

## CHAPTER 14

# Multi-Agent Simulation for Evacuation Process Analysis

Multi-agent simulation (MAS) is a numerical method to simulate behaviours of human being or its organisation in a given environment. An agent, which mimics one or a few behaviours of human being, takes spontaneous actions interacting with other agents and the environment. An algorithm is needed for numerical methods to solve mathematical problems, rules according to which agents take actions are needed for MAS. Results of MAS change depending on the initial state of the agents, and hence Monte-Carlo simulation is carried out to output qualitative patterns or quantitative trends for the agent behaviour.

MAS is a relatively new numerical method. The recommended textbooks<sup>1</sup> to learn the basic of MAS are [Weiss (1999)], [Sun (2006)], [Russell and Norving (2009)] and [Yoav and Leyton-Brown (2009)]. It should be noted that the spectra of the MAS researchers are wide, ranging from theoretical computer science (or artificial intelligence) oriented studies, such as [Ishida (2000)], to practical application oriented studies, such as [RoboCupRescue (2009)]; see also [Kitano *et al.* (1997)].

This chapter presents the application of MAS to analyse the emergency evacuation process of a crowd, who move out from a public space right after an earthquake, assuming that individuals of various motion ability evacuate in a disorganised manner. MAS is not familiar in earthquake engineering since it is aimed at analysing social science problems rather than natural science or engineering problems. Thus, detailed explanations will be given to the design of agents, the acquisition of agent data and the construction of a model for agents' environment.

The present MAS is an example of the action simulation of integrated earthquake simulation, presented in Chapter 11. The importance of

---

<sup>1</sup>See also [Axelrod (1997)], [Sallach and Macal (2001)] and [Gilbert and Troitzsch (2005)] for researches related to social sciences.

analysing individual, community or social actions<sup>2</sup> after a large earthquake should be emphasised. This is because the results of such analysis contribute to make more rational and efficient plans for retrofitting and recovering an urban area before and after an earthquake, respectively, as well as to strengthen the risk management of earthquake disaster. Collaboration of earthquake engineering researchers with social science researchers is required to develop reliable tools which are shared by these two parties,—after a large earthquake should be emphasised, and MAS<sup>3</sup> is a candidate of such tools.

### 14.1 Evacuation Process Analysis

If a near fault earthquake hits a modern densely populated urban area, it would cause human causality which has not been experienced. This is due to the change in the modern society. For instance, the acceleration of aging and the promotion of barrier-free community result in the presence of less agile people in public spaces, such as town squares, railway stations or shopping malls. The processes of the evacuation from the public spaces right after a large earthquake might be more disorganised than before. The safety of the public spaces during the emergency evacuation needs to be reconsidered, assuming that the spaces are used by individuals with lower motion ability.

Extensive studies on emergency evacuation have been made for fire evacuation procedures of residential buildings, especially for high-rise buildings; see [Gwynne *et al.* (1999)]. Securing safety is of primary importance, and various measures have been invented, for instance, installation of fire doors and walls is a typical hardware measure, and preparation of emergency broadcast or guiding system is a software measure. It is, thus, necessary to analyse processes that a crowd evacuates from a public space in order to identify possible problems and to take proper measures (see [Waldau *et al.* (2007)]).

The analysis of emergency evacuation processes is not a new subject. However, it is usually assumed that a *homogeneous* crowd or individuals with the same motion ability evacuate in an organised manner. Conventional analysis based on this assumption is not applicable to the current problem. If a *heterogeneous* crowd or individuals with various motion ability is assumed, the resulting evacuation processes will be disorganised. It is

---

<sup>2</sup>In particular, the analysis of recovery processes of regional or domestic economic activities is of primary importance.

<sup>3</sup>Further studies of MAS are strongly recommended for readers who are interested in this subject.

such a disorganised state<sup>4</sup> that the evacuation process analysis needs to investigate.

## 14.2 Numerical Methods for Evacuation Process Analysis

There are many numerical methods to analyse emergency evacuation processes, and they are applied to the evacuation from natural disasters, which include earthquake and tsunami, as well as, flooding and hurricanes. Typical numerical methods, which are used in such analysis, are simulation of a physical model, cellular automata and *multi-agent analysis* (MAS). Table 14.1 presents the brief summary of these three methods;

Table 14.1. A summary of numerical methods used for the evacuation process analysis.

	Simulation of physical model	cellular automata	MAS
Model of individual	Velocity and density of fluid	Cell state (state changes if cell is occupied by individual)	Agent with distinct data
Model of public space	Physical space model where fluid flows	Grid consisting of a set of cells environment for space	
Model of moving	Fluid mechanics (conservation of mass, etc.)	Cell state changes probabilistically	Agent takes spontaneous action with interaction of other agents
Characteristics	Flow velocity changes depending on flow density	Probabilistic rule of changing cell state	Simple setting of agent's attributes and functions
Target	Organised state for homogeneous crowd	Almost organised state for almost homogeneous crowd	Disorganised state for heterogeneous crowd
Limitation	Not applicable to heterogeneous crowd	Quantitative analysis only	Need to follow KISS Principle

<sup>4</sup>An extreme case of such a disorganised state is panic. It is surely an important issue to prevent the occurrence and spread of panic during the emergency evacuation. The present MAS, however, is too primitive to analyse human behaviour related to panic.

see [Waldau *et al.* (2007)] for a list of references; see also [Sugiman and Misumi (1988)], [Okazaki and Matsushita (1993)] and [Hori *et al.* (2008)].

### 14.2.1 *Simulation of physical model*

In this simulation, a crowd is modeled as fluid. Velocity and density of the crowd are formulated as those of a certain fluid, and the temporal and spatial change in these quantities is computed according to the physical laws (see [Jiang (1999)] and [Gwynne *et al.* (1999)]). The accuracy of the simulation is high for the case when a homogeneous crowd moves in an organised manner or for the case when the crowd goes to a narrow gateway to cause stacking. The simulation of a physical model is used to design public spaces or inside spaces of residential buildings.

Another physical model used for evacuation analysis is a potential model (see, for instance, [Yokoyama *et al.* (1995)]). It assumes a certain potential the gradient of which determines an individual's movement. The potential has several attributes which account for the complexity of a space where he/she moves and his/her motion ability. Although this simulation is simple and produces apparently reasonable results, the reliability depends on the validity of assumed potential.

The simulation of a physical model is often used in earthquake engineering. For instance, simulation is made for the emergency evacuation from tsunami, and a situation where residents in a village evacuate from an assumed tsunami is analysed (see, for instance, [Katada *et al.* (2005)]). It is surely a rational choice to use the simulation of a physical model for the evacuation process analysis, if a more or less organised state is assumed for the evacuation processes.

### 14.2.2 *Cellular automata*

Cellular automata (CA) use a certain system which consists of cells, the state of which changes according to simple probabilistic rules. As for the evacuation process analysis, a cell represents a small space and the cell state is whether the space is occupied or not by an individual (see [Kirchner and Schadschneider (2002)] [Helbing *et al.* (2000)] and [Helbing *et al.* (2003)]). Even though the probabilistic rule is simple, the pattern of the cell state becomes complicated when numerous cells are used, for instance, a pattern when a crowd moves smoothly or a pattern when a crowd is stacked at some spaces is obtained. The cell automata are suitable to find possible patterns

of the emergency evacuation, although it has a limitation in quantitative analysis.

There are many examples to apply CA to study the movement of a crowd. For instance, CA are applied to analyse the movement of passengers in a railway station. Categorising passengers into groups which go to the same direction and assigning specific probabilistic rules for the groups, this CA simulation computes the temporal and spatial change in the crowd density, to find unsmooth paths and a possible alternative path for the passengers.

An example of the application of CA to the evacuation process analysis is in the simulation of the emergency evacuation from an underground shopping mall after an earthquake. Constructing a suitable cell model for the mall, this simulation computes the movement of a crowd as it goes to exit the mall. A disorganised state is observed for the movement. It is shown that there are several patterns for the evacuation processes depending on the initial state of cells.

### 14.2.3 MAS (*Multi-Agent Simulation*)

As mentioned, MAS is aimed at constructing a system, which consists of agents and an environment (see [Weiss (1999)]). Each agent takes spontaneous action interacting with its surrounding agents and environment, and hence MAS is able to reproduce or predict complicated patterns of the agent behaviour by properly designing the agents and environment.

MAS has been applied for the analysis of fire evacuation procedures; see [Farinelli *et al.* (2003)] and [Musse and Thalmann (2001)]. Suitable agents and environment are constructed so that sophisticated simulation is carried out for the evacuation processes. MAS is also applied to study the risk control<sup>5</sup> of earthquake disasters. Fire departments and police officers are modeled as agents, and simulation is made to optimise the allocation of these officers for fire fighting and rescuing the injured.

When MAS is applied to the evacuation process analysis, the two elements of MAS, namely, an agent and an environment, must be designed. The brief explanation of these elements is as follows:

- agent: an agent is a model of an individual with distinct motion ability. It sees its surroundings, thinks the next movement and moves accordingly.

---

<sup>5</sup>A system which uses MAS to simulate emergency situations is developed for the risk management of a nuclear power plant, as well.

- **environment:** an environment is a model of a public space where individuals evacuate. The configuration of the space has to be modeled properly so that the simulation becomes realistic.

In constructing these elements, attention must be paid to the fact that human behaviour is more complicated than the response of lifeless objects which is governed by physical laws. However, if many cases are simulated, a certain pattern could be found. MAS seeks such a pattern using a coarse model which ignores the complexity of actual human behaviour. Therefore, the two elements of MAS are often constructed in a simple manner, which is referred<sup>6</sup> to as the *KISS* (Keep It Simple and Stupid) Principle.

It is certainly true that there is a limitation of the accuracy and reliability of MAS. Regarding the evacuation process analysis, a reasonable use of MAS is to compare the relative safety of different public spaces. Evacuation time in which all (or a certain portion of) agents complete evacuation is used as an index for the comparison. Difference in the evacuation time might be more meaningful than the evacuation time itself, since some errors in computing the evacuation time are canceled by computing a difference.

Evacuation processes will change depending on the composition of a crowd who happens to be in a public space and the location of the individuals. Therefore, MAS needs a Monte-Carlo simulation, in which agents are randomly generated and distributed in an environment. The Monte-Carlo simulation provides a probabilistic distribution of the evacuation time. A certain exceptional case might be computed in the Monte-Carlo simulation, but a possibility that such a case happens is evaluated at the same time.

### 14.3 Design of Agent and Environment for Multi-Agent Simulation

An object-oriented<sup>7</sup> programming language, C++, is used for a code of the present MAS, and an agent of MAS is coded as an object (see the class diagram of an object `agent` shown in Fig. 14.1). The most important design item is a datum for the moving speed. Each agent moves with its distinct speed so that a set of agents become a model of a heterogeneous crowd.

---

<sup>6</sup>The KISS Principle is generally a terminology of software engineering; KISS sometimes stands for Keep It Short and Simple.

<sup>7</sup>See Section 13.1 for a more detailed explanation of objects.

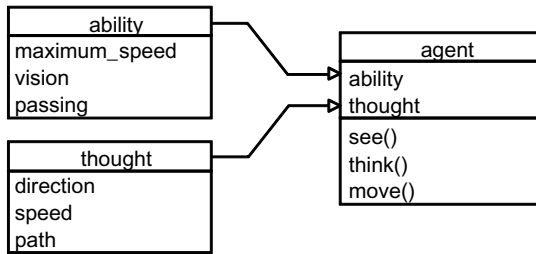


Fig. 14.1 A class diagram of an agent.

According to the KISS Principle, however, this datum should be designed as simply as possible.

The object **agent** has two data, namely, **ability** and **thought**, which are described as follows:

- **ability**: a datum **ability** consists of attributes related to motion ability, such as the maximum speed, field of vision and probability of passing.
- **thought**: a datum **thought** consists of attributes related to intellectual actions, such as determining direction and speed of the movement and choosing a path at an intersection.

The item of maximum speed of the datum *ability* is randomly given to an agent according to an assumed distribution, which, as will be explained later, is the measured distribution for human being movement. The items of vision and passing are common to all agents and characterised as the visuality radius and the probability of forcible passing, which is used when an agent attempts to pass another agent. A passing zone is introduced in the front of each agent; this zone is a rectangle, and passing of another agent is attempted if it is located in this zone. Table 14.2 summarises these items. The items of direction and speed of the datum **thought** are selected according to the rules that are described as the methods of the agent. The item of path stores the memory of places where the agent has moved. They are used to prevent the agent from moving around the same place.

The methods of the object **agent** are **see**, **think** and **move**, which are described as follows:

- **see**: a method **see** is to grasp nearby agents and environment.
- **think**: a method **think** is to select an option of the movement.
- **move**: a method **move** is to take an option of the movement according to the selected option.

Table 14.2. Items used for the data **ability**.

$\mu$	Average of maximum moving speed [m/s]
$\sigma$	Standard deviation of maximum moving speed [m/s]
$R$	Radius of field of vision [m]
$D$	Size of passing zone [m] (passing zone is $D \times 2D$ )
$m$	Speed reduction ratio at passing
$\theta$	Modification angle at passing [deg]
$P$	Forcible passing probability

Targets of the method **see** are other agents in the passing zone and walls located within the visibility radius. Options of the method **think** are

- 1) moving without changing the direction and speed;
- 2) passing with changing the direction and speed;
- 3) stopping.

The second option (passing) is that when another agent is in the right or left part of the passing zone, the direction is changed by a fixed passing angle, denoted by  $\theta$ , and the speed is reduced by a fixed ratio, denoted by  $m$ . The third option (stopping) is selected according to the forcible passing probability when other agents are located in both parts of the passing zone. The passing and stopping options serve as a mechanism that causes a disorganised state to the agent movement. The method **move** takes the option that is chosen in the method **think**. However, if the agent hits a wall after passing, the method **move** changes the direction so that it moves along the wall.

As will be explained in Section 14.4, the mean and standard deviation of the maximum speed are  $\mu = 1.4$  m/s and  $\sigma = 0.6$  m/s. Suitable values need to be determined for other parameters of the datum **ability**. To this end, the speed reduction due to the increase in the agent density is computed by changing the values of the parameters. A simple rectangular route is used as an environment. Figure 14.2 shows the relation between the agent number and the average moving speed when the visibility radius, the passing zone size, the speed reduction ratio, and the forcible probability are  $R = 2.5$  m,  $D = 0.5$  m,  $m = 0.5$  and  $P = 1$ , respectively. As seen, the average of the moving speed decreased<sup>8</sup> as the agent number increases; more agents take a

---

<sup>8</sup>In the simulation of a physical model or passenger flow analysis, the average speed of a crowd is given as a function of the spatial density of individuals. The present MAS does not need such a function. It is able to reproduce the function to some extent by choosing suitable rules for passing and stopping.

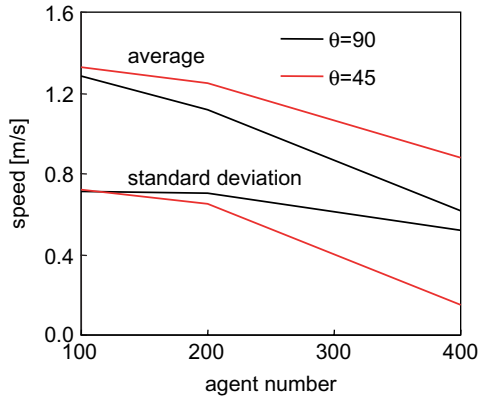


Fig. 14.2 The relation between the agent number and the average speed in the rectangular route.

passing or stopping options more often as the agent density increases. Note that the amount of the speed decrease depends on the passing angle,  $\theta$ .

The passing angle and the speed reduction ratio are the parameter that mainly determine the speed reduction due the agent density increase. To determine their values, three pairs,  $(\theta, m) = (90, 0.5)$ ,  $(45, 0.5)$ ,  $(90, 0.25)$ , are used, and the relation between the evacuation time and the number of agents, which move out from the route, is presented in Fig. 14.3. The evacuation time is shortened for  $\theta = 45$  deg than for  $\theta = 90$  deg when

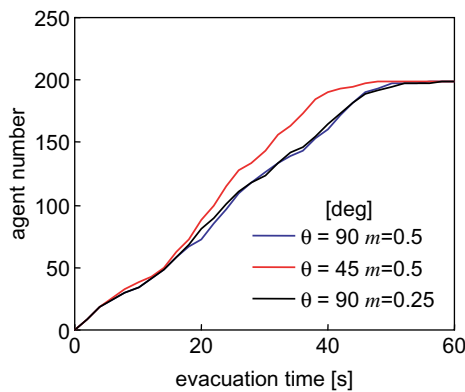


Fig. 14.3 The relation between the evacuation time and the number of agents which move out from the L character route.

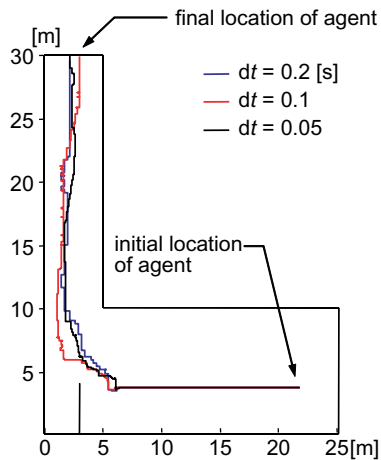


Fig. 14.4 Trajectories of an agent moving in the L character route.

$m = 0.5$  is used, but there is no significant difference between  $m = 0.5$  and  $0.25$  when  $\theta = 90$  deg is used. While the evacuation time depends on the choice of  $(\theta, m)$ , little changes are observed when  $(\theta, m)$  take a value around  $(60, 0.5)$ . Thus, the present MAS uses this pair.

A suitable value must be chosen for the time increment, denoted by  $dt$ . To this end, an L character route, which has an exit at the left top, is used to make agents turn the corner, and the dependence of the agents' trajectory on  $dt$  is examined. Three trajectories of one agent ( $dt = 0.2, 0.1, 0.05$  s) are presented in Fig. 14.4. The trajectories do not coincide, and no trend is observed for the convergence of the trajectory as  $dt$  becomes smaller. However, spatial difference in the trajectories is around 10 cm. Since MAS is aimed at evaluating the safety of a public space, such difference is negligibly small. Thus, the present MAS uses  $dt = 0.2$  s, in order to reduce computation time.

#### 14.4 Measurement of Individual Walking Speed by Image Analysis

The maximum speed of an agent is the most important item of the datum ability since the present MAS is aimed at analysing the evacuation processes. However, there are no data for individuals' walking speed during the emergency evacuation right after an earthquake. An attempt is made to measure individual's walking speed by analysing video tapes which

record the movement of individuals in an emergency situation (see [Hori *et al.* (2008)]). From a video tape, 30 digital images per a second are captured, and the location of an individual in each digital image is measured so that his/her walking speed is computed. A distribution of the walking speed is, thus, obtained by applying this image analysis to many individuals in the video tape.

Identifying an individual's location in a digital image is made by using pattern matching. A pattern is a set of pixel data for a distinct part of the individual, such as head or face. A reference pattern is chosen for the first digital image, and a pattern, which has the best match with the reference, is chosen for other digital images. For simplicity, a square of  $5 \times 5$  pixel in a digital image is used to specify the distinct part, and pixel data are converted in the gray scale. The reference pattern is given as a  $5 \times 5$  matrix, denoted by  $[G_{ij}]$  ( $i, j = 1, 2, \dots, 5$ ). An error function, which measures the matching of the pixel data, is defined as

$$E(i, j) = \sum_{k,l=1}^5 (g_{i+k, j+l}^n - G_{kl})^2, \quad (14.1)$$

where  $[g_{ij}^{(n)}]$  is the pixel data of the  $n$ -th digital image. By definition,  $(i, j)$  that minimises  $E$  is the position of the left bottom corner of the distinct part in the  $n$ -th digital image. Converting  $(i, j)$  in the pixel unit to a coordinate, the actual location of the target individual is obtained every 1/30s.

#### 14.4.1 Walking speed distribution in crowded situation

Image analysis, using pattern matching, was applied to a video tape of 198 pedestrians walking during the Firework Festival of Yokohama City, July 18, 2004. The footage was filmed at an intersection between two large streets. As a typical example, one individual's trajectory obtained by the image analysis is presented in Fig. 14.5. The pixel conversion is 1 pixel to 0.025 m; the width of the cross walk at the intersection is 16 m, and it has the size of 640 pixel in the digital images.

Figure 14.6 shows the distributions of pedestrians' walking speed<sup>9</sup> in a smooth flow and a crowded state. The horizontal and vertical axes are the walking speed and the cumulative frequency, which is standardised, so that the maximum frequency becomes one. The normal distribution that fit these

<sup>9</sup>Note that the image analysis measures a component of individual's speed in the direction from the left to right or vice versa in the digital images.

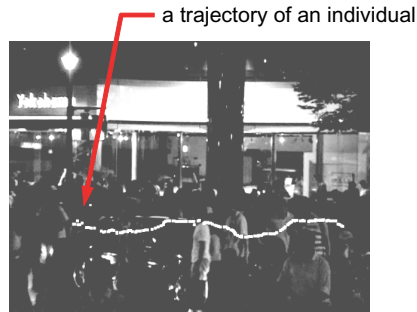


Fig. 14.5 A trajectory of an individual walking in a crowded situation captured in digital images. Each point is obtained by applying the image analysis to a digital image captured from a video tape.

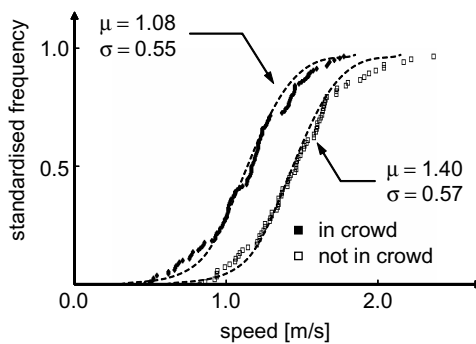


Fig. 14.6 The distribution of individuals' walking speed measured by the image analysis; the distributions are made for individuals in a crowded state and for individuals walking smoothly.

distributions is plotted in a dashed line; the mean and standard deviation are 1.40 m/s and 0.57 m/s for the smooth flow and 1.08 m/s and 0.55 m/s for the crowded state.

MAS is carried out in order to reproduce the observed distribution; the normal distribution that fit the observed distribution for the smooth flow is used as the maximum speed distribution of an agent. An environment made for the intersection is shown in Fig. 14.7. A model of traffic signals which change in the same time interval as the actual ones is put in the environment. The forcible passing probability is  $P = 1$ .

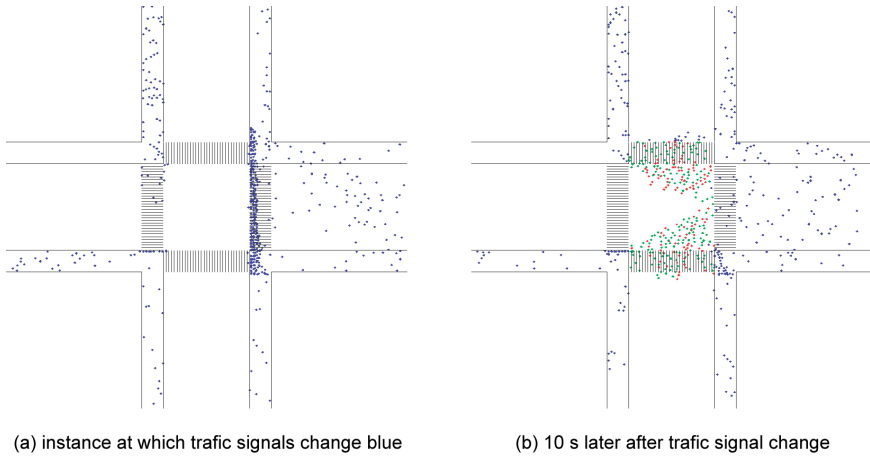


Fig. 14.7 Snapshots of the agent spatial distribution when the traffic signals change.

As an illustrative example of the spatial distribution of agents, Fig. 14.7 presents snapshots of the intersection at the instance when the signals turn blue and 10 s later. It is seen that the agents move in a disorganised manner.

The distributions of the agent speed in a smooth flow and a crowded state are plotted in Fig. 14.8. The measured distribution of pedestrians' walking speed is plotted for the comparison. As seen, good agreement is obtained for the observed and simulated distributions. In careful examination, however, there are some disagreements between the distributions for the crowded state; slow agents tend to move more slowly than slow

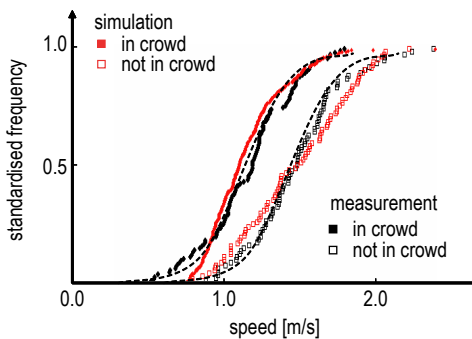


Fig. 14.8 The agent speed distribution computed by MAS.

Table 14.3. The comparison of the walking speed distribution measured by the image analysis and the agent speed distribution computed by MAS.

	Measured value		Simulation	
	In crowd	Not in crowd	In crowd	Not in crowd
Mean [m/s]	1.08	1.40	1.06	1.39
S.D. [m/s]	0.55	0.57	0.51	0.59

pedestrians. This is a limitation of MAS that is constructed according to the KISS Principle. Table 14.3 summarises the mean and standard deviation of the observed and simulate distributions. The relative error of estimating these values by means of MAS is less than 10%.

#### 14.4.2 Individual speed escaping from tsunami

There are several video tapes which record people escaping from the tsunami that was caused by the 2004 Sumatra Earthquake [International Tsunami Information Center (2009)]; see. The speed of individuals escaping from the tsunami is measured by applying the image analysis which uses the pattern matching to these video records. This subsection presents results of the image analysis applied to a video tape which is shown in Fig. 14.9.

The video camera which recorded escaping people was not firmly fixed. The position of a target individual in digital images captured from the video

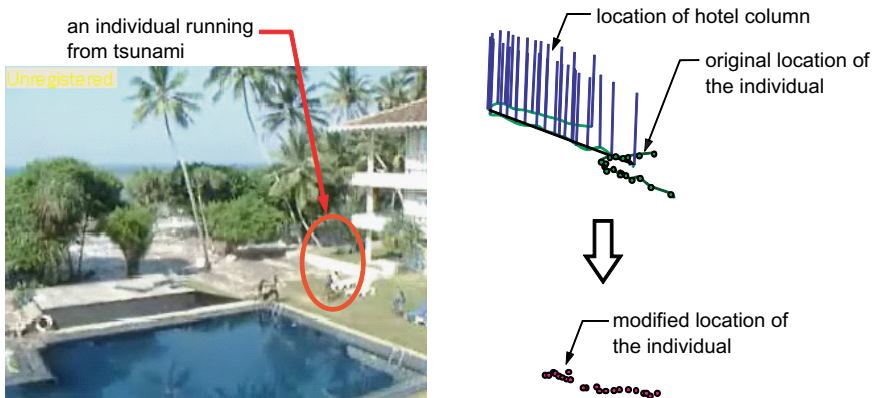


Fig. 14.9 An example of digital image captured from a video record; people escape from the tsunami caused by Sumatra Earthquake, 2004.

Table 14.4. The moving speed of four individuals measured by the image analysis of a video record of Sumatra Earthquake, 2004.

	Speed [m/s]
Fast	3.3 ~ 4.7
Middle	2.8 ~ 4.0
Slow (1)	2.4 ~ 3.3
Slow (2)	2.2 ~ 3.1

tape need to be modified by estimating the movement of the video camera. A simple modification is to use a reference, i.e. a hotel column located on the right part of the digital images as a reference, and the relative position of the target individual from this reference is converted to the actual<sup>10</sup> location (see Fig. 14.9).

Four individuals are analysed, and their moving speeds are summarised in Table 14.4; upper and lower bounds are given since the measured speed is not constant and an error in identifying the location is estimated 1/2 pixel. The speed measured for the four individuals is two or four times faster than the average of ordinary walking speed, 1.3 m/s. However, at the fastest speed, it takes 20 s to run 100 m. Comparing Table 14.3, it is seen that there is large variability in the speed shown in Table 14.4, even though the data are only for the four individuals. This suggests that there will be larger variability in the moving speed during emergency evacuation.

### 14.4.3 Individual speed evacuating during earthquake

There is a video tape which records people evacuating in a shopping mall during the 2005 Miyagi-Ken Oki Earthquake. Customers inside shops or on a mall street start to run during the earthquake. Relatively clear images are taken for fifteen individuals, and their moving speed is measured by applying the image analysis which uses the pattern matching. As an example, one individual's trajectory is shown in Fig. 14.10.

<sup>10</sup>In the video camera, individuals move along the hotel perimeter, hence, the three-dimensional location is measured by the image analysis. The accuracy of measuring an out-of-plane component of the location is much lower than that of measuring in-plane components.



Fig. 14.10 A trajectory of an individual escaping from Miyagi-ken Oki Earthquake, 2005.

Table 14.5. The moving speed of individuals measured by the image analysis of a video record of Miyagi-ken Oki Earthquake, 2005.

Male	Speed [m/s]	Female	Speed [m/s]
A	5.9	A	3.1
B	3.3	B	3.2
C	5.9	C	4.0
D	3.0	D	4.2
E	4.5	E	2.7
F	3.0	F	3.0
G	3.9	G	2.8
H	3.0		
Mean	4.05 m/s		
S.D.	1.34 m/s		

Table 14.5 presents the results of analysing the individuals' moving speed; fast moving speeds are for individuals who run during the evacuation. The average and standard deviation of the moving speed are 4.1 m/s and 1.3 m/s, respectively. The moving speed is considerably faster than the average walking speed at an ordinary state, 1.3 m/s, and the standard deviation is larger than that measured for pedestrians walking in a crowded state, which is presented in the preceding subsection. These results suggest a disorganised state during the emergency evacuation.

There is a limitation in the accuracy of measuring individual's moving speed by using the image analysis which uses the pattern matching. This is partially because pixel data are less sensitive to the out-of-plane movement of a target in a digital image. However, the size of the target image changes when the target moves in the out-of-plane direction. Taking advantage of this fact, developed is an image analysis which uses a three-dimensional (3D) virtual computer model for a recorded place,

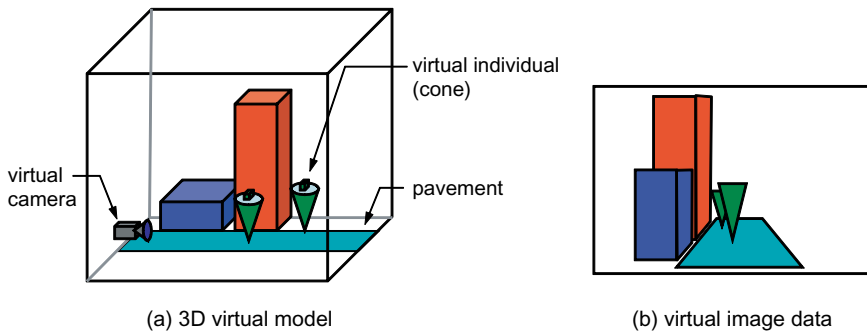


Fig. 14.11 Image analysis using a 3D virtual model.

in order to make more accurate measurement. Figure 14.11 presents a schematic view of a 3D virtual model of the shopping mall and a virtual digital image taken by a virtual video camera. The 3D location of a target is measured by finding the location in the 3D virtual model so that the pattern and size of its image in the virtual digital image match those of the real digital image best.

The procedures of the image analysis, which uses the 3D virtual model, are summarised as follows:

- i) a 3D virtual model is constructed by using the configuration of the shopping mall which includes woods, a pavement and a wall recorded in the video tape.
- ii) a virtual video camera is put<sup>11</sup> in the 3D virtual model, so that the location of the woods, pavement and wall in the virtual digital images matches that in the real digital images.
- iii) the virtual camera takes virtual digital images of an individual's model (a cone).
- iv) the location of the model is determined so that the pattern and size of the target image match with those of the real image.

Two virtual digital images of the shopping mall and an individual are shown in Fig. 14.12; the corresponding real digital images captured from the video tape are shown for the comparison. The image analysis is applied to an individual in the center of the real digital image; this individual is female A in Table 14.5. The individual's location is measured every 1 s and

<sup>11</sup>Note that it is necessary to specify the location as well as the orientation and focal length when a virtual camera is put in the 3D virtual model.

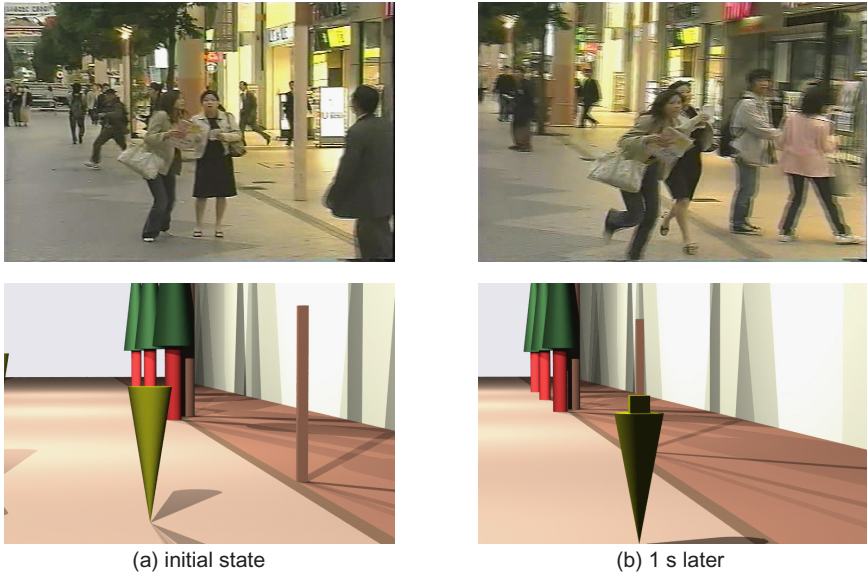


Fig. 14.12 The comparison of the real and virtual digital images.

Table 14.6. The moving speed of an individual measured by the image analysis which uses the 3D virtual model.

Time	Speed [m/s]	Average [m/s]
0–1	1.03	
1–2	3.55	2.80
2–3	2.79	

the moving speed is calculated. The results are summarised in Table 14.6. The average speed is 2.8 m/s, and the relative difference from the speed measured in the previous image analysis, 3.1 m/s, is 10%. Even though this difference does not mean that the accuracy is increased, the image analysis, which uses a 3D virtual model, could be an alternative of the image analysis which uses the pattern matching in order to make possibly more accurate measurement.

## 14.5 Construction of Environment Using Digital Data

While many numerical simulation methods are available, there are only limited cases where these methods are actually applied to emergency

evacuation analysis. This is primarily because the methods are still in a developing stage. Another reason is the fact that constructing a model for these methods is laborious.

As for MAS, a public space needs to be modeled as an environment in which agents move. There are digital data available for the public space, for instance, GIS (Geographic Information System)<sup>12</sup> is for a road network and CAD (Computer-Aided-Design) for a building, such as a station or a shopping mall. It is principally possible to extract spaces, which will be an evacuation route from these digital data, and convert them to a MAS environment.

#### 14.5.1 Methodology of automatic data conversion

The basic idea of the data conversion is simple. A MAS environment is a set of polygons, which describe the configuration of the public space, and information about these polygons is stored in the digital data. The data conversion simply transforms the information to the polygons. However, it is not easy to make this conversion robust, since the digital data have numerous elements with distinct attributes. To solve this problem, a methodology which uses objects is applied. That is, the information stored in the digital data is converted to an object of a common structure, and then this object is converted to another object which describes a polygon of the MAS environment. Class diagrams for objects, which are designed for the digital data and the MAS environment, are presented in Fig. 14.13.

An object **GIS** which consists of the datum **boundary** is designed for GIS; see Fig. 14.13a). The datum **boundary** is designed as an object for a perimeter of a road. An object **CAD** which consists of the data **member**, **stairs** and **wall** is designed for CAD. These data are designed as objects, and **member**, **stairs** and **wall** are for a structure member, stairs and a wall, respectively. The contents of the objects, which are designed for the data of GIS and CAD, are a set of points which describe the configuration of a target.

An object **environment** is designed for a MAS environment. This object consists of two key data, namely, **corridor** in which agents move and **path** which connects objects **corridor**. These data are designed as an object,

---

<sup>12</sup>GIS which is used in this section is of shp format. For GIS of other format, some (possibly minor) modification is needed in the automatic data conversion. In Japan, major roads which automobiles use are stored in GIS of a common format. However, many narrow and small roads are not stored in them.

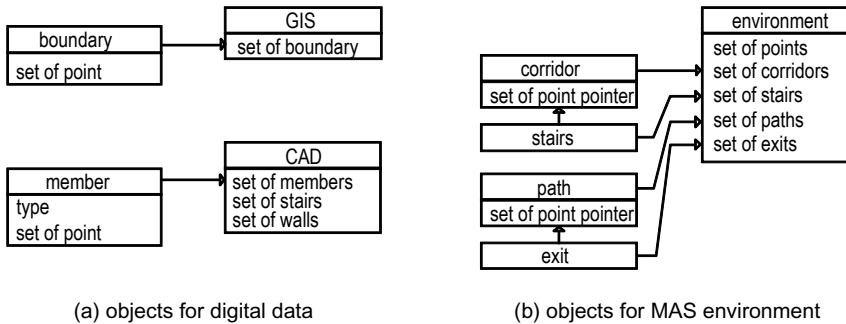


Fig. 14.13 Class diagrams for objects which are used in the automatic data conversion.

and another object `point` is introduced so that the object `corridor` and `path` can share the points which describe the environment configuration. The object `environment` has two other data which are given as objects `stairs` and `exit`; they are inheritance of the object `corridor` and `path`, respectively. The object `stairs` is for stairs or an elevator, and the object `exit` is for an exit through which an agent go out of the environment.

### 14.5.2 Automatic data conversion for GIS

An entity of the object `corridor` is made by converting a set of entities of the object `boundary` which form a road. A suitable set of `boundary` entities have to be found. However, GIS does not store information about such a set (or a set of perimeters which form a road). Thus, a method to find a suitable set has to be developed. To this end, introduced<sup>13</sup> is an `ImageData`, a set of grid data the value of which changes depending on a thing which occupies the grid, such as a road, a building or its perimeter. A pair of parallel `boundary` entities, which form the two sides of a road, can be chosen by using `ImageData`. This pair is converted to a rectangular `corridor` entity. Similarly, a set of `boundary` entities, which form a three-forked road, an intersection or a curved or cranked road, can be chosen, and they are converted to a `corridor` entity of more complicated configuration. When a set of `corridor` entities are converted, it is straightforward to construct `path` entities by finding shared edges of the `corridor` entities.

<sup>13</sup>The `ImageData` could be understood as a simple aerial digital photograph if a grid of the `ImageData` is regarded as a pixel of the photograph.

The procedures of the automatic data conversion for GIS are summarised as follows:

- i) extract information about road perimeters stored in the GIS.
- ii) construct **boundary** entities for all perimeters.
- iii) construct an **ImageData** by using the **boundary** entities.
  - iii.i) assign to a grid zero or one if a **boundary** entity passes it or not, respectively.
  - iii.ii) form clusters by connecting grids which have the value of  $-1$ .
  - iii.iii) find a cluster which corresponds to roads, examining the area and configuration of the cluster
- iv) choose a pair of **boundary** entities which form a road using the **ImageData**.
- v) convert the pair to a **corridor** entity.
- vi) construct a **path** entity for an edge which is shared by two **corridor** entities.

The construction of the **ImageData** plays a key role in enhancing the robustness of the automatic data conversion. Figure 14.14 illustrates the procedures of the construction; a) shows a set of **boundary** entities; b) shows that four clusters are formed; and c) shows that a three-forked road is identified in the **ImageData**.

### 14.5.3 Example of automatic data conversion for GIS

A top view of a road network, which is stored in GIS, is shown in Fig. 14.15. Most roads are narrow, and there are several clusters of short roads. An environment, which is automatically converted from this GIS, is shown

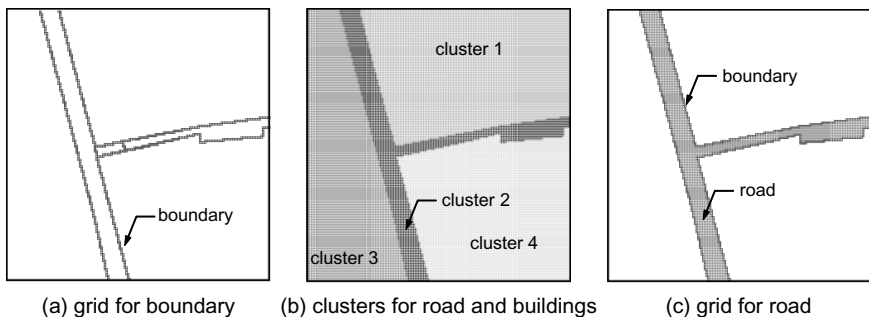


Fig. 14.14 Procedures of finding a road using **ImageData**.

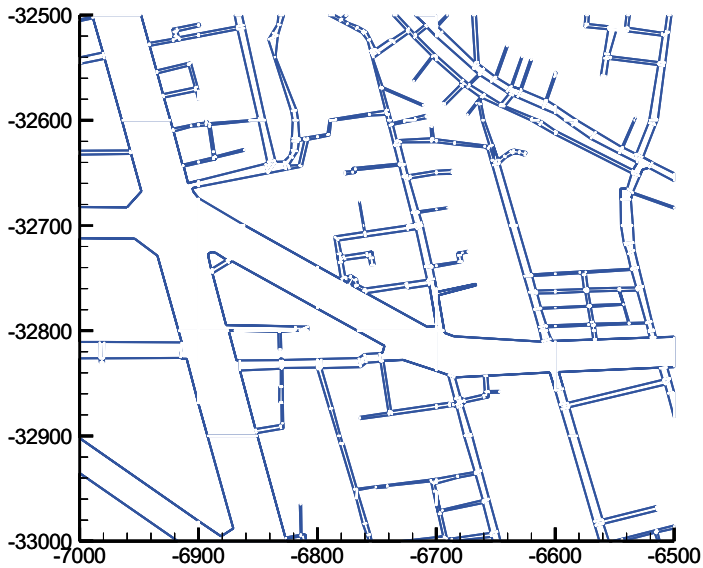


Fig. 14.15 A street network formed by the building perimeters stored in GIS.

in Fig. 14.16. It is seen that the automatic data conversion is successfully made.

In constructing an `ImageData`, connection of neighbouring grids has to be analysed to form clusters. Numerical computation needed for this analysis increases linearly to the square of the grid number. For efficient computation, a target domain is divided into several small zones each of which the automatic data conversion is separately applied to. An environment made for the whole domain is constructed by connecting the environments made for the small zones. The environment shown in Fig. 14.16 is actually constructed in this manner; gray lines are intersections between divided small zones.

#### 14.5.4 Automatic data conversion for CAD data

While CAD files<sup>14</sup> are generally in binary format, such as `dwg`, it is assumed in this subsection that the files in ASCII format of `dxf` are given.

<sup>14</sup>There are many commercial applications for CAD, and each application produces binary/ASCII files which have distinct properties. It is not trivial to make robust data conversion for such CAD files even though the format of these files is common.

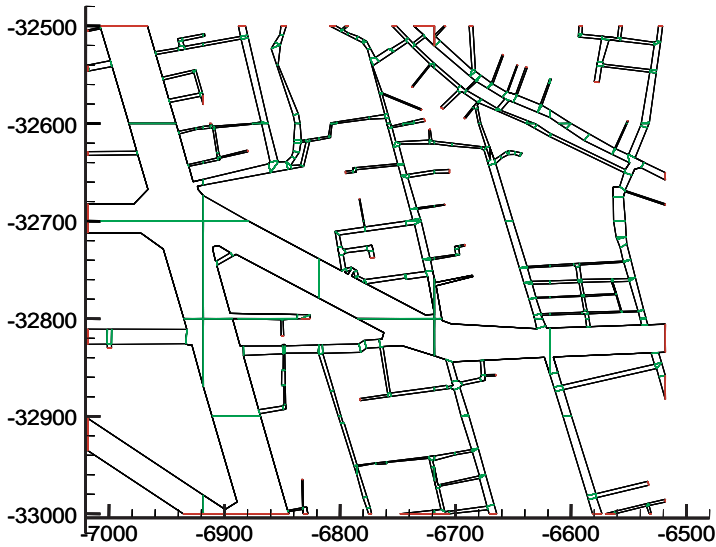


Fig. 14.16 A MAS environment for a street network made by the automatic data conversion.

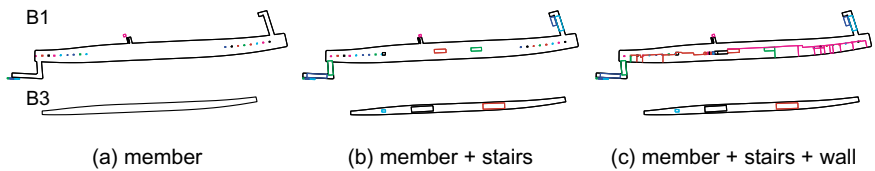


Fig. 14.17 The processes of the CAD data extraction.

From these files, data for **member**, **stairs** and **wall** entities are extracted. Figure 14.17 shows extracted data; a) is for **member** entities which are first extracted; b) is for **stairs** entities which are added to **member** entities; and c) is the final form in which **wall** entities are added. Other data, such as material properties, do not have to be extracted.

Since CAD is used to design structures, information about empty spaces, which will be an evacuation route, is not stored. By using an **ImageData**, it is possible to extract the empty spaces in the same manner as the automatic data conversion of GIS. Unlike GIS, however, the CAD data are described in unit of millimeter<sup>15</sup> to describe the geometry of structure members, and

<sup>15</sup>An **ImageData** converted from the CAD data needs grids of a few centimeters, and the size of the **ImageData** becomes huge; for instance, when the CAD data of a large

the data conversion that uses the `ImageData` of the corresponding grid size needs huge computation. The *direct* conversion is considered as an alternative, i.e. a set of near-by entities of CAD data are combined to form a polygon from which an entity of a MAS environment is constructed. The configuration of the entities is complicated for places where many structure members are closely located. It is, thus, difficult to make the direct conversion automatically, and there are cases where manual conversion is needed.

The procedures of converting a CAD file to a MAS environment are summarised as follows:

- i) extract `member`, `stairs` and `wall` entities from a CAD file.
- ii) determine a set of near-by `member` entities which form an empty space.
- iii) construct a `corridor` entity for the empty space.
- iv) construct a `path` entity for the intersection of two `corridor` entities.
- v) construct a `stairs` entity so that `corridor` entities in different floors are connected.

The construction of `stairs` entities<sup>16</sup> needs some special care; information stored in a CAD file is used to draw plan view for each floor, and stairs connecting floors appear in two plan views.

#### 14.5.5 *Example of automatic data conversion of CAD data*

A CAD file for an actual subway station is used to construct a MAS environment. CAD data extracted from these files are shown in Fig. 14.18; there are around 700 line segments. A line segment is given as a data set which starts from a mark of `AcDbEntity` and accompanies data starting from a mark of `Line` followed by coordinates of the two end points of the line segment. There are other marks<sup>17</sup> which identify the type of the data set (see Table 14.7). The data set following the mark of `member`, `stairs/esca` or

---

underground shopping mall the dimension of which exceeds  $10^2$  m are converted, the number of grids is more than  $10^5 \times 10^5$  if its size is  $10^{-3}$  m.

<sup>16</sup>Since an object `stairs` is introduced, the present MAS is able to compute agents moving from one floor to another. An environment for a subway station uses `stairs` entities. The present MAS has an option which reduces the movement of an agent while it is in a `stairs` entity.

<sup>17</sup>The marks shown in Table 14.7 are used in the CAD file that is studied in this subsection. Other CAD files possibly use different marks.

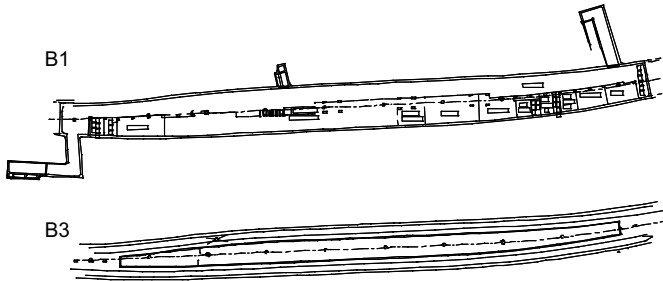


Fig. 14.18 Perimeters of structure members stored in a CAD file.

Table 14.7. Marks for data stored in a data set of `AcDbEntity`.

Mark	Meaning
DEFOPINTS	Reference point
Member	Outline of structure member
Center	Center of structure member
Geography	Line for geographical object
Dimension	Line for dimension
Separator	Line for room separation
Stairs/esca	Line for stairs and escalator
Steel pipe	Line for steel pipe column
Title	Line for title
Letter	Line for letter

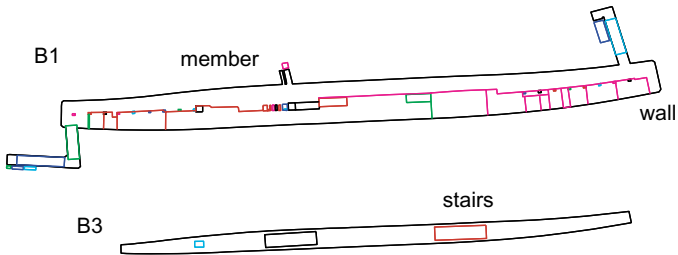


Fig. 14.19 The `member`, `stairs` and `wall` entities obtained by the direct conversion.

separator is used to extract a `member`, `stairs` or `wall` entity, respectively. The extracted entities are shown in Fig. 14.19.

Using these entities, the automatic data conversion is made, and the resulting `corridor` and `path` entities are presented in Fig. 14.20; a) is for the two-dimensional top view of the constructed environment and b) is a

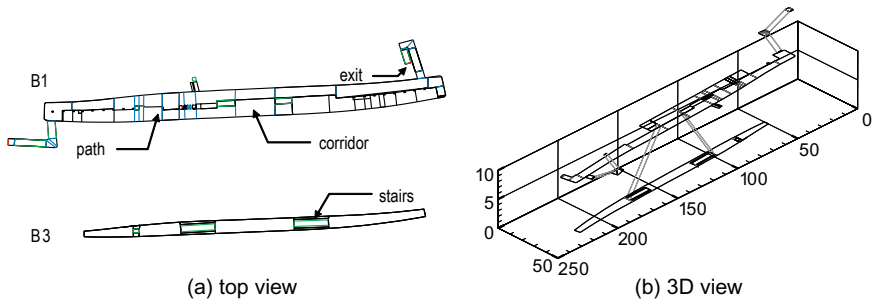


Fig. 14.20 A MAS environment for a subway station made by the automatic data conversion for CAD data.

three-dimensional view. It is seen that the data conversion is successfully made.

## 14.6 Examples of Multi-Agent Simulation for Evacuation Process Analysis

This section presents several examples of MAS for the evacuation process analysis in order to examine the safety of public spaces during emergency evacuation. The target public spaces are a road network, a subway station and an underground shopping mall. It should be emphasised that *slow* agents, whose maximum speed follows a walking speed distribution of aged individuals, are introduced. The presence of the slow agents leads to higher heterogeneity of agents so that evacuation processes become more disorganised. The distribution of aged individual walking speed is measured by using the image analysis, and the measurement is made in two public parks (see [Hori *et al.* (2008)]). Table 14.8 shows the average and standard deviation of the walking speed of the aged individuals in the two parks.

MAS uses a Monte-Carlo simulation in which agents of distinct maximum speed and initial positions are randomly generated. As shown in

Table 14.8. The walking speed distribution of aged individuals measured in two parks.

	Park 1	Park 2
Mean [m/s]	1.12	1.03
S.D. [m/s]	0.26	0.13

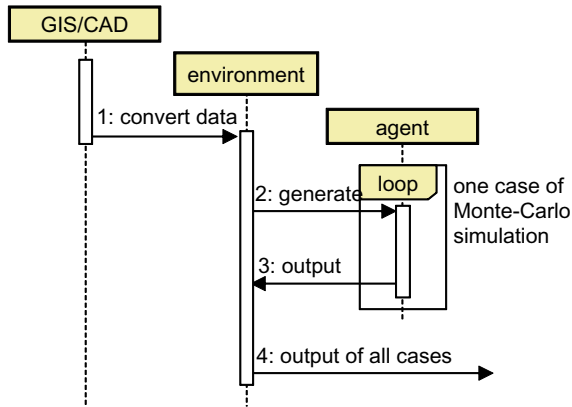


Fig. 14.21 Procedures of a Monte-Carlo simulation of MAS.

Fig. 14.21, the procedures of the Monte-Carlo simulation are summarised as follows:

- i) construct an environment from digital data by applying the data conversion,
- ii) generate a set of agents randomly and locate them randomly in the environment.
- iii) carry out one case of MAS for the agents generated in ii).
- iv) repeat ii) and iii) and output results of all the cases.

The average and standard deviation of the evacuation time, i.e., time in which all agents complete evacuation, is obtained by carrying out 200 cases; they take on a more or less the same value as the number of the cases exceeds 200. For instance, Fig. 14.22 shows the convergence of the standard deviation when a rectangular evacuation route studied in Section 14.3 is used; the standard deviation is normalised with the value of 800 cases. As seen, the standard deviation converges around 200 cases.

### 14.6.1 Road network

A MAS environment shown in Fig. 14.16 is used as a network of evacuation routes. The parameters used for the present MAS are summarised in Table 14.9. As shown in this table, the maximum number of agents is 5,000. The whole area of the evacuation routes is 64,000 m<sup>2</sup>, and the maximum agent density is 0.08/m<sup>2</sup>. Thus, a crowded state is not assumed for the evacuation process in the present MAS.

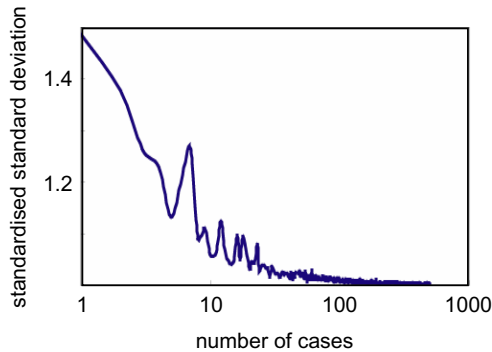


Fig. 14.22 The convergence of the standard deviation of the evacuation time.

Table 14.9. Parameters used for the road network analysis.

Number of agent		500/1000/2000 /3000/4000/5000
Modification angle at passing [deg]		60
Speed reduction ratio [%]		50
Slow agent ratio [%]		20
Average of maximum moving speed [m/s]	Normal	1.4
	Slow	1.1
S.D. of maximum moving speed [m/s]	Normal	0.6
	Slow	0.3
Forcible passing probability	Normal	1.0
	Slow	0.5

As an illustrative example to show the movement of agents, snapshots for the spatial distribution of agents are presented in Fig. 14.23. The snapshot is taken every 60s, the number of agent is 2,000 and the agent is expressed as a circle of 50 cm radius. After 60s more than 50% of agents complete evacuation. In the present MAS agents do not have information about the location of `exit` entities and have to keep searching a near-by `exit` entity until one is found. Thus, there are some agents which keep *wandering* around the environment. After 180s 90% of agents complete evacuation since agents moving in wide evacuation routes reach the `exit` entities. However, agents in a cluster of narrow evacuation routes keep wandering around there, since they do not find an `exit` entity.

The average of the evacuation time distribution is computed for different numbers of agents, and the results are presented in Fig. 14.24.

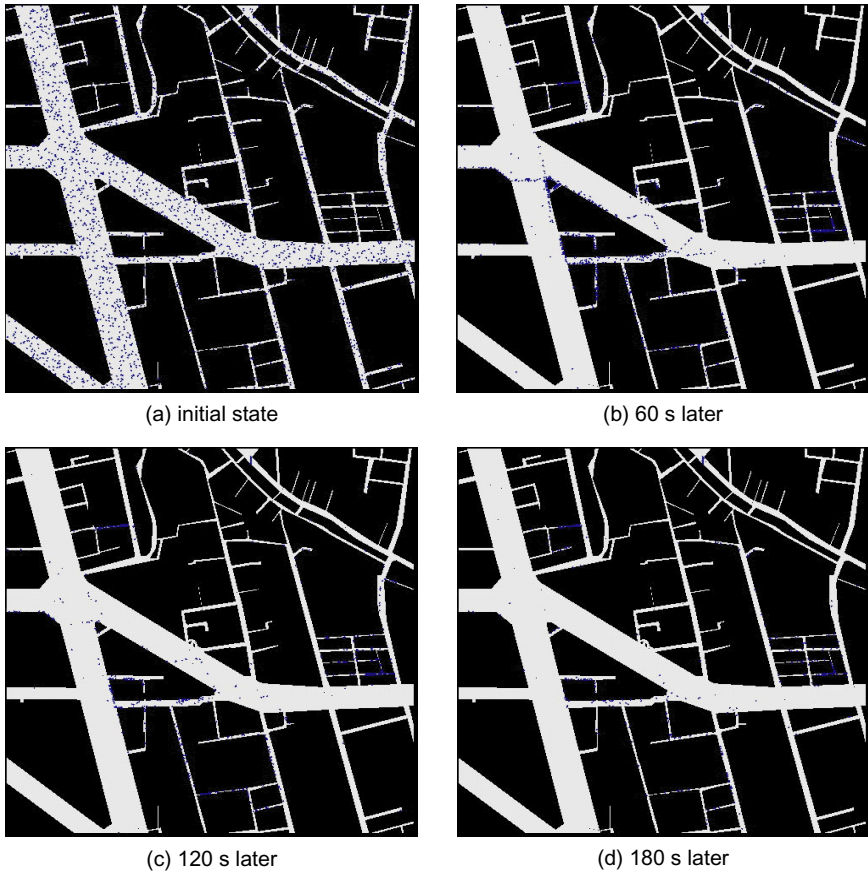


Fig. 14.23 Snapshots of the agent distribution taken every 60 s in the street network.

The horizontal axis is for the evacuation time and the vertical axis is the ratio of agents which complete evacuation within the designated evacuation time. The average evacuation time, in which 50% of agents complete evacuation, does not change depending on the number of agents. However, the average evacuation time tends to become longer as the number of agents increases. This implies that more agents are wandering around the environment for a longer time as the number of agents increases.

In order to examine the effects of the presence of slow agents on evacuation time, two cases of the slow agent ratio, zero and 20%, are simulated; there are 500 and 5,000 agents. The average of the evacuation time distribution is shown in Fig. 14.25; a number in a parenthesis indicates the slow

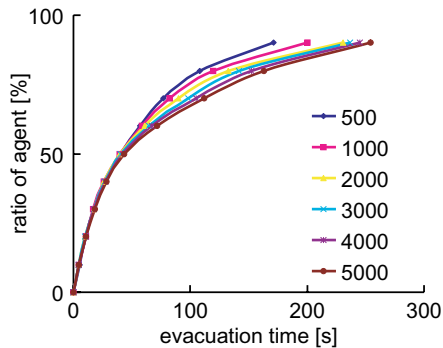


Fig. 14.24 The average of the evacuation time distribution: effects of the number of agents.

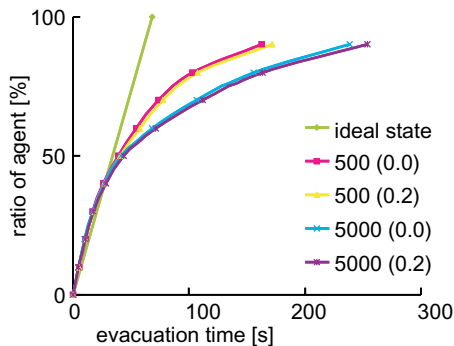


Fig. 14.25 The average of the evacuation time distribution: effects of the presence of slow agents.

agent ratio. The evacuation time distribution for an ideal state, in which all agents move smoothly at the same average speed, is presented for comparison. It is seen that approximately 40% of agents complete evacuation as in the ideal state. The presence of slow agents slightly changes the evacuation time distribution so that more time is needed for the evacuation. Viewing along the horizontal axis, the delay due to the presence of slow agents is around 10 s.

As mentioned, agents do not have information about the location of exit entities. Some agents wander around a complicated network of narrow evacuation routes even though they have memory about the corridor entities which they have passed. The increase in the evacuation time when there is 5,000 agents shown in Fig. 14.25 is caused by this wandering. The

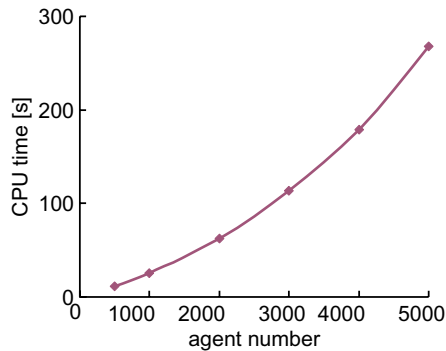


Fig. 14.26 The relation between the agent number and the CPU time.

presence of slow agents contributes the increase in the evacuation time, but the amount of increase is negligibly smaller if compared with that due to wandering. This result is interpreted as follows: the major fact that prevents smooth evacuation is not the presence of slow individuals, but wandering around places with which individuals are not familiar.

Scalability of parallel computation is examined for the present MAS. A PC cluster<sup>18</sup> which consists of 8 CPU (AMD Opteron 875, 2.2 GHz, 4 GB memory) is used, and ten cases of Monte-Carlo simulation are carried out to measure the CPU time. As shown in Fig. 14.26, as the agent number increases, the CPU time increases almost linearly, which supports the scalability of the present MAS. There is a trend that more CPU time is needed for a larger number of agents, but this is mainly because the number that passing and stopping options are taken increases.

### 14.6.2 *Subway station*

Small and large subway stations are studied as an example of comparing the safety of different public spaces by means of MAS. An environment for the small subway station is the one presented in Section 14.5 (see Figs. 14.18 and 14.20, respectively, for the CAD data and the environment). For the large subway station, the CAD data and the environment obtained by the

<sup>18</sup>When there are 500 agents, the CPU time of this PC cluster is 20 s for one case. It becomes 340 s for a PC (Pentium 4, 2.8 GHz, 2 GB memory).

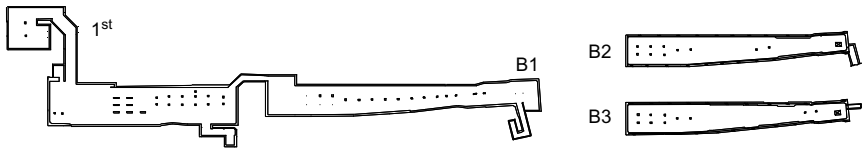


Fig. 14.27 Structure members of the large subway station stored in CAD.

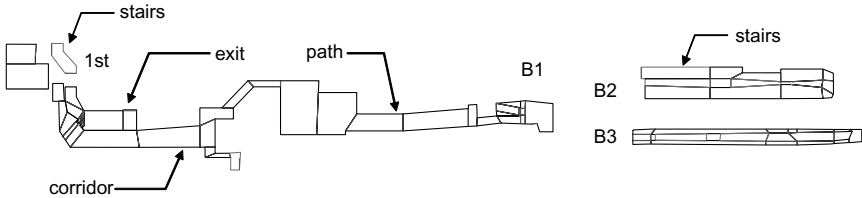


Fig. 14.28 A MAS environment for the large subway station.

Table 14.10. Parameters used for the subway station analysis.

Number of agents		70/200/300
Modification angle at passing [deg]		60
Speed reduction ratio [%]		50
Slow agent ratio [%]		0/20
Average of maximum moving speed [m/s]	Normal	1.4
	Slow	1.1
S.D. of maximum moving speed [m/s]	Normal	0.6
	Slow	0.3
Forcible passing probability	Normal	1.0
	Slow	0.5

data conversion are shown in Figs. 14.27 and 14.28, respectively. The parameters<sup>19</sup> used for the present MAS are summarised in Table 14.10.

The evacuation time distribution of 200 cases of Monte-Carlo simulation is plotted as a three-dimensional graph in Fig. 14.29; the number of agents and the slow agent ratio are 200 and 0%, respectively; the vertical axis is the number of agents that complete evacuation, not the cumulative number of the agents. It is seen that the evacuation time distribution is different

<sup>19</sup>The maximum number of agents is 300 as shown in Table 14.10. This is because passengers using a large subway station per day is around 80,000. This means that the average passengers per hour is 4,500 if the operation time of the station is 18 hours, and that, except for rush hours, passengers staying at a subway station is of the order of 100.

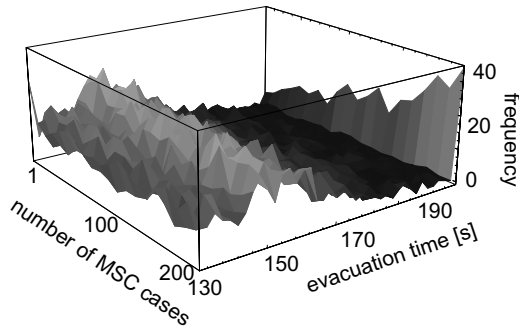


Fig. 14.29 The evacuation time distribution of 200 Monte-Carlo simulation cases for the small subway station.

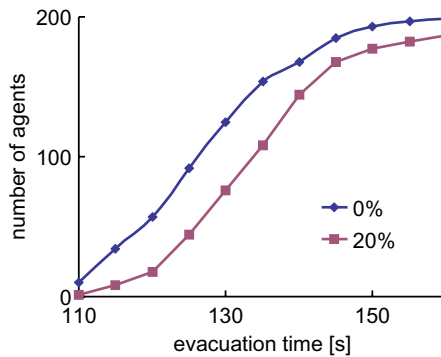


Fig. 14.30 The average of the evacuation time distribution for the small subway station.

from each other. However, in most cases, the distribution has a peak around 150s; there is another peak at 200s, since the Monte-Carlo simulation is stopped at 200s.

When there are 200 agents, the average evacuation time is computed for the case when the slow agent ratio is 0 and 20%. The results are shown in Fig. 14.30. It is obvious that the presence of slow agents delays the evacuation process. However, the delay is around 10s, for instance, the evacuation time for 100 agents to complete evacuation is changed from 126s to 135s.

For the large subway station, the average evacuation time distribution is shown in Fig. 14.31; there are 200 agents and the slow agent ratio is zero and 20%. Like the small subway station, the presence of the slow agents delays the evacuation process, for instance, the increase in the evacuation

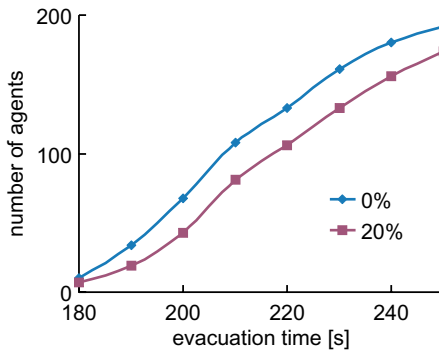


Fig. 14.31 The average of the evacuation time distribution for the large subway station.

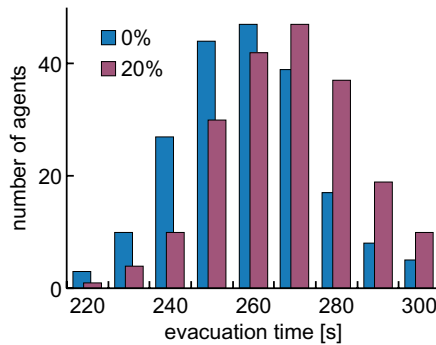


Fig. 14.32 The evacuation time distribution for 80% of agents to complete evacuation in the large subway station.

time is around 12s for 100 agents to complete evacuation. This delay is similar to that for the small subway station. However, longer evacuation time is computed for the large station; since the `corridor` area is larger, agents have to move a longer distance to reach an `exit` entity.

To examine the effects of the slow agent presence in detail, Fig. 14.32 plots the distribution of the evacuation time for 80% of agents to complete evacuation; when there are 200 agents. The delay due to the presence of slow agents is obvious. However, the amount of delay is around 20s, since it seems that the distribution<sup>20</sup> of agent evacuation time is shifted to the right by 20 s when 20% of the agents are replaced with the slow agents.

<sup>20</sup>It should be noted that the distribution shown in Fig. 14.32 looks like a normal distribution, with a slightly large tail.

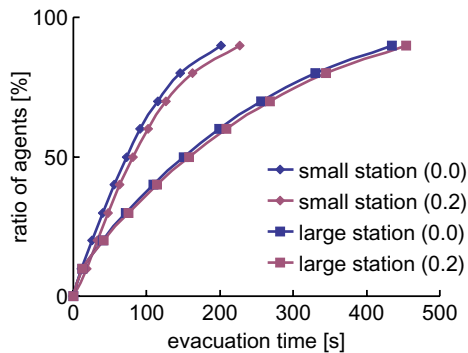


Fig. 14.33 The comparison of the average of the evacuation time distribution for the small and large subway stations.

MAS is carried out in order to make more quantitative comparison of the evacuation time distribution for the two subway stations. The density of agents per unit area is set the same for the two stations. The area of all **corridor** entities of the large subway station is  $7,500\text{m}^2$ , which is 2.3 times larger than that of the small subway station,  $3,300\text{m}^2$ . Hence, the number of agents is set at 300 and 680 for the small and large subway stations, respectively.

The average of the evacuation time distribution is shown in Fig. 14.33. The evacuation time is almost the same for 10% of agents to complete evacuation in the two stations. The evacuation time for a larger percentage of agents to complete evacuation becomes longer for the large station, for instance, the evacuation time for 80% of agents to complete evacuation is 200s and 450s for the small and large subway stations, respectively. The ratio of the two evacuation times is 2.2, which is similar to the ratio of **corridor** areas of the two stations. The width of **corridor** entities is more or less the same in the two stations, and hence the ratio of **corridor** area gives a ratio of average distance, which is needed for an agent to complete evacuation.

To study the difference in the effects of the slow agent presence between the two subway stations, Fig. 14.34 shows a distribution of the delayed evacuation time, which is caused by the presence of slow agents. The delayed evacuation time is the increase in the evacuation time caused by the presence of 20% of slow agents. It is seen that longer delay is caused for the small station than for the large station. While the difference in the delayed evacuation time varies, the maximum difference is less than 10 s. Compared

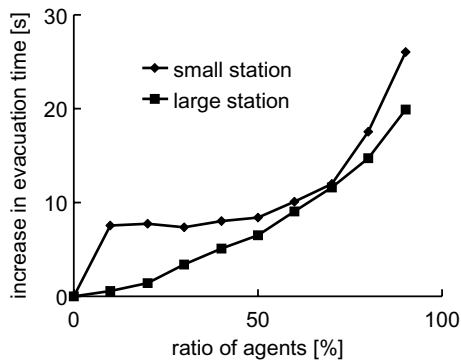


Fig. 14.34 The comparison of the delayed evacuation time caused by the presence of slow agents for the small and large subway station.

with the delay due to agents' wandering, this difference is not significant at all.

Based on these simulation results, the following conclusions are drawn regarding to the safety of the two subway stations: 1) if the agent density is the same, longer evacuation time is needed for the large subway station, mainly because longer distance must be travelled for an agent to reach an exit; and 2) the presence of slow agents causes longer delay, but the delayed evacuation time is negligible compared with the delay due to wandering. Thus, no significant difference in the safety<sup>21</sup> between the small and large subway stations is found during an emergency evacuation.

### 14.6.3 Underground shopping mall

An *earthquake early warning* (EEW) system, which measures a P-wave of an earthquake by using a seismograph network and provides strong ground information to the public, has been operating in Japan since 2007. While there are numerous applications, this system can be used to smoothen the emergency evacuation in a public space right after an earthquake, since individuals who receive an EEW are able to prepare for the upcoming strong ground motion. However, there is a possibility that panic would spread in the public space if there are two groups, a group of individuals,

<sup>21</sup>As shown in Fig. 14.29, there are exceptional cases in which the evacuation time becomes very long; 10 out of 200 cases are regarded as such exceptional cases. Therefore, it is interpreted that the probability that exceptional delay in the evacuation process would occur is around 5%.

who receive an EEW and the other group of individuals, who do not. An attempt is made to apply MAS to analyse possible positive and negative effects of EEW on the emergency evacuation.

An underground shopping mall is used as a public space. Figure 14.35 shows CAD data for the mall; these data are extracted from a file whose format is not dxf, but the automatic data conversion explained in the preceding section is applicable with some minor modification. The constructed environment is presented in Fig. 14.36. The domain decomposition is used to reduce computational costs. There is no `stairs` entity in the environment, and four `exit` entities are set at the four corner of the mall.

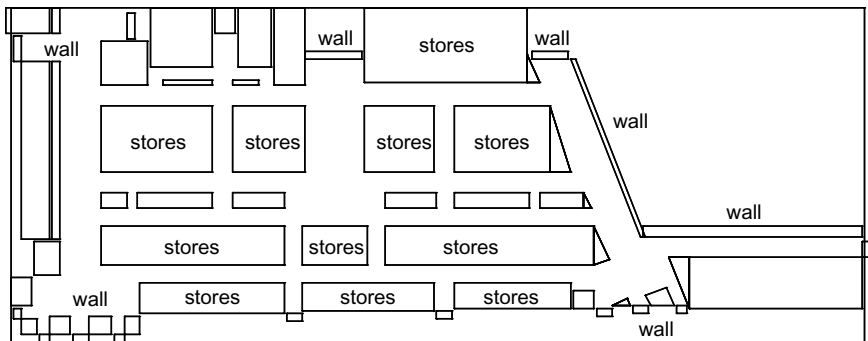


Fig. 14.35 CAD data for a large underground shopping mall.

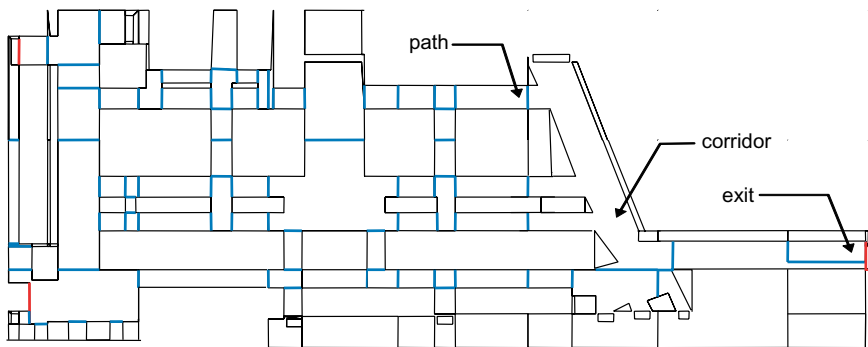


Fig. 14.36 A MAS environment constructed from the CAD data for the underground shopping mall.

Table 14.11. The maximum speed distribution of an agent that receives an EEW and an agent that does not receive an EEW.

Time [s]		$0 < t < 10$	$10 < t < 50$	$50 < t$
Agent receiving EEW	Mean [m/s]	4.1	0.0	4.1
	S.D. [m/s]	1.3	0.0	1.3
Agent not receiving EEW	Mean [m/s]	1.4	0.0	4.1
	S.D. [m/s]	0.6	0.0	1.3

It is supposed<sup>22</sup> that individuals who receive an EEW start evacuation before the strong ground motion hits the mall while other individuals start evacuation after the strong ground motion stops. The scenario of this situation is described as follows:

- i) agents who receive an EEW start evacuation 10 s before strong ground motion hits the environment.
- ii) all agents stop during the duration of the strong ground motion 30 s.
- iii) agents who do not receive the EEW start evacuation after the strong ground motion stops.

As seen, it is 10 s that an agent who receives an EEW can spend evacuating prior to the strong ground motion. A faster distribution is used for the maximum speed of an agent who starts evacuation; the average and stand deviation are 4.1 m/s and 1.3 m/s, respectively. The maximum speed distribution for agents that do and do not receive an EEW are summarised in Table 14.11. The other parameters used in the present MAS are summarised in Table 14.12. Note that the maximum number of agents is 1,000. Since the area of all `corridor` entities is 113,000 m<sup>2</sup>, the maximum density is 0.08 /m<sup>2</sup>.

When there are 1,000 agents, a snapshot of the spatial distribution of agents is taken every 60 s (see Fig. 14.37). After 60 s, most agents move along walls of `corridor` entities; the agents, who do not have information of `exit` entities, think that the direction along the walls is the way to move out from the `corridor` entity in which it is located. It should be noted that there is a dead end at the left part of the environment. When agents enter

<sup>22</sup>This situation corresponds to the case where the evacuation of the agents which receive an EEW causes a crowded state near `exit` entities before the strong ground motion hits the model.

Table 14.12. Parameters used for the underground shopping mall analysis.

Number of agents	200/300/1000	
Modification angle at passing [deg]	60	
Speed reduction ratio [%]	50	
Slow agent ratio [%]	0/20	
Reduction ratio of average and S.D. for slow agents [%]	50	
Forcible passing probability	Normal	1.0
	Slow	0.5
Ratio of agents which receive EEW [%]	0/10/30	

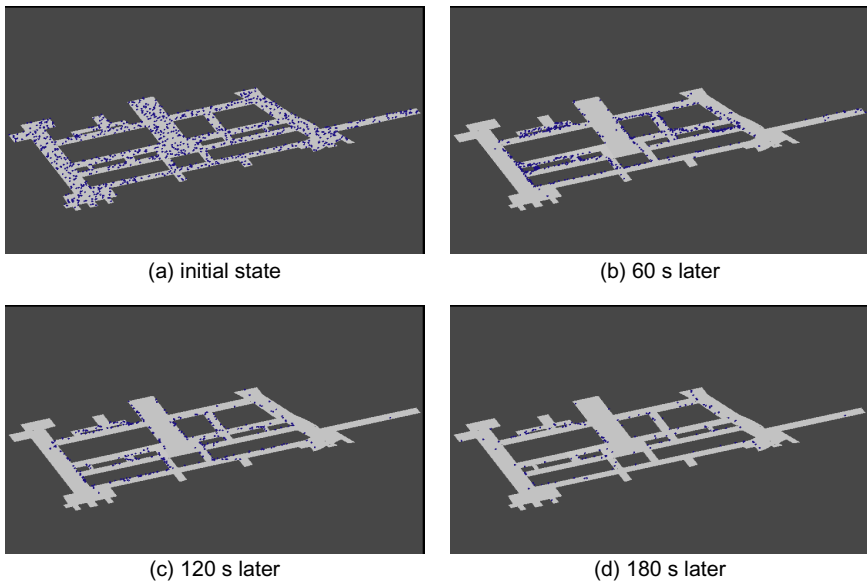


Fig. 14.37 Snapshots of the agent distribution taken every 60s in the underground shopping mall.

this dead end, they have to go back following<sup>23</sup> the paths they have passed. It is shown that the number of agents, which enter the dead end, decreases as the time increases.

<sup>23</sup>The path of **thought** data of an object **agent** stores **corridor** entities which it has moved through. If it cannot find a **corridor** entity in which it has not moved, the agent moves back to these entities according to the path until it finds a **corridor** entity which is new to it.

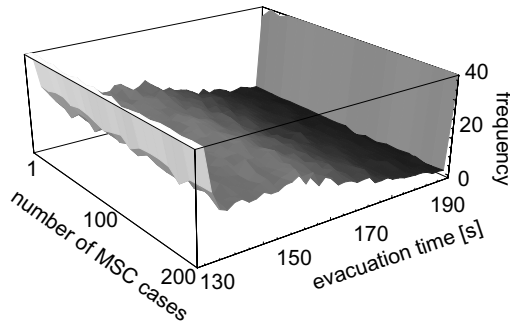


Fig. 14.38 The evacuation time distribution for the underground shopping mall.

The evacuation time distributions of 200 cases of Monte-Carlo simulation are shown in Fig. 14.38; the number of agents, the slow agent ratio and the ratio of agents who receive an EEW are 1,000, 10% and 0%, respectively. The variability of the distribution is relatively smaller than that for the small subway station, which is shown in Fig. 14.29. This is probably because there are 4 exit entities in the present environment, so the evacuation process becomes smoother.

To compare the effects of EEW on the emergency evacuation, two cases of the ratio of agents which receive an EEW, 10 and 50%, are studied, and the distribution of the evacuation time for 80% of agents to complete evacuation is presented in Figs. 14.39 and 14.39, respectively; the number of agents is 200 or 1,000 and the slow agent ratio is 0 or 30%; the horizontal axis is the evacuation time and the vertical axis is the accumulated number of the Monte-Carlo simulation cases in which 80% of agents complete evacuation by the designated evacuation time. For all pairs of agents and slow agent ratio, the evacuation time is shortened due to the increase in the ratio of agents who receive an EEW. For instance, 80% of agents can complete evacuation before 160 s when the ratio is 50%, but there are some cases in which 80% of agents do not complete evacuation when the ratio is 10%.

The presence of slow agents delays the evacuation time for 200 or 1,000 agents (see Fig. 14.39). However, the delay is not significant, for instance, the increase in the evacuation time is less than 10 s for Fig. 14.39. In Fig. 14.40, the increase is much smaller than 10 s, which means that the delay due to the presence of slow agents is decreased if more agents receive an EEW.

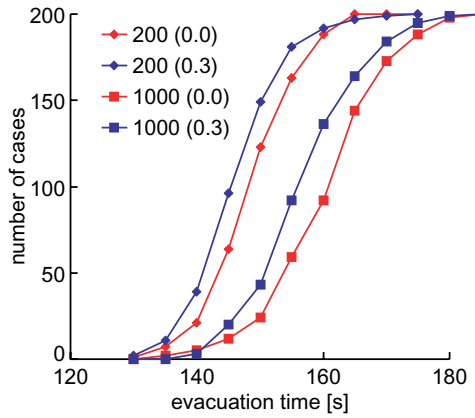


Fig. 14.39 The distribution of the evacuation time for 80% of agents to complete evacuation in the underground shopping mall; the slow agent ratio is 10%.

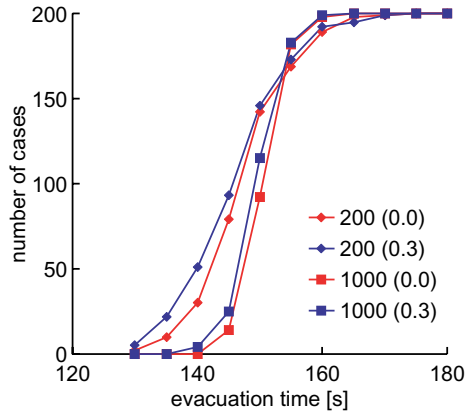


Fig. 14.40 The distribution of the evacuation time for 80% of agents to complete evacuation in the underground shopping mall; the slow agent ratio is 50%.

In the right top of Fig. 14.40, the evacuation time for the slow agent ratio 30% becomes shorter than that for the slow agent ratio 0%. Although only five cases among the 200 cases produce this result, it is suggested that the presence of agents receiving an EEW, fully cancel the effects of the slow agent presence on the evacuation time.

The following conclusions could be drawn, regarding to possibly positive and negative effects of EEW on the emergency evacuation: 1) the evacuation

time is shortened as the ratio of agents receiving an EEW increases and 2) the presence of agents receiving an EEW reduces the increase in the evacuation time due to the presence of slow agents. While more studies are surely needed to make solid conclusions about EEW, positive effects of EEW on the emergency evacuation should not be underestimated; this is simply because agents who receive an EEW can start evacuation before the strong ground motion.