TENDENKO: Agent-Based Evacuation Drill and Emergency Planning System

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Abstract. Evacuation drills are conducted periodically to practice smooth evacuations from buildings and rescue operations at emergency sites. An agent-based evacuation simulation provides a platform for simulating human evacuation behavior during emergencies, which can be affected by various social and human factors. These factors include agent characteristics, societal behavior codes, evacuation guidance, and so on. These factors make it difficult to conduct evacuation drills and develop prevention plans for unexpected emergencies. TENDENKO aims to simulate evacuation drills at buildings where real drills cannot be conducted, and to improve evacuation planning for the building to save more lives during future emergencies.

1 Introduction

During emergencies, it is extremely important to safely exit buildings and perform rescue operations quickly. Evacuation drills are conducted periodically at schools and shopping malls to practice smooth evacuations and effective rescue operations. The drills are used to estimate the time taken to exit buildings (exit time) and improve prevention plans for predictable emergencies. However, it is difficult to conduct drills involving many people in various scenarios in real environments.

Disaster reports have provided crucial lessons on reducing human casualties. One key lesson is that people tend to respond individually during emergencies. Emergency information is usually announced through speakers or circulated as people communicate with each other. The rapidity with which people respond to announcements and the behavior people demonstrate can influence their own lives and those of the people around them. Evacuation announcements significantly influence human behavior during emergencies.

In a study on a 1965 Denver flood, Drabek found that most behavioral responses could be classified into four categories, namely appeals to authority, appeals to peers, observational confirmation, and latent confirmation [1]. Documents held by the National Institute of Standards and Technology (NIST) related to the World Trade Center attacks on September 11, 2001, and reports from the cabinet office of Japan on evacuations during the Great East Japan Earthquake (GEJE) and resulting tsunami on March 11, 2011, reveal similar

F. Grimaldo and E. Norling (Eds.): MABS 2014, LNAI 9002, pp. 167–179, 2015.
DOI: 10.1007/978-3-319-14627-0_12

evacuation behavior patterns and individual responses over the past 50 years, despite changes in the way people communicate [2,3].

To evaluate the effectiveness of evacuation drills, it is necessary to analyze human evacuation behaviors from two perspectives: the perspective of the evacuee and the perspective of the rescue responder. The evacuee perspective is concerned with how quickly and safely they can evacuate buildings. Conversely, rescuers are concerned mainly with how smoothly and efficiently they can reach target points and begin rescue operations. TENDENKO[1] provides three features in simulating the evacuation of a crowd of heterogeneous agents (i.e., evacuees and rescuers) in realistic situations. First, emergency information is announced to agents; agents then communicate information about the evacuation via various methods. Second, agents have social and personal relationships between them and behave according to their roles within these relationships. Third, some rescue agents move against the flow of evacuee agents, thus introducing perception-driven behaviors at the reactive level.

The remainder of this article is organized as follows. Section 2 describes the background and provides a review of the literature. In Sect. 3, features in the emergency planning fields are described. Evacuation scenarios and simulation results are discussed in Sect. 4, and a summary is provided in Sect. 5.

2 Background and Literature Review

2.1 Emergency Behaviors and Lessons

The International Organization for Standardization (ISO) published a technical report providing information on evacuees' behavior during evacuations in fire emergencies, and evaluated the impact on aspects contributing to securing human lives [4]. They divided evacuation time into several stages:

t_{pred} : The interval before the actual emergency occurs.
t_{warn} : The interval between emergency occurrence and the time authorities initiate alarms or warnings to individuals.
t_{evac} : The time it takes individuals to reach safe locations after hearing the alarms. It is comprised of pre-travel activity time (PTAT) and the time individuals require to move to safe locations.

Table 1 illustrates the time sequence for information dissemination during the GEJE. There were approximately 45 min before the tsunami's full impact. This period comprised two stages: t_{warn}, from 14:46 to 14:49, and t_{evac}, from 14:49 to 15:15. According to the GEJE report, only 40 % of evacuees heard the loudspeaker emergency alert warning. Of those that heard the warning, 80 % recognized the urgent need for evacuation, while the other 20 % did not understand the announcement because of noise and confusion.

For the World Trade Center (WTC) attack, the NIST report indicates that, when the planes crashed into the buildings, evacuation messages were announced

[1] Named after a Japanese tradition of saving lives from tsunamis.

Table 1. Event sequence for the GEJE (March 11, 2011)

Time	Events
14:46	Emergency earthquake alert system
	Earthquake bulletins broadcasted
	The earthquake continued for about 6 min
14:49	Tsunami warnings were issued: "A big tsunami will hit at around 15:10"
15:15	Aftershocks occurred
15:00–15:25	An initial, relatively small, tsunami struck
15:25–15:40	A much larger tsunami arrived

in buildings following guidelines provided in a manual. Individuals in both buildings (WTC1 and WTC2) began to evacuate when WTC1 was attacked. When WTC2 was attacked 17 min later, approximately 83 % of WTC1 survivors remained inside the tower. Approximately 60 % of survivors remained inside WTC2. WTC1 and WTC2 were similar in size and layout, and nearly an equal number of individuals were present in both buildings during the attacks. The NIST report identified dissimilarities in evacuation percentage fluctuations between the two buildings. The differences originated from interactive and social factors related to leadership or evacuation guidance announcements.

Drabek pointed out similar factors in sections of his study entitled "But not everyone responds the same" and "Confirmation: a likely action" [1]. People typically attempt to confirm the information in warning messages in numerous ways.

These disaster reports share common lessons:

- Some individuals evacuated immediately when the disasters occurred. However, others failed to evacuate, even though they heard the emergency alarms sounded by the authorities.
- The latter category included individuals with family members located in remote areas, those who attempted to contact their families by phone, and others who continued to work because they believed they were safe.
- Once individuals understood their situation and received emergency information and building layouts, and were able to address concerns about their families' safety, they implemented the announcement information. They also benefitted from communication with other individuals.

2.2 Evacuation Simulation Systems

During emergencies, the behavior of humans differs from their usual behavior. People's mental condition affects their behavior. For example, when people fear for their physical safety, they tend to think of only themselves, and flee a building without considering anything or anyone else. However, when no anxiety is experienced, people tend to consider others and evacuate together. Based on the empirical findings of their study, Perry et al. summarized these human relationship factors in the decision-making process [5].

Agent-based simulation (ABS) provides a platform for the development of computing behavior related to interactive and social issues [6]. Through ABS, Pelechano et al. illustrated that communication among people improved evacuation rates [7]. They devised a scenario focusing on two types of agents: (1) leaders who help others and explore new routes; and (2) agents who might panic during emergencies that occur in unknown environments. Tsai et al. developed ESCAPES, a multi-agent evacuation simulation system incorporating four key features: (1) different types of agents; (2) emotional interactions; (3) informational interactions; and (4) behavioral interactions [8]. Using a multi-agent system, Prikh et al. simulated human behavior in the aftermath of a hypothetical, large-scale, human-initiated crisis in the center of Washington D.C. using a multi-agent system [9]. Okaya et al. proposed an information dissemination model among people during evacuation and presented simulation results using a large number of people [10]. These key features have been used to estimate evacuation times during building design processes or to develop prevention plans that might minimize damage and loss of human lives.

Hui et al. developed a network information diffusion model [11], and Abbas investigated how local preferences affected the network development [12]. These studies focused on information diffusion in human relationship networks.

3 Agent-Based Evacuation Drills and Planning

3.1 Agent States Transitions from Hearing Information to Evacuation

The sounding of alarms and subsequent guidance provided by authorities changed the behavior of individuals during emergencies. PTAT in t_{evac} represents the elapsed time between the moments individuals first heard warnings until the time they began to evacuate. PTAT involves two stages, namely recognition of the emergency and responding to it. Agent behavior during these two stages plays a critical role in the speed of the evacuation.

Figure 1 illustrates how individuals internally process authorities' guidance information and transfer this information to others. Individuals obtain information by experiencing the emergency as it unfolds around them: They hear authorities' announcements or exchange emergency information with each other by communicating (these actions are represented by solid black arrows in Fig. 1). Once they have received the information, individuals attempt to comprehend it by comparing it with their own knowledge and/or experiences. Next, they plan their subsequent actions based on their comprehension (these actions are represented by dotted blue arrows in Fig. 1).

The authorities, as one component of the environment, serve as an information source. Messages sent to individuals comprise warnings related to predictable emergencies or guidance that provides evacuation instructions. Individuals select

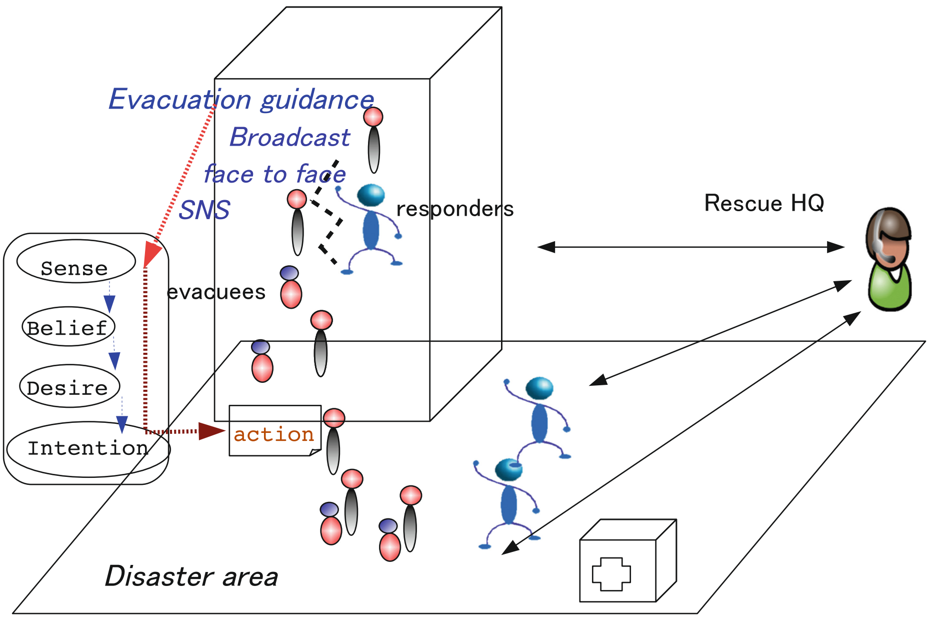


Fig. 1. Information diffusion model and agent behavior (Color figure online)

their actions based on their own knowledge and experiences, and their roles in the community. The Belief-Desire-Intention (BDI) model represents individuals' internal selection processes. Mental biases are represented by the filtering functions that operate from sensing data to the set of belief, from the belief to desire, and the desire to the set of intention.

3.2 Guidance Information Transfer During Emergencies and Evacuation

Noise can affect the dissemination of information during emergencies and can prevent individuals from selecting appropriate strategies that could help them evacuate safely and quickly. The first stage involves individuals' abilities to sense environmental data. Some individuals miss announcements or misunderstand messages. The second stage involves individuals' action choices based on their personal databases, including personal relationships comprised of data compiled by their senses.

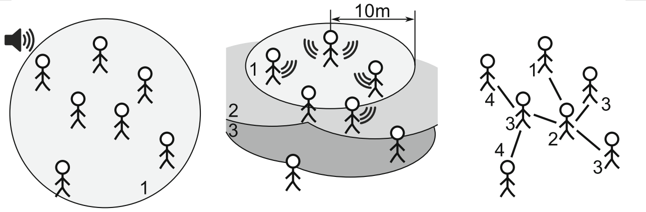
The choice of actions during the second stage can be reviewed according to Weaver's levels in Shannon's communication model [13]:

Level A: How accurately can the symbols of communication be transmitted? (The technical problem)

Level B: How precisely do the transmitted symbols convey the desired meaning? (The semantic problem)

Table 2. Communication methods used to communicate emergencies to others.

types	broadcast	face-to-face	SNS
range	entire building	surrounding	no range
number	large	small	middle
trust	low	middle	high



Level C: How effectively does the received meaning affect conduct in the desired way? (The effectiveness problem)

During emergencies, it is assumed that individuals hear evacuation warnings or guidance (Level A). This level is related to the type of communication devices employed. After hearing the messages, people transfer the message content to others. Some contents may be missed because of the "broken telephone" effect and new information added to messages by recognizing dangers involved in the situation outlined in the announcement (Level B). In a situation where the speaker desires people to seek refuge in a safe location, the intent of the speaker is completed when people start evacuating to safe locations (Level C). The dotted red arrow in Fig. 1 illustrates communication that occurs at Levels B and C.

Information passed on to people during emergencies is usually announced through speakers or shared by people communicating with each other. As soon as individuals hear announcements by the authorities or receive phone calls from others, they tend to perform the following actions: transfer the information to others; confirm the information with people nearby; or evacuate. How quickly a person responds to announcements or calls depends on how trustworthy they regard the source. Three different types of communications are modeled, namely broadcast (announcement), face-to-face (word of mouth), and social network (e-mails) (Table 2).

Broadcast: Announcements by authorities are broadcast to the general public through a PA system.

Face-to-Face: People speak to others in their vicinity. The communicator may be a stranger to the receivers. The area the voice reaches(range) is limited, and the message is disseminated following the "broken telephone" pattern, which often results in changes to the message.

Social network: SNS provides simultaneous communication transmission methods using the Internet. In numerous instances, receivers receive messages from friends and therefore tend to trust them.

3.3 Reactive-Level Behavior from Perception of Agents' Roles

People swerve when nearly colliding with each other. When people see responders approaching, they automatically make way for them to pass. While these two behaviors are similar, they do differ at a conscious level. The motions in the latter scenario are reactive-level behaviors. Our system categorizes the agents around an agent into three groups to take into account the unwritten behavior codes of the agent's community:

G_g**:** normal agents, agents around the agent make no special considerations for the agent and the agent expects that no considerations would be made for itself.
G_h**:** agents with high priority, the agent gives them special consideration.
G_l**:** agents with low priority, the agent expects that special considerations are expected from them.

The normal agent unintentionally makes way for rescuers and the disabled, who are categorized as G_h agents. For occupants, a rescue responder is a G_h agent, whereas, for the other responders, the responder is categorized as a G_g agent by other responders.

4 Simulations for Evacuation Drills and Planning

4.1 TENDENKO: Simulation Platform

During emergencies, the behavior of humans differs from their usual behavior. Social relationships among people, their emotions, and other factors are also different from individual to individual. TENDENKO consists of an authority setting mode and an evacuation simulation mode. The evacuation simulation mode can simulate the behavior of people during emergencies, while considering people's social and psychological factors [10]. The main components of the simulation system are described below.

Agents: The number, location, role, and type of agent are set in the authority mode according to the drill scenarios. Agent roles are rescuers, security officers, and evacuees. The different agent types specify their actions upon hearing the alarm: some people evacuate immediately; others do not, despite hearing the announcements sounded by authorities. Agents' behaviors are represented in the BDI models [14].
Environments: The environments are 3D CAD models of buildings with different communication model parameters. Three different types of communication models are implemented in the current version. Table 2 lists three types of parameters: broadcast (announcements), face-to-face (word of mouth), and social network (e-mails).
Dynamic Model: The motions of an agent are simulated based on the forces determined by Helbing's social force model. The force comprises two forces: motions to go to the place of the agent's targets and interaction forces to avoid collision with other agents and walls around the agent. The difference

in the categories of other agents is considered when calculating the interaction force of reactive-level motions.

4.2 Examples of Evacuation Drill Scenarios

Followings are examples of evacuation drill simulations.

Subterranean shopping mall evacuation. Many people visit malls. Figure 2 (a) illustrates a subterranean mall in our city, Nagoya. The mall has approximately 90 shops distributed into three rows; there are two main walkways between the rows. Exits to the ground level are located every 50 m. A total of 4,039 people were randomly positioned throughout the mall. After reviewing TENDENKO's simulation, the management company of this subterranean mall prepared emergency manuals, and periodically conducts drills based on these manuals.

Building evacuation and rescue operations. Many people work in buildings. During emergencies, rescue teams enter the building to conduct rescue operations as the building occupants evacuate the building. Figure 2 (b) shows the facade of a five-story library building and an image of the agents' behavior on the second floor. The scenario depicted is of 1,000 occupants (200 occupants on each floor) evacuating the building at the same time, during which a rescue team enters the building to implement rescue operations.

4.3 Results of Evacuation Simulation

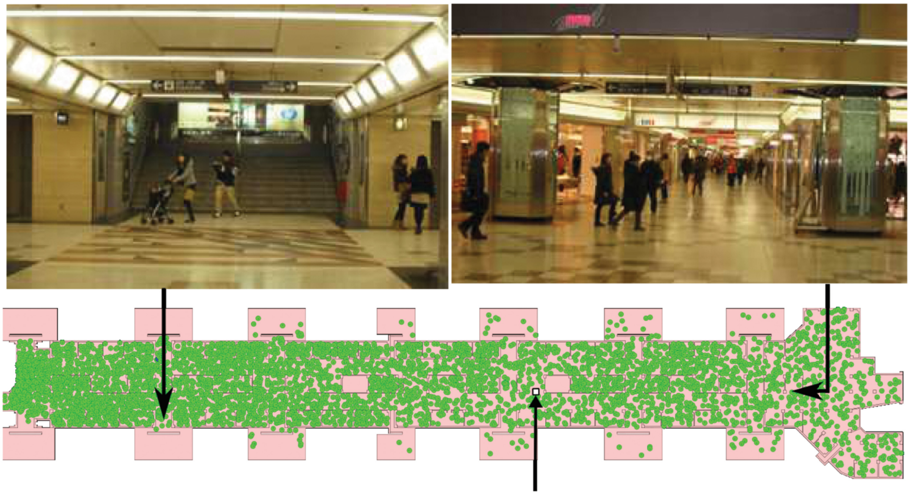
Evacuation at a Subterranean Shopping Mall. Evacuation scenarios at the shopping mall were as follow: Fire alarms were set off to communicate the need to move to safe locations to people. Evacuation guidance was simulated through three communication styles.

Scenario 1: At the start of the emergency, all agents were taken through the evacuation guidance once.

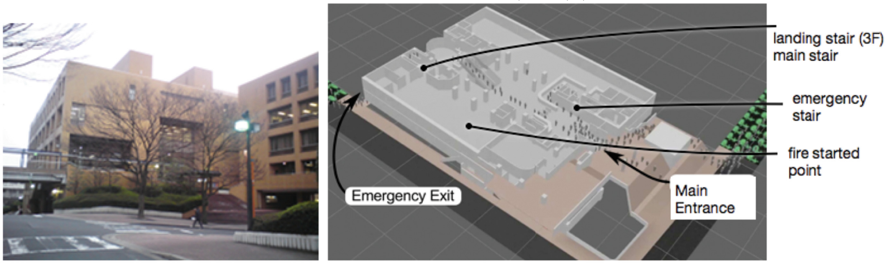
Scenario 2: The PA system was assumed to be disabled during the emergency. Therefore, emergency news were transmitted through face-to-face communication. People within 10 m of the speaker were able to hear the guidance.

Scenario 3: People exchanged information through their mobile-phones or SNS. A Facebook social circle was used as an example of such networks [15]. Figure 3 indicates the distributions of nodes in the network used in the simulation.

The graphs in Fig. 4 indicate how agents evacuated the mall (evacuation rate: the left vertical axis) and the number of agents who heard the announcement (diffusion rate: the right vertical axis). As indicated in Sect. 3.2, various factors influence agents' decisions to begin evacuating during an emergency. For example, how precisely the information is transferred to others and whether they start action. In TENDENKO, the factors are treated as a parameter of p that agents



(a) Image depicting the mall interiors and the initial position of 4,039 agents. (Arrows point to agents who communicate emergencies face-to-face or via social networking services (SNS).)



(b) Library facade (left) and image of agent behavior on the second floor (right).

Fig. 2. Evacuation drill places and simulations.

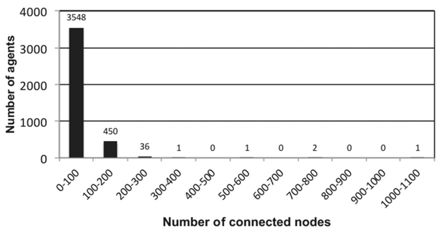
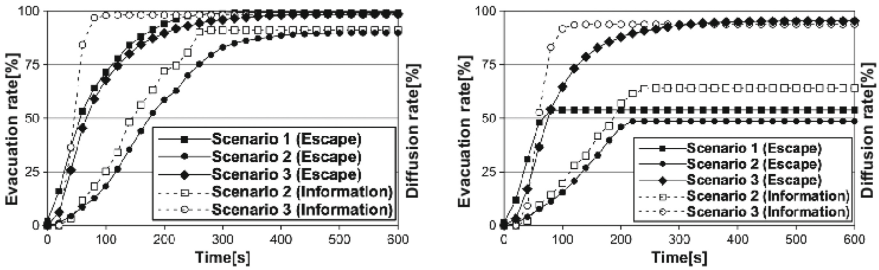


Fig. 3. Distribution of node degress in the SNS Network.

process sensing data. This parameter represents the rate at which an agent initiates actions after receiving guidance or calls along the flow as a dotted red arrow in Fig. 1.



(a) case of p=100%.

(b) case of p=50%.

Fig. 4. Evacuation rates and diffusion rates based on three communication styles. (a) All people evacuate instantly when they hear alarm announcement. (b) Half people evacuate instantly and others continue shopping.

Scenario 1 in Fig. 4 (a) is an ideal scenario because all people instantly started evacuating upon hearing the announcement (rate $p = 100\,\%$). In Scenarios 2 and 3, an agent (pointed by an arrow in Fig. 3) spoke first to others around him/her or sent mails to SNS friends. Half the number of receivers evacuated instantly, while others continued shopping (rate $p = 50\,\%$) as shown in Fig. 4 (b). Figure 5 are snapshots of evacuation simulation. The following can be deduced from the graphs:

1. The evacuation rate is proportional to the diffusion rate. Broadcast rates were limited to a certain rate and the rates of other types of communication over time.
2. Communication via the SNS network among agents leads them to carry out quick evacuation.
   (a) At $p = 100\,\%$, the evacuation rate with SNS (scenario 3) is nearly equal to the evacuation rate with guidance (scenario 1).
   (b) At $p = 50\,\%$, the evacuation and diffusion rates with SNS (scenario 3) increase as per the progression of steps, becoming nearly $100\,\%$. This is because people who received messages from SNS friends multiple times had more prompts to start evacuating than others who heard the messages only form people around them.

These results indicate that the provision of accurate information is a crucial factor in guiding evacuations during emergencies. In addition, while broadcast communication among agents is ideal, this does not guarantee the dissemination of information to all people during an emergency.

4.4 Evacuation from Building and Rescue Operations

Figures 6 (a) and (b) illustrate the counterflow of occupants and fire responders at the main entrance. The occupants (light-colored body with dark arrow) exit from left to right and the responders (black body with white arrow) enter the

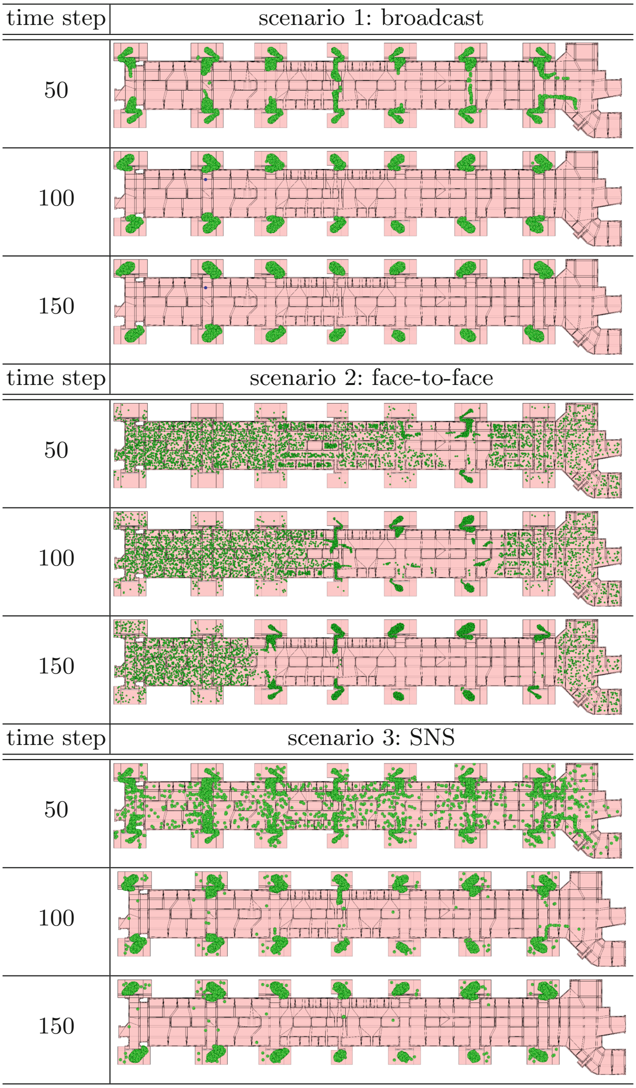
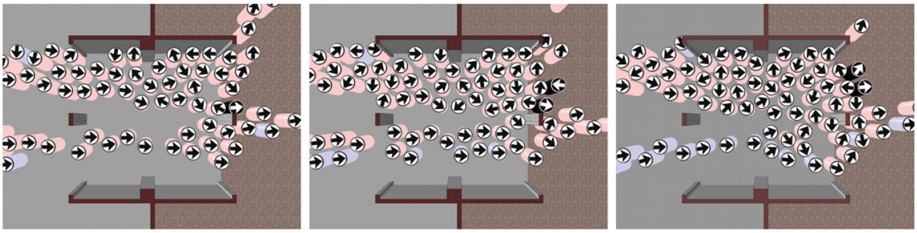
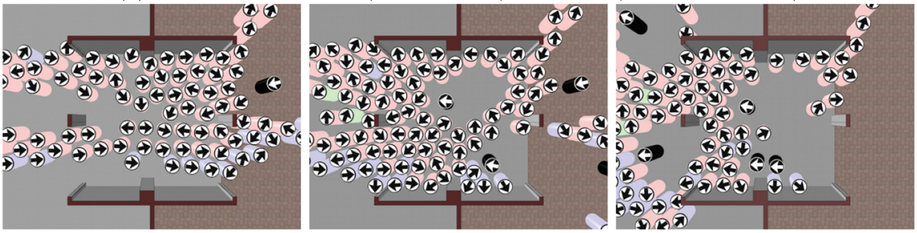


Fig. 5. Snapshots of evacuations at steps 50, 100 and 150.

building from right. The triangles on their heads indicate the directions of their movements. Figures 6 (a) and (b) are snapshots of occupants without and with perception-driven behavior respectively. The time-sequence is ordered from left to right. The simulation time steps are 40, 45 and 50 respectively. In the case of occupants without perception-driven behavior, the rescue team cannot enter the building against the flow of evacuating occupants. In the case of occupants



(a) without perception (responders (black body) remain outside)



(b) with perception (responders move inside against occupants (light color body))

Fig. 6. Building evacuation simulation: Snapshots of counter-flows between occupants and rescue responders entering the building from the right (Color figure online).

with perception-driven behavior, the occupants recognize the rescue agents in the G_h category and make way for the responders to enter the building. The rescue team can enter and move to the appointed position in the building.

5 Discussions and Summary

During emergencies, emergency information is crucial in ensuring that all people are safely evacuated from buildings and that rescue operations can be conducted quickly. Today, nearly everyone has a mobile phone, and people communicate with each other using SNS. This type of communication has increased the number of people who can be alerted of ongoing emergencies, and thus has the potential to assist in the instant evacuation of many more people than previously possible. In addition, SNS can help improve emergency prevention plans.

TENDENKO supports communication among agents by providing evacuation guidance to agents via face-to-face and SNS communication models in addition to the traditional broadcast announcements using PA systems. The differences in communication methods, the content of such communication, and the source of announcements can yield different simulation results. The simulation results we obtained indicate that, to plan for real situations, TENDENKO can evaluate existing emergency planning systems and improve the effect of such planning in buildings and areas where evacuation drills cannot be conducted.

This work was supported by JSPS KAKEN Grant Number 24500186.

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