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Agent-Based Evacuation Behavior Simulations and Evacuation Guidance

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Abstract: Building evacuation analysis has recently received increasing attention, as people are keen to assess the safety of occupants. Reports on past disasters indicate that human behavior characterizes evacuation during emergencies. The understanding and modeling of human behavior enable improved design of evacuation plans to better reflect the needs of occupants — for example, to reduce evacuation time, a composite of pre-movement time and travel time. In this paper, we demonstrate that information at the time of emergencies affects human behavior and that this behavior affects pre-movement time and the time it takes to move people to safe places. Information is shared with people via announcements and through interpersonal communication. We have modeled and simulated information transfer in an agent-based evacuation system, using BDI models that represent the diversity of human psychological states and using ACL-based communications that dynamically change people's beliefs. The model enables an evacuation simulation to consider the effect of information on human behavior and calculate evacuation time, including pre-movement time. The simulation results demonstrate that methods of guidance improve evacuation time, and they reveal phenomena in agent behaviors that have not been simulated by other methods.

Keywords: evacuation simulation, human behavior, evacuation guidance

1. Introduction

Pedestrian dynamics and crowd analysis are becoming a common framework for many multidisciplinary studies, ranging from building simulation and architectural design to sociology and behavioral analysis [1]. It is widely accepted that proper evacuation saves many lives in emergencies and that preparations for them as a routine are important. Evacuation drills have been conducted at schools and shops with intent to enable safe and quick exit, and to conduct rescue operations properly in emergencies. It is difficult to conduct physical drills that involve many humans and real environments. Evacuation simulation systems have been employed to analyze behaviors, calculate the egress time from buildings, and check the design of the buildings and prevention plans [2].

Human behaviors in emergencies have been reported in past disasters. The National Institute of Standards and Technology (NIST) reported occupant behaviors at the World Trade Center (WTC) on September 11, 2001 [3]. The cabinet office of Japan reported how people evacuated during the Great East Japan Earthquake (GEJE) and the resulting tsunami, which occurred on March 11, 2011 [4]. Those reports have two issues in common:

(1) Some people evacuated at once, but others did not evacuate immediately after authorities alerted them about the emergency. People know that accidents and subsequent guidance from authorities are important in deciding their actions. They started their evacuations at several different times.

(2) Some people thought of family members in remote places and tried to contact them by phone, while the majority of people moved to a safe place. Information on the emergent situation, layout of buildings, and the safety of family affected their evacuation behaviors after they recognized the peril.

These human behaviors characterize evacuation from buildings in emergencies. In this paper, we show that information is one of the key elements in evacuation and that information transfer affects evacuation behaviors. The remainder of this paper is organized as follows: Related works are introduced in Section 2. Section 3 describes a model of information transfer during evacuation. The simulation and estimation of evacuation scenarios are discussed in Section 4. A summary of the paper is presented in Section 5.

2. Related Works on Evacuation Simulations

2.1 Background

The documents of the NIST and the Japanese Cabinet reported several patterns of evacuation behavior: some people started their evacuation immediately when they heard the warnings, others evacuated after they finished jobs in which they were involved, and still others did not evacuate until they noticed risk to their lives themselves. They got the warnings via broadcasts from authorities, mass media, or calls from family members. **Table 1**

Table 1 What made people start evacuating during two past disasters.

Triggers of evacuation	WTC	GEJE
Prediction of quake or tsunami		✓
Hearing alarms that indicated emergency	✓	✓
Advice from others	✓	✓
Seeing neighbors hurrying to refuges	✓	✓

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shows typical triggers that made people start evacuation.

There is another report on family behavior during a flood in 1965 [5]. It is interesting that the behaviors were similar to ones described in the reports of the two disasters in this century, even though communication methods have changed. Behaviors were categorized into three types of reactions to being warned: some families immediately evacuated, other families attempted to confirm the threat, and still others ignored the initial warning and continued with routine activity. The steps are warning, confirmation of the information, and evacuation.

A technical report from the International Organization for Standardization (ISO) provides information for the evaluation of life-safety aspects during fires [6]. They broke evacuation time down 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 and the time individuals require moving to safe locations.

The report points out that life safety depends on escape time, which is greatly affected by human behavior. Understanding of human behavior enables the design of society to better reflect the needs of occupants, for example, to reduce evacuation time. Evacuation time consists of two stages: t_{warn} and t_{evac}.

2.2 Human Factors in Evacuation Simulations

The NIST simulated some evacuation scenarios for the purpose of estimating the evacuation time from WTC buildings [3]. The travel times of several cases were simulated with several evacuation simulation systems, and we note that the systems use the following assumptions:

(1) People are equal mentally and functionally. In some simulators, sex and age are taken into consideration as parameters of walking speed in pedestrian dynamics models. However, human behaviors such as parents taking care of their children are not considered.

(2) All people start their evacuation simultaneously. Actually, some people evacuate after they finish their jobs. Pre-movement time is not considered in simulations.

(3) All people evacuate with the same knowledge of the building from which they evacuate. In fact, knowledge of evacuation routes differs among people, and some people are assigned to guide others to exits according to announcements from security officials of buildings.

These assumptions neglect some social factors that characterize human behaviors in evacuations: people either come together or break apart during an evacuation according to their human relationships, and people who are unfamiliar with buildings want to know how they can exit.

Pelechano et al. proposed a two-level behavior model that represents physiological and psychological factors observed in real people who find their way toward an exit [7]. They showed that interagent communications to share data about building layout and the presence of leaders that are familiar with buildings improve the evacuation rate. Okaya et al. simulated parents' movements, in which they first go to their children and then evacuate together, using a belief-desire-intention (BDI) model [8]. Tsai et al. presented ESCAPES, a multiagent evacuation simulation system that incorporates four key features: different agent types, emotional interactions, informational interactions, and behavioral interactions [9]. They simulated evacuation scenarios with 200 pedestrians including 20 families of 4 at an airport terminal.

3. Information Transfer Model in Evacuation

3.1 Verification of Prevention Plans for Emergencies

According to the NIST, the safety department of the WTC had templates for evacuation guidance. Phased evacuation is one of the methods that help people evacuate efficiently. The WTC guidance was as follows:

> Your attention please. We are experiencing a smoke condition in the vicinity of your floor. Building personnel have been dispatched to the scene and the situation is being addressed. However, for precautionary reasons, we are conducting an orderly evacuation of floors __. Please wait until we announce your floor number over the public address system. Then follow the instructions of your fire safety team. We will continue to keep you advised.

The guidance seems to be good as a desk plan. It may work during typical fires; however, it did not work well on September 11. In times of emergency, people may act in unforeseen ways, and their behaviors vary according to the physical, social, and mental traits of the individuals. To verify the efficiency of guidance or prevention plans, pre-movement time should be included in evacuation simulations.

3.2 Agent Behaviors and the Role of Information

Information on the situation and personal matters play an important role in deciding actions, and they affect both pre-movement time and travel time in t_{warn} and t_{evac} stages. Regarding information or knowledge of people, the evacuation process has the following phases:

Transfer phase: When emergencies occur, people perceive the occurrence themselves and authorities provide alerts to people. The alerts contain urgent messages conveying that an emergency situation has occurred and giving instructions for people to evacuate to safe places.

Sharing phase: People confirm and share the information that they get by communicating with people nearby. After that, people perform actions according to their personal reasons; some evacuate to a safe place, others hurry to families, and still others join rescue operations.

Transfer and sharing phase: People who are unfamiliar with the building follow guidance from authorities or shop assistants, who act according to rules or manuals prescribed for the buildings. The information that authorities and shop assistants have may vary with time.

3.3 Features of Communication in Emergencies

Information that is passed on to people in emergencies is announced through speakers or shared via personal communication.

Table 2 ACL-based message format.

Type of Message	Function
request	order agent to perform an action
agree	agree to perform an action
inform	inform agent about person or environment
query-if	ask agent about person
query-ref	ask agent about environment

The reports indicate that the following situations occurred during emergencies:

(1) According to the GEJE report, only 40% of evacuees heard the emergency alert warning from the loudspeaker. Of those that heard the warning, 80% recognized the urgent need for evacuation and the other 20% did not understand the announcement because of noisy and confused situations.

(2) In the case of the WTC, messages were announced in the buildings according to a manual when the planes hit the buildings. The manual was prepared for accidents at limited floors of the buildings. The messages did not provide proper guidance to occupants of the buildings according to dynamically changing situations, and people at the impacted floors did not catch the announcement.

We believe three components — content, method, and rate of transmission — are explicitly embodied in communication during emergencies. The content must provide information that helps people evacuate from buildings or save their lives. The messages are transmitted in several ways: broadcasts from authorities, face-to-face oral communication, email, or telephone. The rate represents varying conditions, including those in which people cannot catch all or part of broadcast announcements or information spoken to them.

Content: The content is formulated in the form of Agent Communication Language (ACL). **Table 2** shows typical message types used in evacuations. They are designed to handle situations that are expected in emergencies. An example of such situations, people in an office follow announcements from emergency centers.

Method: The emergency announcement is broadcast to all people in the building, and the people in the office communicate with each other by voice. The difference in methods of transmission should be discriminated.

Rate: Not all people hear the announcement and understand it correctly. The rate — the percentage of people that can hear the announcement or the percentage of the contents they understand correctly — depends on the states of the people and the conditions of the surroundings. Rate is implemented in the environment module of a simulation model.

The following is an example of dialogue after a broadcast announcement:

> A leader of an office says, "Please follow the announcement: use the stairs and go to the emergency exit!" After a while, someone says, "Hey, the stairs are crowded with people, and we cannot use the stairs." Another says, "Why don't we use the other stairway, over there?" The first one says, "That's good idea. Let's ask the leader whether we can use the other stairway."

Table 3 shows examples of messages expressed in ACL. The method component is implemented in commands described in the next section. The rate component is represented as a parameter of the commands.

Table 3 Examples of ACL-based messages.

Broadcast	Face to Face
(inform	(agree
:sender authority	:sender agent3
:receiver civilian	:receiver agent1, agent2
:content	:content
(evacuation-guidance	(action
:go-to exitA	(agent1 agent2 agent3)
:via stairA))	(go-to exitB))
	:in-reply-to message1)

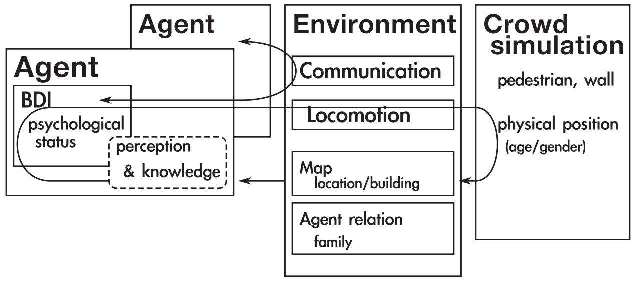


Fig. 1 System architecture of evacuation simulation considering human and social factors.

3.4 Evacuation Simulation Taking Information into Consideration

Modeling how people get information is necessary to simulate evacuation behavior in emergencies. **Figure 1** shows the configuration of our system, which consists of agent, environment, and crowd simulation [8].

Agent and interagents: A human hears the announcement from authorities, confirms the information with people nearby, and performs actions. A BDI model is adopted to represent such a process. Belief is the knowledge and information that agents get in every sense-reason-act cycle. The knowledge is the relationships among agents and the layout of buildings — for example, which agents are in the same family and where the exits are.

Environment module: The module consists of data on environments and setting of conditions. The environments are 3D CAD models of buildings, properties of agents, and relationships of interagents and others. Agents select the method of communication by different commands: TELL/SPEAK/ANNOUNCE commands to transfer information to others, and HEAR/LISTEN commands to get information from others. The condition setting models situations where people cannot hear the announcement clearly, or changes of environment such as a corridor where people cannot pass because of fire.

Crowd simulation: The module simulates the dynamics of groups of people considering physical differences such as sex and age. People do not move in the same direction. Safety personnel go to assigned places and guide people to evacuate. Their movements may be obstacles to the major movements of other people.

4. Evaluation of Evacuation Plans

It is important for the safety department to guide people in evacuating quickly from facilities in emergencies. Evacuation drills have been conducted with the intent to improve prevention plans for predictable situations. However, it is difficult to conduct drills involving many people and using real environments under various scenarios without giving notice to people beforehand. Evacuation simulation is one of the methods for verifying the efficiency of prevention plans for various scenarios.

4.1 Case of Subterranean Shopping Mall

Many people go to malls, and the management company of a mall prepares manuals for emergencies and conducts drills based on the manuals. **Figure 2** (a) shows one of the subterranean shopping malls in our city. About 90 shops are in three rows, and two main streets are between the rows. Exits to the ground are located every 50 m.

An evacuation scenario is as follows: A thousand people are randomly situated in the mall. Fire alarms are announced to the people. People's behavior models are set according to the GEJE report, which showed three types of human reactions when alarms are given.

Instant evacuation: People who feel anxious after experiencing an accident that involved extreme shaking initiate their own evacuation.

Evacuation after tasks: People who do not feel anxious after an accident evacuate after completing their current activity. They do, however, feel anxious when they hear the guidance information.

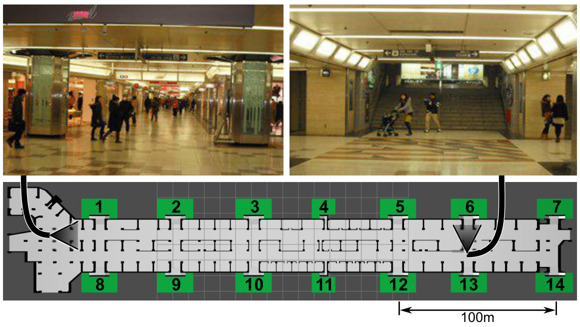
Emergent evacuation: People who do not feel anxious and do not evacuate after completing their current activity or after hearing the evacuation guidance information initiate evacuation when they become extremely anxious after receiving new information from others.

The percentages of the reaction types are 57%, 31%, and 12% respectively. People evacuate according to their BDI model. **Table 4** shows the BDI models of the reactions. Two different evacuation messages are announced.

Message 1 is to evacuate by using exits 1 and 8.

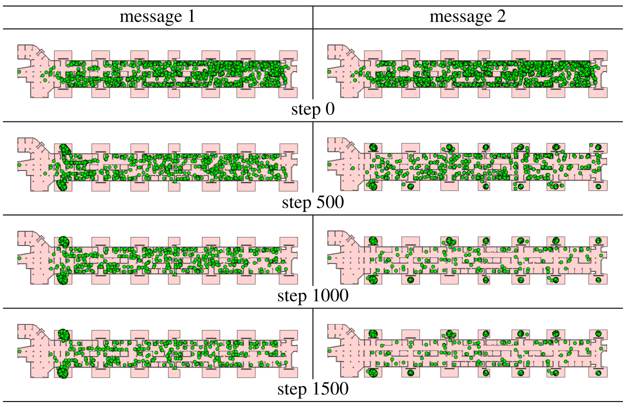
Message 2 is to evacuate by using nearest exits.

Figure 2 (b) and (c) show the time sequence of evacuations and the average of evacuated people of three simulations. At first, more people evacuate after message 2 than after message 1. After congestion starts at exits, the increases in evacuation rates are similar for both cases.

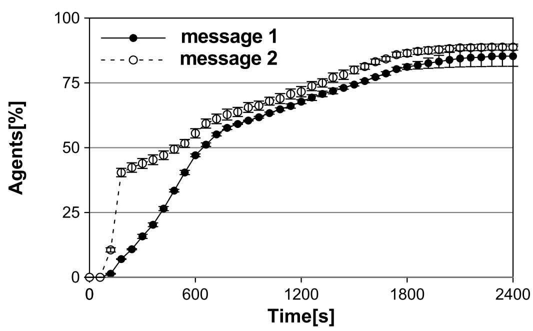


Numbers indicate exits to the ground.

(a) Layout of subterranean shopping mall and photos: One is taken at the left end of one street and the other is at exit 6.



(b) Time sequence of evacuation behaviors



(c) Rates of evacuation from shopping mall

Fig. 2 Simulations of evacuations at subterranean shopping mall.

4.2 Case of a Library Building

Figure 3 shows a five-story building and a snapshot of simulating 1,000 people (200 people on every floor) evacuating from the building. The percentage of agent reaction types are the same as in the case of the subterranean shopping mall. The building is a library of our university that has stairs between floors and two exits. One exit is the front exit, 3.7 m wide, on the second floor,

Table 4 BDI model.

Information	Belief	Desire	Intention
Instant evacuation:			
-	-	Finish Task	Do Task
Broadcast Announcement	Become Extremely Anxious	Escape	Escape
Guidance by staff	Become Extremely Anxious	Escape	Escape
Evacuation after task:			
-	-	Finish Task	Do Task
Broadcast Announcement	Feel Anxious	Escape Finish Task	Escape After Task
Guidance by staff	Become Extremely Anxious	Escape	Escape
Emergency evacuation:			
-	-	Finish Task	Do Task
Broadcast Announcement	-	-	-
Guidance by staff	Become Extremely Anxious	Escape	Escape

-: no data from environment or no change in BDI sets.

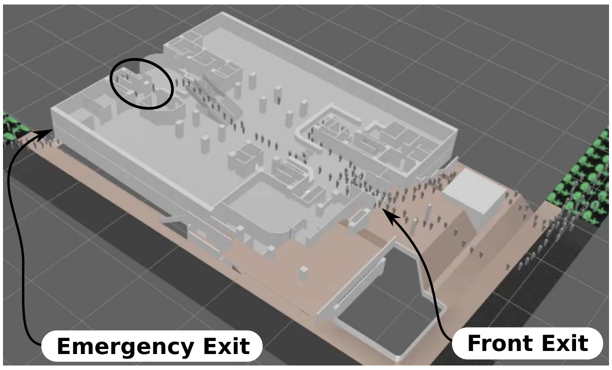


Fig. 3 Snapshot of evacuation behaviors from buildings (The circle indicates the landing referred to in Fig. 5).

Table 5 Guided evacuation routes in phased evacuation.

Building		Plan A		Plan B		Comment
F	exit	emer.	main	emer.	main	
5		✓			✓	security office
4			✓		✓	
3		✓		✓		
2	front		✓		✓	width is 3.7 m.
1	emer.	✓		✓		width is 1.3 m.

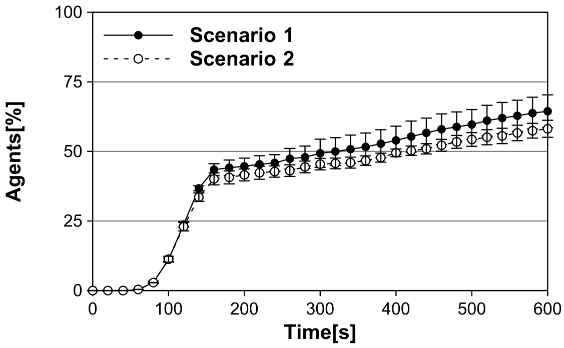


Fig. 4 Rate of evacuation from library by evacuation guidance.

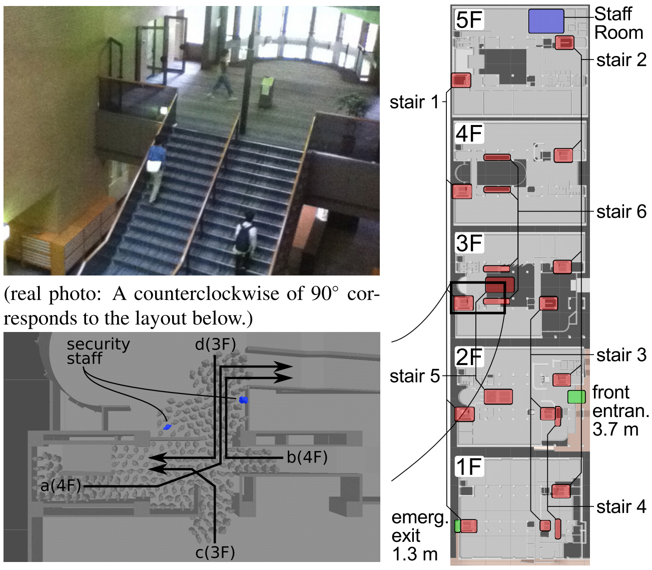
and the other is an emergency exit on the first floor.

4.2.1 Phased Evacuation

Table 5 shows two guided evacuations from the building. People on the first and second floors are guided to evacuate from the exits connected to those floors: the emergency exit and the front exit, respectively. Plan A is designed to ease congestion at staircase landings where people coming from upstairs meet people coming to the staircase from the floor the landing is on. Plan B leads people in proportion to the widths of the exits.

Two scenarios are simulated. Scenarios 1 and 2 are that people evaluate according to plan A and B, respectively. Evacuation guidance is announced once, in the starting step. **Figure 4** shows the percentages of people evacuated in two simulations. The percentage is counted the number of people who passed exits. Plan A (scenario 1) is better than plan B (scenario 2) although we had expected plan B to work better than plan A. Following are reasons the results fall short of our expectation.

- **Figures 5** (a) and (b) shows the congestion that occurred in scenario 2 at landing 3F, and Fig. 5 (b) shows the floor layouts of the building. Agents a and b are at 4F. Agent a uses staircase 1 to descend to 3F from 4F and tries to descend to 2F by staircase 5 to exit through the front exit. Agent b goes down to 3F by staircase 6 and then tries to go down staircase 5 and evacuate through the front exit. Agents c and d are at 3F at the starting step, and they intend to go out the emergency exit via stairs. Their movements at the landing cause the congestion and prevent their smooth evacuation.



(real photo: A counterclockwise of 90° corresponds to the layout below.)

(a) Snapshot of congestion at landing 3F (b) Floor layout

Fig. 5 Congestion at landing 3F and floor layout.

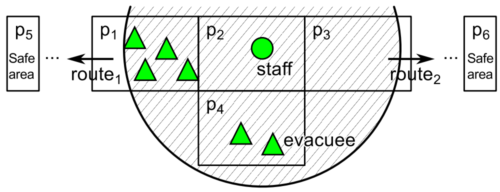


Fig. 6 Perception model of security staff at landing. The staff monitors the numbers of people in neighboring areas.

4.2.2 Situational Staff Guidance

When initial guidance is announced, five members of the security staff proceed from the Staff Room at 5F to the stair landings - one for each floor. There, they orally guide the people evacuating from the building. The difference between an announcement and oral guidance is the range of hearing. The range of an announcement is the entire building, while the range of oral guidance is limited to 3 m.

Two more scenarios are simulated, scenario 3 and 4. Scenario 3 is that guidance is given according to the manual. The manual instructs staff to repeat the initial announcement. Scenario 4 allows the staff to change the guidance according to the situation. **Figure 6** shows the perception model of the security staff. The staff monitors people's motion in two areas, p_1 and p_3. When the congestion in p_1 is heavier than the congestion in p_3, the staff will guide people to go to p_6 via p_3 and vice versa.

Figure 7 shows the percentages of people evacuated in three simulations: scenarios 2, 3, and 4 (described in **Table 6**). Guidance at the landing, used in scenarios 3 and 4, shows better results than scenario 2. In scenario 3, the repeated guidance leads people of evacuation-after-task type and emergent-evacuation type to start evacuation. According to the log file of scenario 4, a staff agent changed the guidance at 100 seconds and it took from 80 to 90 seconds to go from the landing to the front exit. It explains the

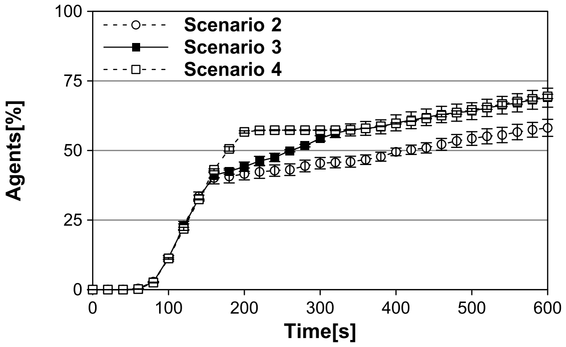


Fig. 7 Rate of evacuation from library with guidance at landings.

Table 6 Scenarios of evacuations. Scenario 3 and 4 are with guidance by security staff at landing.

Scenario	Contents of Guidance	
	broadcast	landing
1	plan A	-
2	plan B	-
3	plan B	plan B
4	plan B	Basically plan B and, when congestions occurs, guidance to a less congested route.

increment in the rate of scenario 4 after 180 seconds in Fig. 7.

5. Discussion and Summary

To verify the simulation, the ideal method is to compare the results with experimental data using people and real environments. However, conducting the evacuation drill experiment without notifying occupants in advance may create social problems and be dangerous. We think that qualitative analysis based on the precedent cases is important for verifying simulation results.

From the reports of the NIST and the Japanese cabinet office, information on disasters is related to evacuation behaviors. Human behavior is affected by people's psychological conditions and the type of information provided during emergencies. The ISO report addresses assessments of the conditions of the occupants of a building with respect to time. Psychological factors and the contents and timing of evacuation guidance, as well as physical factors, must be taken into consideration in evacuation simulations.

We propose an information transfer and sharing model that enables the announcement of an evacuation or information sharing during evacuation. In conjunction with a BDI model that presents the diversity of human behavior and our information transfer using ACL-based communication, our simulation system performs the following:

(1) enables the simulation of evacuation behavior in various scenarios
(2) points out places where congestion may occur
(3) eases congestion through proper guidances

The simulation results reveal phenomena in agent behaviors that have not been simulated through other methods:

(1) Unexpected congestion produced different results than expected in planning evacuation manuals.
(2) Situation-specific guidance changes evacuation behavior and shortens the time taken to evacuate buildings.

These results have not been verified using standards or rules gained from past experiencies. To improve safety, they enable comparison of different prevention plans and relative evaluation help in designing buildings and prevention plans. Building evacuation analysis has recently received increased attention, as the assessment of occupants' safety has become a priority. The simulation of crowd evacuation for prescribed scenarios provides useful tools for checking prevention plans and manuals to improve the safety of occupants. Simulations also evaluate the plans, including methods of evacuation guidance, from the aspect of ISO Technical Report 16738.

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