers in safety and disaster management have proposed theoretical frameworks that describe the processes of seeking information, interpreting the situation, assessing the risk, and making decisions specifically in response to a disaster. For example, Lindell and Perry (2011) applied the Protective Action Decision Model (PADM) to examine the disaster response of occupants in residential fires and study the effect of warning mechanisms on evacuation time. Based on the PADM framework, Kuligowski (2011) studied the actions taken during the pre-evacuation period of the 911 WTC (World Trade Centers) attacks and developed a model to qualitatively describe how occupants made their decisions to evacuate. Reneke (2013) proposed the Evacuation Decision Model to predict the state of the occupants by modeling the level of risk perception and the effect of knowledge, social influence, and alarm as they occur over time during the pre-evacuation period. These frameworks and models synthesize human behaviors in emergencies as process models that can be systematically analyzed further by incorporating factors, such as threats, social relationships, and personal experience, to determine the outcome of evacuation.

In light of prior studies, we conjecture that creating a shikake for egress will require individual, group, and crowd-level characteristics. At the individual level, occupants may refer to their past experiences and knowledge and their perceptions of the situation to decide on their actions. At the group level, the pre-existing social structure (relations between group members) and group norms (expectations of each other's behavior) affect the behavior of an individual. Crowd-level behaviors are emergent phenomena and often follow social norms.

2.2. Current crowd simulation approaches

Different crowd modeling approaches, such as the particle (Helbing et al., 2000; Moussaïd et al., 2011), cellular automata (Burstedde et al., 2001), and agent-based systems (Lin et al., 2010; Galea et al., 1998; Durupinar et al., 2011; Musse and Thalmann, 2001; Aguirre et al., 2011), have been adopted into various simulation software to model crowd movement in virtual environments. Zheng, Zhong, and Liu (2007) have provided detailed reviews of the different simulation models. The following discussion focuses on the agent-based approach which is adopted in the implementation of SAFEgress.

Agent-based systems model the crowd as a collection of autonomous entities known as “agents” to represent the human occupants. These systems allow emergent phenomena as a result of interactions among the virtual agents. Many egress models have recently adopted this approach and proposed different representations of the spatial environment and the agents. One common way of representing the spatial environment is dividing the space into a 2-D array of cells where each cell contains up to a certain number of agents (Lin et al., 2010; Galea et al., 1998). While the grid-based spatial representation benefits from its computational efficiency, the representation limits agents’ spatial movements and can potentially show an unnatural checkerboard pattern when crowd density is high. Another approach is to represent the spatial environment as a continuous space that allows agents to navigate naturally on a continuous plane while considering constraints imposed by the physical geometry of the building (Durupinar et al., 2011; Musse and Thalmann, 2001). Our simulation framework uses the continuous spatial representation which allows a wider array of locomotions of the agents as well as the simulation of high-density crowd scenarios, such as over-crowding and pushing at exit (Aguirre et al., 2011).

In most agent-based systems, the agent navigation routes are usually pre-defined by specifying explicitly the origins and destinations of the occupants (Aguirre et al., 2011; Turner and Penn, 2002). Optimal routes (usually defined in terms of travel time or distance) are obtained by assuming that the agents have good, often perfect, knowledge of the environment. Examples are the way-finding model in EXODUS (Veeraswamy et al., 2009) and the simulation model proposed by Kneidl et al. (2013). Other agent-based systems model an agent's navigation decision as the outcome of decision-making processes, rather than pre-defined or optimized routes. For example, ViCrowd (Musse and Thalmann, 2001) is a crowd simulation tool in which crowd behaviors are modeled as scripted behaviors, as a set of dynamic behavioral rules using events and reactions, or as externally controlled behaviors in real time. MASSEgress (Pan, 2006) gauges an agent's urgency level, evaluate behavior models represented as decision trees, and invokes a particular behavior to determine the navigation target. These models consider agents' behaviors as a perceptive and dynamic process subjected to external changes. We also adopt the perceptive approach in SAFEgress when updating the agents' behaviors.

As noted by Kuligowski and Peacock (2005), a wide variety of computational tools for egress simulation are available; however, human and crowd behaviors are often ignored and group effects on evacuation patterns are seldom explored (Challenger et al., 2009; Aguirre et al., 2011). Only recently have efforts been attempted to incorporate social behaviors into egress simulations. For example, Tsai et al. (2011) implemented exit knowledge, families, and emotional contagion on evacuation and evaluated the impacts of emotional and informational interactions between agents. Similarly, Aguirre et al. (2011) described an agent-based model which attempts to implement the pro social model in simulating emergency evacuations. Features, such as leaders and followers within a group, have been implemented to simulate population at a group level and observe emergent patterns as a result of social relationships. Our model extends the notion of pre-existing social relationships by defining groups with several salient attributes, such as intimacy level and group influence. Furthermore, we incorporate the effect of neighboring crowds on individuals and investigate crowd behaviors, such as herding, on the evacuation patterns.

2.3. Model of spatial representation in simulations

People's knowledge and memory of a space has a significant effect on their route choices. For example, when the desirable destinations (such as the entrance of the building) are not immediately visible, people refer to external information (such as signage) or memory of a specific route (such as following the paths which they traveled before) to determine their travel directions (Gärling et al. 1986). Moreover, researchers in environmental and cognitive psychology have argued that evacuees use their perceptions to guide their navigation (Gärling et al. 1986; Turner and Penn 2002). With proper spatial representation of the environment, Turner and Penn (2002) have shown that natural human movement can be reproduced in simulations without the needs to assign the agents with extra information about the location of destination and escape route.

To simulate the spatial cognitive capability of the agents, a proper representation of the spatial connectivity that can be used for navigation by the agents is needed (Turner and Penn 2002). The spatial connectivity is often represented as a navigation graph or a roadmap. A variety of techniques have been proposed to create a navigation graph from a given building geometry. Most of these techniques have been developed in the field of robotics (Latombe, 1995). Many space discretization techniques (such as Voronoi diagrams) have been used to derive a navigation graph. Although these techniques are commonly used for steering robots, they need to be modified for egress simulation for which human-like cognition and navigation are important. Approaches that are capable of more accurately modeling human perception and cognition are based on visibility graphs (Choset, 2005). A visibility graph consists of nodes defined by the physical geometry of the building, its special features and the destinations of the agents. An edge is added to link two nodes if they are in the line of sight. In our work, we adopt a visibility graph to represent the spatial connectivity of a floor (Chu et al. 2014). The visibility graph is used in SAFEgress primarily as a representation of the continuous space to allow the agents to perceive possible areas to explore, rather than as a navigation guide that dictates the movement by the agents.

3. A simulation framework for modeling human and social behaviors

SAFEgress is an agent-based model designed to simulate human and social behaviors as well as emerging crowd behaviors during evacuations. In the following sections, we first provide an overview of SAFEgress framework and describe each major module of the system. We then briefly discuss the spatial representation, followed by the agent representation and the attributes used to model occupants in an emergency situation. Details of the system and the individual components have been described elsewhere (Chu al et. 2014; Chu and Law 2013).

3.1. System architecture

SAFEgress is an agent-based model designed to simulate human and social behaviors as well as emerging crowd behaviors during evacuations. Figure 1 depicts the system architecture of SAFEgress. The key modules of the framework are the Global Database, Crowd Simulation Engine, and Agent Model, while the supporting sub-modules include the Situation Data Input Engine, Geometric Engine, Event Recorder, Population Generator, and Visualizer.

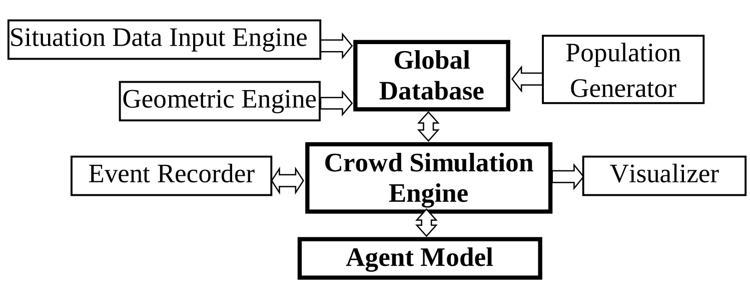


Figure 1. System architecture of SAFEgress (Chu and Law, 2013)

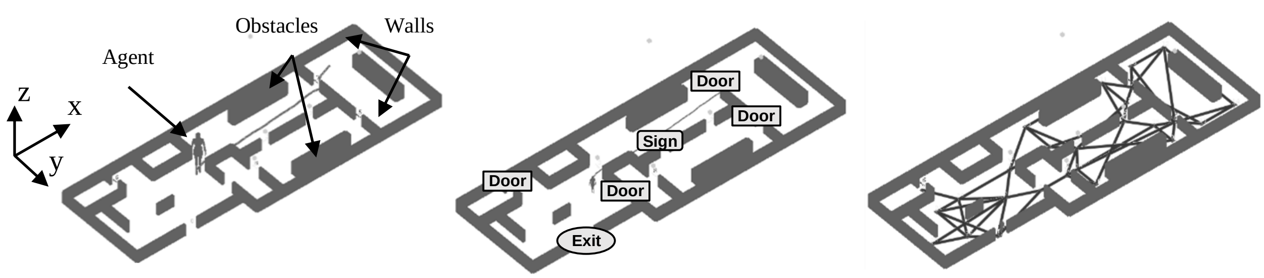
- The Global Database stores all the information about the agent population, the physical geometries, and the status of emergency situations. It maintains the state information (such as mental states, behavioral decisions, locations) of the agents.
- The Crowd Simulation Engine is the key module of the system. It interacts closely with the Agent Behavior Models Database, keeps track of the simulation, and records and retrieves information from the Global Database. The generated simulation results are sent to the Event Recorder and the Visualizer.
- The Agent Behavior Models Database contains the individual, group, and crowd behavioral models. Besides the default behavioral models, new models can be created by users to investigate a range of behaviors under different scenarios.
- 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 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 agent perception, as well as for visualization of simulation results.
- The Event Recorder stores the simulation results at each time step. 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 Population Generator receives input assumptions of the agent population and generates the agents using physical (such as age, mobility, physical size) and behavioral profiles. This module can also generate both pre-defined and random social groups to study different social behaviors.
- The Visualizer, currently implemented using OpenGL, receives the positions of agents, overlays with the virtual 3D model, and then dynamically generates and displays simulation results as 2D/3D visual images.

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. In particular, efficient computational algorithms (such as detecting proximity and spatial visibility) have been carefully designed to allow simulations with a large number of agents.

3.2. Hierarchical space representation

Local building geometry, spatial arrangement of safety signage, and occupants' previous experience and familiarity with the buildings can significantly influence the choice of egress routes in emergencies. We design a space model to represent the virtual environment such that the agents can perform the following tasks:

- move naturally by avoiding collision with physical obstacles and walls;
- detect visible building features such as exit signs and door openings;
- support cognitive abilities of the agents, such as reasoning and acquiring knowledge of the building layouts.



(a) Continuous movement space (b) Representation of building safety features (c) Visibility map

Figure 2. Three components of the hierarchical space model

As shown in Figure 2, the proposed hierarchical space model consists of three layered components: a continuous movement space, sematic representation of the building features, and a visibility graph. Each component of the hierarchical space model is discussed further in the following sections. For computational efficiency, the space model is built prior to simulation and, once constructed, is used throughout the simulation, unless changes are made to the building layout that necessitate an update to the space model.

3.2.1. Continuous movement space

SAFEgress represents the spatial environment as a continuous space (as shown in Figure 2a) that the agents navigate. A typical floor space includes physical obstacles, such as walls and furniture. Agents navigate the virtual space and avoid colliding with physical obstacles. Using the user inputted building geometry, which describes the locations and the dimensions of the physical objects, such as walls and doors, the obstacle model is built to enable the agents to "sense" the physical surrounding and the visible space. To construct the obstacle model, the boundary surfaces of each 3-dimensional physical obstacle are represented as a set of polygon planes. Using the obstacle model, an agent performs two basic tests: (1) collision tests to determine its separating distances from nearby obstacles, and (2) visibility tests to determine if any given point in the virtual space is visible to the agent.

3.2.2. Sematic representation of building safety features

In an emergency situation, people observe relevant building features such as exits and exit signs to guide them to safety. These safety features provide additional information to the agents, such as the possible directions of travel leading to exit or outlet options. As illustrated in Figure 2b, three safety features (namely exits, exit signs, and doors) are included in the space model.

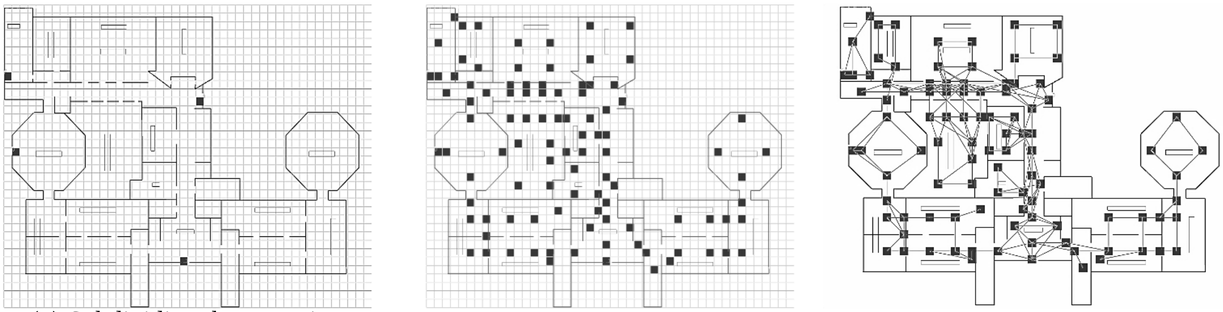
- Exit: The exit objects represent the outlets of the floor. The agents are equipped to visibly detect the exit objects. If an agent decides to escape through a particular exit object, the agent navigates towards the location of the exit object. Once reaching the exit, the agent is considered as physically exited from the floor space. The attributes describing an exit object are its spatial location and angle of orientation.

- Exit Sign: The exit sign objects represent the exit signs installed in a building as part of the egress system. The signs can be either directional or non-directional. Non-directional signs are attraction points for agents to move close to. A directional exit sign includes additional navigation direction. As an agent detects and decides to follow an exit sign, the agent extracts and follows the directional information as posted on the sign. The attributes describing the exit sign object include its spatial location, angle of orientation and, optionally, the directional information (such as left or right).
- Door: The door objects are similar to exit objects which serve as "attraction points" to the agents. Unlike an exit object which discharges the agent upon arrival, the agent remains in the floor space and continues to navigate until reaching an exit object. The attributes describing a door object are its spatial location and angle of orientation.

Although the selected building safety features (namely, exit, exit sign, and door) do not represent all the possible features that are found in a building, they are the most salient features pertaining to egress design and have great influence on people's evacuation decisions.

3.2.3. Visibility graph

Navigation during an evacuation is motivated by the subsequent movements towards closer to the final destination (Gärling et al., 1986; Turner and Penn, 2002). Even with no apparent visual cues in the surroundings, humans move naturally in a direction that allows them to move further. To emulate natural human movement, we represent an obstacle-free space by populating the space with navigational points. Furthermore, we construct a visibility map to link the navigational points to represent the connectivity in the obstacle-free space. As shown in Figure 3, the visibility map is constructed using the following procedure:



(a) Subdividing the space into square cells and initializing **exits as navigation points**

(b) Adding navigation points to the cells with maximum visibility zones

(c) Linking the navigation points which are visible to each other within a certain radius

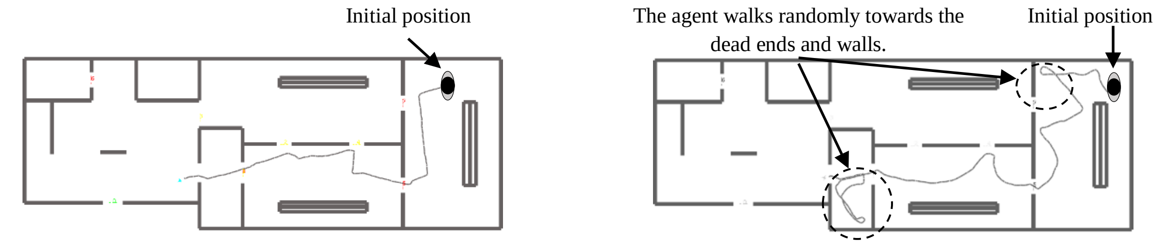
Figure 3. A procedure for generating visibility map (Chu et al. 2014)

(1) The continuous space is first discretized into square cells to form a 2-D grid for computational efficiency. The cells with the building features (such as exits, doors, and windows) are identified as an initial set of navigation points (Figure 3a).

(2) For each cell on the 2-D grid, we compute the area that is visible from an agent in that cell (visibility area). The cells that has the largest visibility area among its neighboring cells are identified and become navigation points. Figure 3b illustrates the navigation points constructed for a floor space.

(3) Edges are added to link the navigation points that are visible to each other within a certain radius. The resulting visibility map is a graph that represents the connectivity of traversal areas in the obstacle-free space (Figure 3c). Specifically, Figure 3c shows the graph in which the nodes are the locations of the building safety features and the intermediate navigation points, and the edges are pairs of nodes that are visible from their locations.

The full visibility map represents the spatial connectivity of the floor which is customized based on the building geometry and locations of the safety features. By querying the visibility map with its current location, an agent “perceives” the possible navigation directions in the virtual space and makes subsequent navigation decisions. Three basic rules are observed to define the use of the visibility map by the agents:



(a) Agent's trajectories with visibility graph

(b) Agent's trajectories without visibility graph (relying on collision avoidance)

Figure 4. Agent's trajectories navigating space with and without visibility graph

Rule #1: *An agent can detect the navigational points that are within the line of sight at each simulation step.*

As humans can only perceive their local obstacle-free surroundings, the virtual agents can access only the "visible" portion of the visibility map to decide their navigation directions. An agent queries the visibility map with its current navigation point (determined based on its current location) to identify any connecting navigation points that are visible to the agent. Figure 4 illustrates the differences of the agent's trajectories with and without the visibility graph. With the notion of the visibility map as shown in Figure 4b, instead of relying on local collision avoidance with obstacles which can cause unnatural trajectories (such as walking towards walls or blockages), the agent navigates the environment by detecting visible navigational points and moving with reference to the next navigation points.

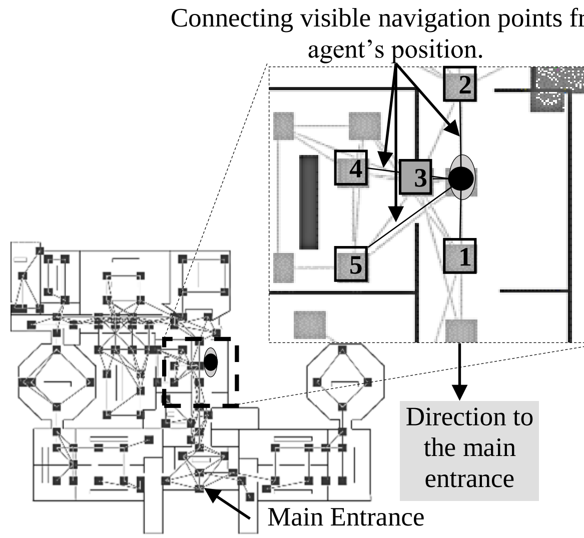
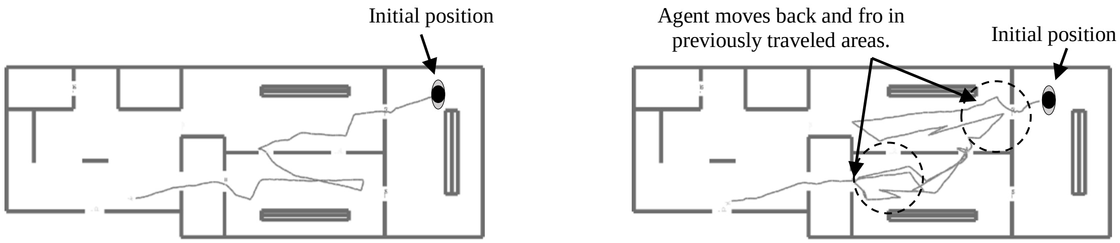


Figure 5. Illustration of visible navigation points from an agent (Chu et al. 2014)

Rule #2: *An agent chooses intermediate navigation points based on its navigation destinations and its knowledge of the building.*

When an agent does not have a particular navigation destination, it chooses randomly one of the navigation points to explore the space. When the agent has a particular navigation destination, it selects the next navigation target based on its knowledge of the building layout. For example, an agent having the knowledge of a familiar exit would choose among the navigation points the one that is nearest to the familiar exit (Gärling et al., 1986; Turner and Penn, 2002). As illustrated in Figure 5, the agent, with knowledge of the main entrance as its familiar exit, can weigh heavily and choose among the five visible navigation points the navigation point labeled 1 to move closer to the main entrance. On the other hand, if an agent does not have prior knowledge of the spatial layout, unless being influenced by other information, the agent assigns equal weight to all the options and choose a navigation target randomly.



(a) Agent's trajectories with "memory"   (b) Agent's trajectories without "memory"

Figure 6. Agent's trajectories navigating space with and without memory

Rule #3: *An agent "memorizes" the traveled space to avoid backtracking.*

During the simulation, an agent can memorize the areas traveled by registering the traveled navigation points in its cognition module. Less weight will be assigned to the visible navigation points that it has traveled before. By doing so, the agent may avoid repeatedly visiting the same area. This cognitive ability to memorize the previously traveled areas is particularly important for generating a natural navigation trajectory in a situation that an agent has no prior knowledge of the environment and attempts to explore the surroundings for exit. Figure 6 illustrates the differences in the trajectories by an agent with and without memory. As shown in Figure 6a, the agent with memory tends to explore new areas with little backtracking. In contrast, as depicted in Figure 6b, the agent without memory moves repeatedly back-and-forth to the same areas.

With the notion of visibility map, the agents in SAFEgress can perceive the surrounding to: (1) identify the obstacle-free space as visible navigation points; (2) transverse through the visible navigation points and travel to a particular destination, such as the entrance used to enter the building, through intermediate navigation points which are visible to the agents; and (3) construct a working memory of the spaces that have traveled.

3.3. Agent representation of occupants

In SAFEgress, each individual is modeled as an autonomous agent who interacts with the dynamic environment and with other agents. Each agent is given a set of static and dynamic attributes to mimic the occupants. The choice of the attributes is crucial since they implicitly determine the range of simulation tests users can perform with SAFEgress. We select the attributes that are deemed important as reported by other researchers.

3.3.1. Static attributes

Static attributes are defined prior to the simulation to specify their population type, experience profile, social group affiliation, and social traits. The agents' attributes, listed in Table 1, can be further categorized into three levels—individual, group, and crowd as described below (with the static attributes shown **in bold)**:

- At the individual level, an agent has a **physical profile**, a **level of familiarity** (Mawson, 2005) with the building, and prior **known exits** (Sime, 1983) of at least one that the agent enters. The physical profile includes attributes such as age, gender, body size, travel speed, and personal space.
- At the group level, the attributes defined for social groups include a **group leader** (if any), the **group intimacy level** (e.g., high intimacy for a family group), the **group-seeking property** (describing agents' willingness to search for missing members), and the **group influence** (describing the influence of a member to the others in the same group) (Aguirre et al., 2011; McPhail, 1991). The agents belonging to the same group share the same group attributes.
- At the crowd level, an agent's social position is defined by the **social order** which reflects the likelihood of the agent to exhibit deference behavior (Drury et al., 2009). The lower the social order, the higher the chance for the agent to defer decision to other agents when negotiating the next move. A special agent, such as authority figures, a safety personnel, etc., may have **assigned roles**, and is responsible for executing actions, such as sharing information and giving instructions (Kuligowski, 2011).

Table 1. Agents' static attributes at the individual, group, and crowd level

Individual	Group	Crowd
• Physical profile ○ Age ○ Gender ○ Body size ○ travel speed ○ personal space • Familiarity • Known exits	• Group intimacy level • Group seeking • Group leader(s) • Group influence	• Social order • Assigned roles

3.3.2. Process model and dynamic attributes

Based on the studies by researchers in disaster management and fire engineering about occupants' behaviors during emergency (Lindell and Perry, 2011; Kuligowski, 2011), we implement a five-stage process model (perception – interpretation – decision-making – execution – memorization) to update the agents' behaviors. Each stage in the process model is implemented as an independent computational module. Table 2 summarizes the dynamic attributes which describe the perceived information and the states of an agent at each stage. During the simulation, the dynamic attribute values are updated at each process stage as described below (with dynamic attributes shown **in bold**):

- The Perception Module updates four attributes:
    - **Emergency cues**, such as smoke and alarm, that are visible or audible to the agent
    - **Visible floor objects**, such as doors and signs, that are visible to the agent
    - **Visible group members** that are visible to the agent
    - **Neighboring agents** that are visible to and are located within a certain radius from the agent
- The Interpretation Module maps the current knowledge of the agent into a set of internal thresholds which describe the **urge** and **well-being** of the agent.

- The Decision-making Module invokes the decision tree modeling the behavior assigned to the agent. Given the agent's characteristics and the invoked decision tree, it looks up the agent's **behavior** and determines the long-term **navigation goal**, such as the familiar exit of the agent or the location of the group leader, and the intermediate **navigation point** given the agent's knowledge and location.
- The Locomotion Module calculates the agent's movement toward the navigation target and returns the updated **spatial position** of the agents, which are Cartesian coordinates (x, y, z) in the continuous space.
- The Memory Module registers the decision made during the simulation cycle and updates the **spatial knowledge**. The **spatial knowledge** is an array storing the navigation points that the agents have visited. The agents remembered the traveled navigation points and can later refer to the **spatial knowledge** to avoid backtracking.

Each stage mimics a cognitive process or an act by an occupant during evacuation. Collectively, these stages define the behavioral process of the occupants.

Table 2. Agents' dynamic attributes updated at different stages

Perception	Interpretation	Decision-making	Locomotion	Memory
• Emergency cues • Visible floor objects • Visible group Member • Neighboring agents	• Urge • Well-being	• Behavior • Navigation goal • Navigation point	• Spatial position	• Spatial knowledge

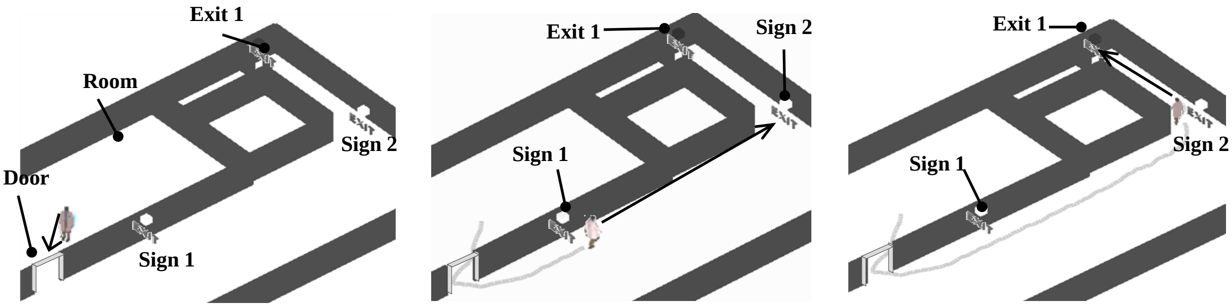
4. Implementing human and social behaviors

During evacuation, occupants may refer to their previous knowledge of the building, visual perceptions of the floor, and social cues, such as the presence of group members and others' movements, to determine their evacuation routes. This section describes a number of examples to illustrate the capability of SAFEgress to simulate some plausible behaviors exhibited by occupants in emergencies. These behaviors include following building features, following familiar exits, group behavior, and herding behavior. In each example, we discuss the motivation and observation of the behavior, as well as describe the implementation in the prototype.

4.1. Following cues from building features

The spatial arrangement of exit signs with different visual displays are important factors that can affect the movement pattern (O'Neill, 1991; Johnson and Feinberg, 1997). In situations where the occupants are unfamiliar with the environment, people rely heavily on the information from the signage to guide their navigation. Therefore, exit signs should be arranged in a proper way to provide markings of exits and escape routes in buildings and to assist the occupants in leaving the buildings effectively in case of emergency.

In SAFEgress, each agent can decide their navigation based on the perceived floor objects representing the building features, such as exit signs and doors as described in Section 3.3.2. At each simulation step, the agents detect visible floor objects and navigate the space according to the direction given by the floor objects. Figure 7 illustrates the process that an agent navigates the space by perceiving and following the guidance from the visible floor objects and escaping via visible exits. Initially, the agent chooses to navigate toward the only visible floor object, which is the door as shown in Figure 7a. After exiting the room via the visible door, the agent detects new floor objects, which are the two exit signs (Sign 1 and Sign 2). As the agent detects more than one visible objects, the agent weighs each object according to three criteria: (1) the object type (namely exits, doors, and signs), (2) the distance of the object from the agent, and (3) the number of times of prior visits to the object. Because both objects are “sign” objects and have not been visited before by the agent, the agent chooses to navigate toward the nearest sign, Sign 1, which is indicated in Figure 7b. Upon arriving at Sign 1, the agent evaluates all visible objects and chooses to go to Sign 2 (Figure 7b). As the agent moves near Sign 2, the agent detects a new floor object, Exit 1; the agent then weighs all the visible floor objects, chooses to go to Exit 1, and exits the floor (Figure 7c).



(a) Agent moves towards visible door

(b) Upon arriving at Sign 1, the agent chooses to move towards Sign 2

(c) Agent navigates toward the detected exit

Figure 7. Navigation by following building features

We further apply SAFEgress to analyze the effects of different exit sign arrangements on egress performance. Figure 8 shows the floor layout of a museum which consists of several exhibition halls with four main exits (the entrance, the north exit, the west exit, and the café exit). The floor space is populated with a total of 360 agents who have medium level of familiarity and have no prior knowledge of exits. They exit the floor by following the cue from floor objects. We model different exit sign arrangement with the same building model to trigger different navigation patterns of the agents. The effects of signage arrangements on evacuation outcomes are compared by: (1) changing the number of exit signs and (2) rearranging the orientation of the exit signs.

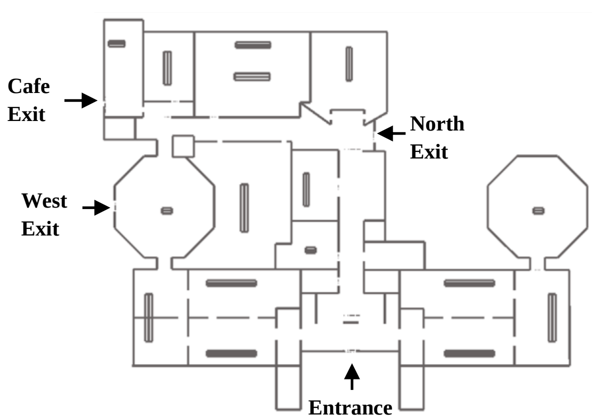
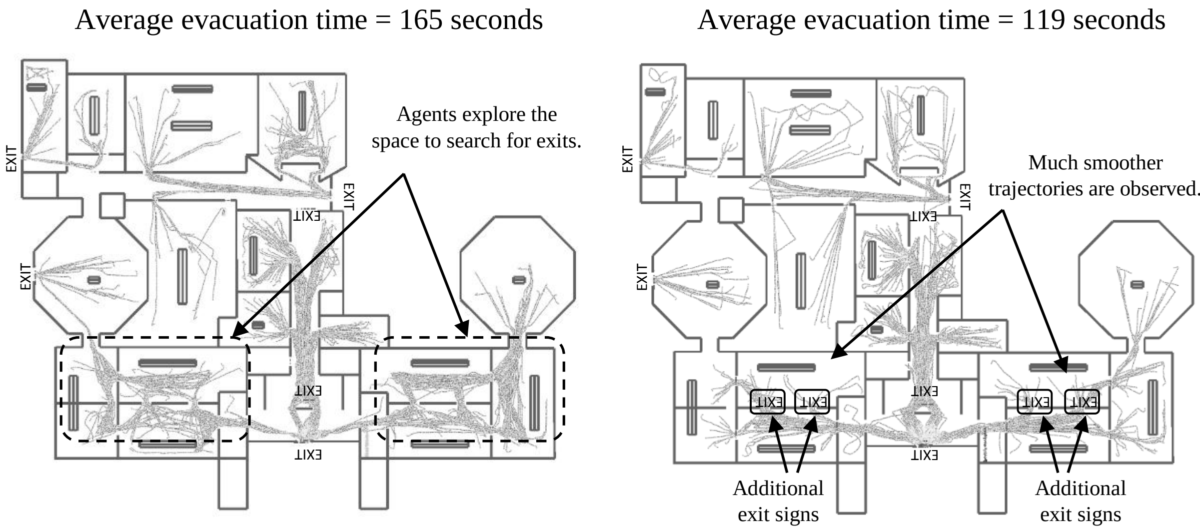


Figure 8. Building layout and exit locations



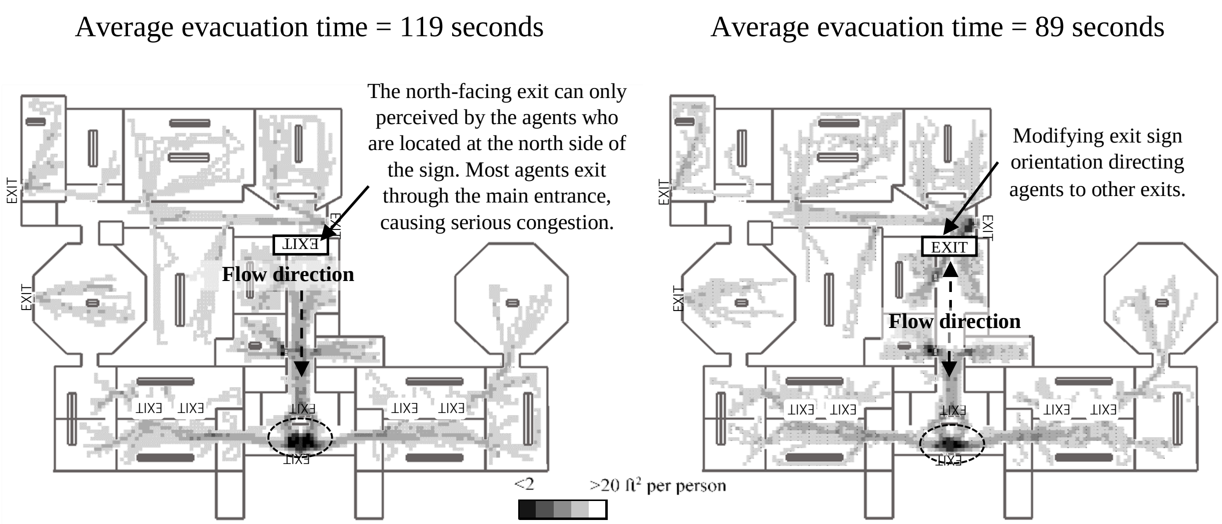
(a) Initial layout of signage arrangement. (b) Layout with additional signage.

Figure 9. Evacuation patterns of evacuation assuming different signage arrangements

The first test studies the effect of additional exit signs on evacuation performance. Figure 9a shows the initial layout of exit signs and the trajectories of agents exiting the building. The total evacuation time is 165 seconds (averaged over 10 simulation runs). As highlighted in the figure, in this initial exit sign arrangement, agents take detours and explore the floor before find their way to exit. With additional exit signs posted, as shown in Figure 9b, the agents travel with more direct routes, and the evacuation time takes 119 seconds (a decrease of 28% in time compared to that of initial layout of fewer exit signs).

The second test illustrates how changing the exit orientation can help direct crowd flow. As shown in Figure 9, with the sign arrangement in the first test case, agents tend to exit through the main entrance and cause the congestions at the main entrance. As shown in Figure 10, we change the facing direction of an exit sign (depicted with rectangular box) in the main aisle. With the proper exit orientation, more agents perceived the exit sign and its direction and evacuated through the near exit. As a consequence, the evacuation time is 89 seconds, a further improvement of 25%. This example clearly illustrates the importance of appropriately arranging exit sign to effectively guide the crowd for evacuation and alleviate congestion.

Assessing the effectiveness of a signage system is difficult in real setting because this kind of assessment requires experiments with occupants in the buildings. Modeling salient safety features in egress simulations allows designers to improve egress performance by analyzing different evacuation patterns as a result of different signage systems.



(a) Original the exit directing flow towards main entrance.

(b) Re-orientation of exit sign directing flow to other exits.

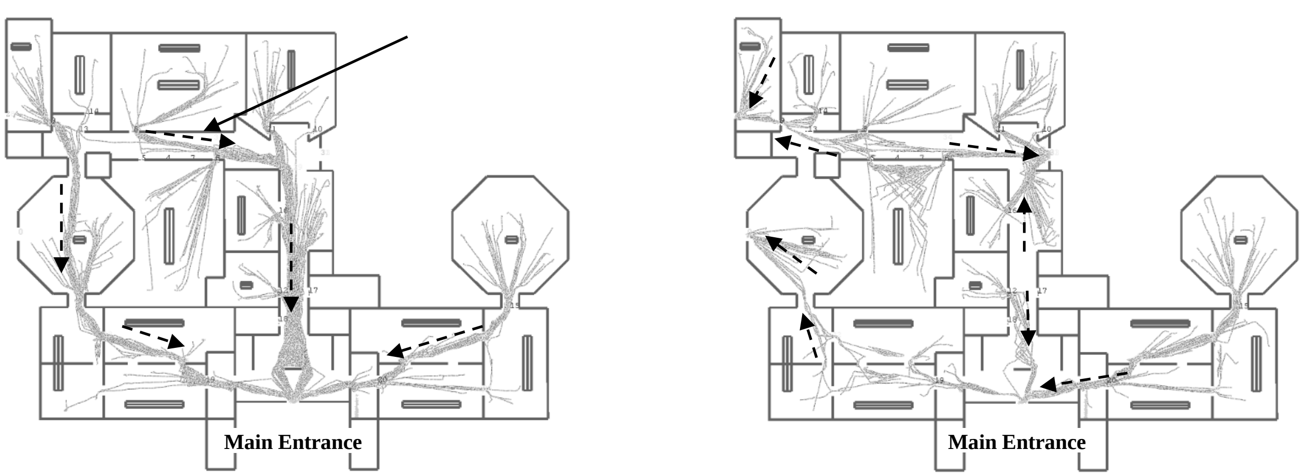
Figure 10. Congestion patterns assuming different signage arrangements

4.2. Following familiar exits

Occupants choose evacuation routes based on their previous experience and knowledge (Mawson, 2005; Sime, 1983; Tong and Canter, 1985). Occupants who visit the building regularly may have learned their preferred exits over time or have knowledge of the nearest exits. They may also have evacuation drill experience from which they learned the instructed evacuation routes in case of emergency. To incorporate the effect of known exits into agents' route choices, we make use of the agents' static parameter, known exit(s). We model the "following familiar exits" behavior as follows: prior to the simulation, the user assumes the parameter value of the attribute, known exits, of the agents, indicating that the agents have knowledge of one or more known exits. During the simulation, the agents query the spatial model with the known exits and retrieve the shortest paths to the known exits. At the decision making stage, the agents choose to move to the visible navigation points along the shortest paths to get to their known exits.

Figure 11 shows an example floor plan and evacuation patterns resulted from assigning different known exits to 200 agents. In Case 1, agents have the knowledge of the main entrance and exit through the main entrance. The arrows in Figure 11a show the emerging crowd flows as agents travel to the main entrance. In Case 2, agents have the knowledge of all exits and choose to evacuate through the nearest exit given their initial starting positions. The arrows in Figure 11b show the diverging crowd flows as agents travel to their nearest exits. Besides the differences in the crowd flow patterns, the assumption of different known exits also changes the evacuation time significantly. The average evacuation times over 10 simulation runs are 106 seconds and 70 seconds for Case 1 and Case 2, respectively. The longer evacuation time in Case 1 is due to the longer travel distance and congestion at the main entrance.

Average evacuation time = 106 seconds   Average evacuation time = 70 seconds



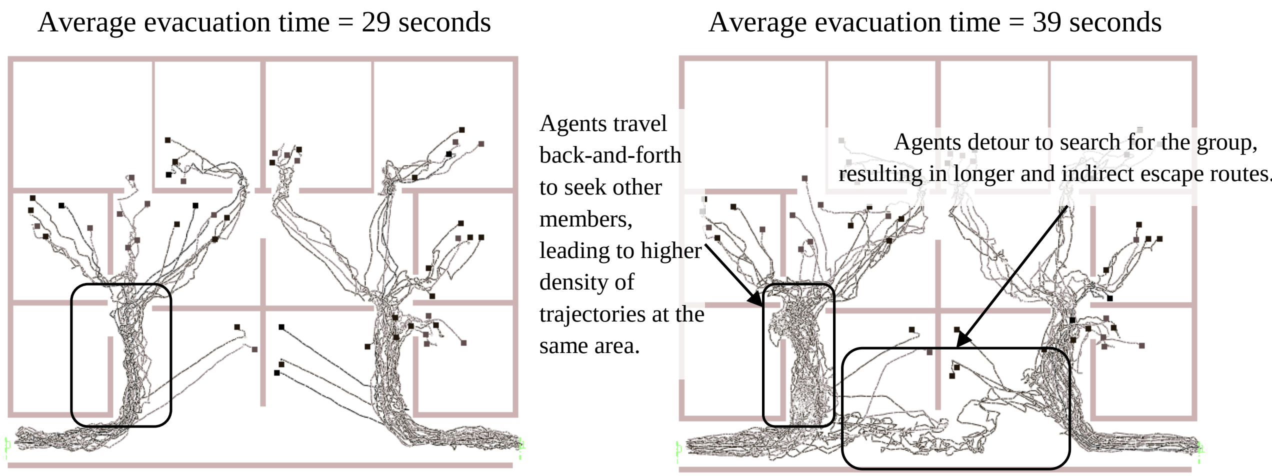
(a) Agents exit through main entrance   (b) Agent via the nearest exits

Figure 11. Evacuation patterns with different exit assignments

4.3. Navigating with social group

During evacuation, members belonging to a group, such as families and close friends concerned the safety of their group members, and often seek out and evacuate with the entire group even when evacuation is urgent (Aguirre et al. 2011; Sime 1983). We model this group behavior using two group-level static attributes: group separation distance (measured as the desirable physical distance between members) and group-seeking (measured as the desirable percentage of members that are visible). We assign a low value (average distance of 4ft to each visible group member) to the group separation distance attribute (i.e. agents try to maintain close proximity with other group members) and a high value to the group-seeking attribute (i.e. all group members have to be visible to the group) to simulate agent groups with close relationships. Figure 12 shows a comparison of the evacuation patterns of agents with and without group affiliations by varying the group-seeking attribute.

In the example showing in Figure 12, we assume all 50 agents evacuate at once. We test the effect of group affiliation on evacuation patterns. The first case assumes each agent evacuates as an individual through its familiar exit (which is the nearest exit to the agent). Figure 12a shows the evacuation pattern of agents without any group affiliation, and the average evacuation time is 29 seconds (averaged over 10 simulation runs). In the second case, we test the effect of group behaviors by assigning all agents with group affiliation (group size ranges from three to five agents). All groups are assigned with a high group-seeking value, such that all members in the group have to be visible to each other before the members in the group start to evacuate. In this case, as shown in Figure 12b, agents pace back-and-forth, and even detour, as they seek other group members. In this scenario, the average evacuation time increases to 39 seconds (averaged over 10 simulation runs). The longer evacuation time in the group-seeking scenario is possibly contributed by longer and indirect routes taken by the agents as they search for the missing group members. By varying the value assigned to the group-seeking attributes, we can alter the level of desire for the group to look for other members. Similarly, by adjusting the group separation distance of the social group, we can simulate different types of groups with different levels of intention to follow other group members. Depending on the initial distribution of the group members and their relationships, group behaviors in egress simulations affect the evacuation time and the escape routes.



Note: Black squares (■) indicate initial positions of the 50 agents.

(a) Evacuation as individuals via nearest exits (b) Evacuation with group affiliation

Figure 12. Evacuation patterns with and without group affiliation

4.4. Following crowds

As the first signs of a potential threat are often ambiguous (Tong and Canter, 1985), people may spend a substantial amount of time to investigate and interact with one another before deciding how to respond (Sime, 1983). The movement of some evacuees toward different exits provides others with social cues of the availability of alternative exits. Often, as opposed to moving towards familiar exits, people may follow social cues and choose the exits preferred by the crowd as they observe others' actions. We model the "following the crowd" behavior as follows: during the simulation, the herding agent (who is seeking to follow other agents) perceives the space and detects visible floor objects. At the decision making stage, the herding agent assesses, for each visible floor object, the number of neighbors who are traveling towards the floor object. The herding agent chooses the visible floor object with the highest number of neighboring agents traveling towards because the agent considers the movement of its neighbors as a social cue to explore potential areas for exits. If there are no visible floor objects that other agents move to, the agent then will adopt other navigation strategies, such as referring to their known exits (as described in Section 4.1) or following the visual cues (as described in Section 4.2).

Figure 13 illustrates the differences in agents' trajectories when 100 agents with and without crowd following behavior. As shown in Figure 13a, when agents follow only visual cues, the usage of the two exits is about even. When half of the agent population (i.e. 50 agents) exhibit crowd following behavior, as shown in Figure 13b, one of the exits became more congested. In real situation, the escape routes taken by the occupants who initiate the evacuation can have an impact on the congestion patterns as other occupants who are unsure or unfamiliar with the situation will tend to follow the crowd. Herding and overcrowding phenomena emerge as the crowd triggers individuals to exhibit crowd following behaviors. By including the perception of crowd movement, our framework captures the emergence of crowd following phenomenon.

(a) Agents with individual behaviors exiting via the nearest exits

(b) Agents with herding behaviors and with individual behaviors

Figure 13. Evacuation patterns with and without herding behaviors

5. Discussion

The building geometry unique to each building and the layout of building emergency features (such as exit signs and doors) can trigger different navigation decision of the occupants during egress. SAFEgress allows users to assess different building geometries and egress systems in a flexible manner. Furthermore, sensitivity analysis on different agent attributes can be conducted in SAFEgress to identify and assess the impacts of important social factors in different physical and environmental settings, as illustrated in the four examples presented in this paper. This kind of analysis can give insights to architects, building designers, and facility managers to design user-centric safe egress and improve emergency procedures and training programs.

Our simulation results confirm the needs of incorporating occupants' perception, previous knowledge, and social behaviors in egress simulation. In our examples, we show that different arrangements of exit signs, social settings of the agents and prior knowledge and familiarity with the building could trigger different crowd behaviors and crowd flow patterns. By embedding individuals into groups, our model has the capabilities to model occupant behaviors such as the spreading of information within social groups and crowds (Rydgren 2009; Hoogendoorn et al. 2010) and the role of authorities (Kuligowski 2011). In broader terms, we see our approach to modeling social behavior to be in line with recent efforts in computational social science to capture emerging social behaviors using computer-simulation and large datasets made available through digital technology and new forms of communication (Lazer et. al., 2009). The described platform represents a step forward toward incorporating social science knowledge of social interactions into engineering models that capture human behaviors.

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